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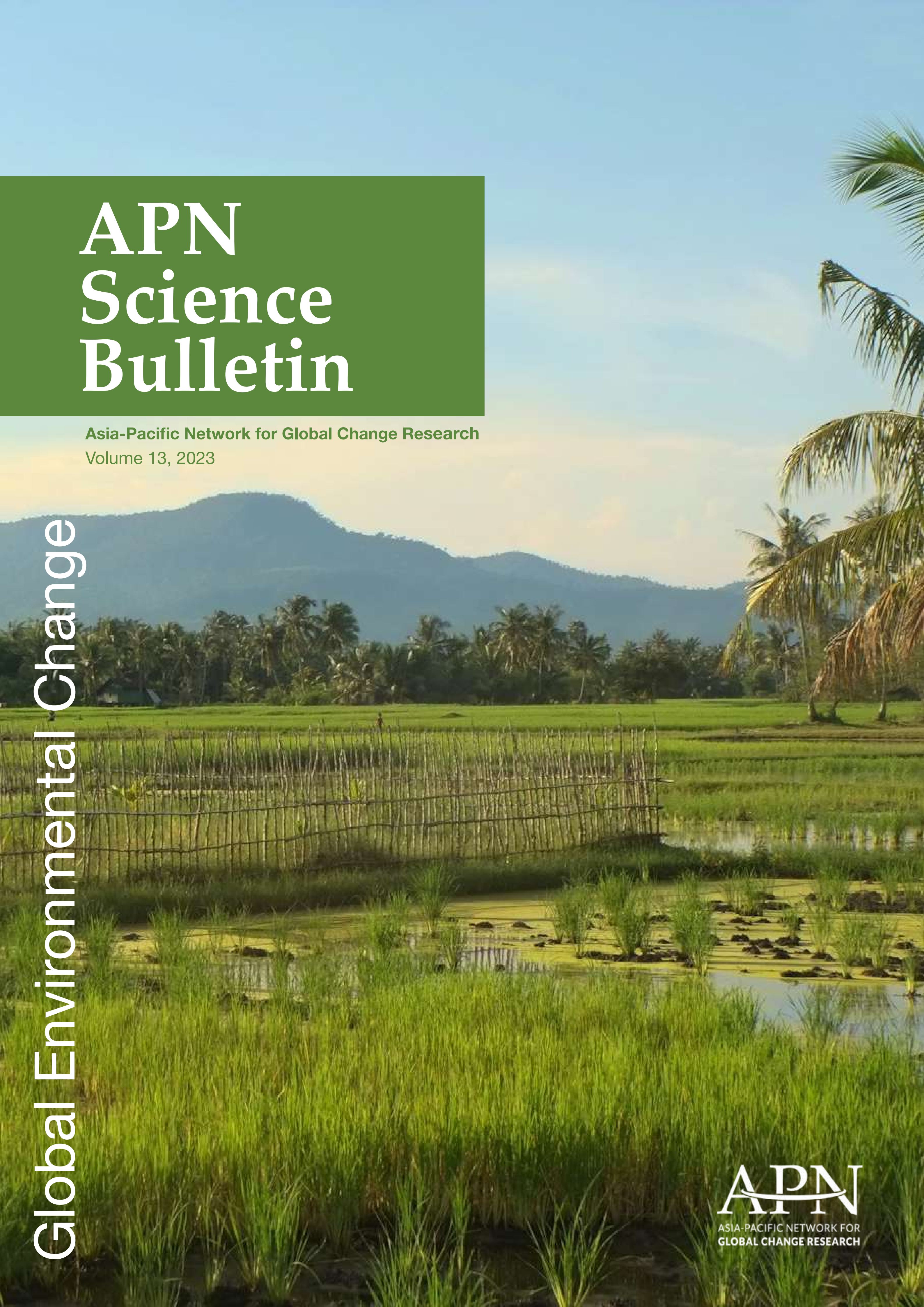

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■ The APN Science Bulletin is a peer-reviewed digital publication that features research and capacity building projects funded by APN. The Science Bulletin is intended for readers from both science and policy-making communities, as well as young scientists in the Asia-Pacific region who are keen on promoting global environmental change, sustainable development and the science of sustainability.

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Preface

This collection of articles in the APN Science Bulletin 2023 compilation presents a comprehensive overview of research initiatives and projects that address the pressing challenges posed by climate change and its impacts on ecosystems, natural resources and human well-being. Each study highlights the critical need for robust climate information at regional scales, emphasising the importance of tailored, data-driven solutions in fostering sustainable development and informing global change policies.

The articles collectively underscore the importance of capacity building and the engagement of early career professionals, particularly in the Asia-Pacific region. By promoting active participation and networking, these initiatives enhance scientific knowledge and strengthen international collaborations, which are vital for advancing climate science and effective management strategies.

A recurring theme throughout these studies is the focus on enhancing local adaptive capacities, especially in vulnerable rural and urban communities. Projects aimed at improving resilience in Southeast Asian farming communities, for example, demonstrate the effectiveness of sustainable farming techniques and multisectoral collaborations in addressing climate change impacts. Similarly, efforts to develop low-cost micro-irrigation systems and climate-smart agriculture practices highlight the potential for innovative solutions to improve food security and community resilience.

Urban areas also receive significant attention, with research examining greenhouse gas emissions and identifying low-carbon pathways in major Asian cities. These studies provide critical insights into the unique challenges and opportunities faced by urban centres in mitigating climate change and promoting sustainable development.

Furthermore, the articles explore the development of tools and frameworks for water security assessment, disaster waste management and air quality management. These contributions are essential for enhancing the decision-making capabilities of policymakers and ensuring the sustainability of environmental and resource management practices.

In addition, the collection addresses the complexities of groundwater resilience, the impacts of climate change on high-altitude farming regions and the development of climate-smart agriculture strategies. These studies emphasise the importance of localised, context-specific approaches to adaptation and resilience building.

In summary, this compilation offers valuable perspectives on global change policy-relevant research and sustainability. By integrating scientific research, capacity building and community engagement, these studies advance our understanding of climate resilience and inspire future initiatives aimed at safeguarding our planet for generations to come. The diverse array of projects and their findings provide a roadmap for effective action, reinforcing the need for continued collaboration and innovation in addressing global change.

Linda Anne Stevenson

Managing Editor, APN Science Bulletin
Acting Director, APN Secretariat

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Technical report

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Promoting involvement of early-career scientists from the Asia-Pacific region in regional integrated and sustainable development through active participation and networking

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ABSTRACT

Climate change is affecting global ecosystems, natural resources, and human well-being. The near- and long-term future sustainable development of society requires robust climate change information at regional scales. To contribute to the purpose mentioned above, the World Climate Research Programme's Coordinated Regional Climate Downscaling Experiment (WCRP CORDEX) initialised a collaboration with the Asia-Pacific Network for Global Change Research (APN), as the two programmes share common goals in advocating climate science as well as transferring climate knowledge for effective management. This APN project, entitled "Promoting Involvement of Early Career Scientists from the Asia-Pacific Region in Regional Integrated and Sustainable Development through Active Participation and Networking", was a result of this collaboration. Specifically, the project was aimed at supporting early-career scientists from the Asia-Pacific region to attend an international science conference on regional climate science (ICRC-CORDEX 2019) and facilitate them in international partnership-building. It also contributed to enhancing communication and cooperation amongst regional climate research teams within and beyond the Asia-Pacific region. As one of the most important activities of the conference, the project supported an event for early-career scientists. The completion of the project consolidated global collaboration between the climate research community and that of adaptation-impact studies, as well as facilitated interaction with end-users. It was also a successful showcase of the scientific strategies of APN and CORDEX.

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KEYWORDS

CORDEX, regional climate downscaling, impact and adaptation, international science conference

HIGHLIGHTS

- CORDEX contributes to advancing climate science and sustainability at the regional level.
- APN supported a successful event for early-career scientists as an essential part of ICRC-CORDEX 2019.
- APN-funded early-career scientists and students were active in the conference and helped in achieving the project's objectives.
- ICRC CORDEX-2019 contributed to APN's mission of promoting regional and interdisciplinary cooperation.
- ICRC CORDEX-2019 contributed to achieving APN's goal of supporting capacity development within and beyond the Asia-Pacific region.

1. INTRODUCTION

Regional climate downscaling with limited-area dynamical models and statistical models has the advantage of being able to reproduce more detailed and authentic mesoscale responses to various climate forcings. As such, the method can be applied across a range of applications, from single-event simulations (e.g., climate extremes) to integrated earth system studies (e.g., the response of the monsoon system to global warming). When the World Climate Research Programme (WCRP) endorsed the Coordinated Regional Climate Downscaling Experiment (CORDEX), it was the first global coordinated effort to identify robust climate change signals over various CORDEX domains covering most of the world's land surface, as well as provide a solid scientific basis for impact assessments of climate change at local to regional scales across the globe.

In the face of the urgent requirements stemming from regional "vulnerability, impact and adaptation" (VIA), as well as from policymakers in formulating strategies and taking action in Asia and elsewhere around the world, ICRC-CORDEX 2019, an international science conference on regional climate science, was organised and invited regional climate science communities from different areas of the globe to share their achievements and discoveries on regional climate downscaling. Held from 14–18 October 2019 in Beijing, China, ICRC-CORDEX 2019 was hosted by the WCRP and the Institute of Atmospheric Physics, Chinese Academy of Sciences (IAP/CAS), with joint support from global organisations including the Asia-Pacific Network for Global Change Research (APN), Swedish Meteorological and Hydrological Institute (SMHI), Nanjing University, and others. At the conference, the overall achievements in applying advanced downscaling methods in regional studies, along with the benefits and extra information such methods provide to VIA, climate change scenarios at a regional scale, and new technology in climate studies, were presented. ICRC-CORDEX 2019 was also a platform for presenting new frontiers in regional climate science research, including the integration of biochemical processes, regional oceans, and human–climate interactions in the regional climate system, as well as the application of convection-permitting models with resolutions of less than 4 km in simulating regional climate and extreme climate events. Emphasis was placed on how the climate change information produced by CORDEX can serve regional sustainable development such that a pathway for systematic study ranging from observations to models to applications, can be paved. The overall achievements of CORDEX in scientific understanding and its crucial role in social development were therefore fully highlighted.

For Asia, the most populated area in the world, meteorological data show that it has suffered from global change and related disasters during the past few decades, and the situation is likely to continue into the future. Considering the regional imbalance in resilience due to different levels of socioeconomic development in the Asia-Pacific region, climatologists must secure robust climate change projections at fine spatial scales, along with skillful translation of the data into effective and actionable information for end-users, policymakers and the general public. APN and WCRP CORDEX share the common goals of increasing regional coordination in the Asia-Pacific region and worldwide, and fostering communication and knowledge exchange between academic communities and users for science-based application of climate information in sustainable development. Joint efforts have been made to achieve these goals by predicting future climate change based on improved understanding of the climate system, assessing its impact, and supporting applicable policymaking and regional sustainability. With the long-term support of APN, CORDEX teams in the Asia-Pacific region have a history of collaboration in investigating various climate phenomena, boosting the level of understanding regarding climate processes and the climate system, and endeavouring to support development at a regional level. Coordinated efforts have also been put in place to support the development of regional earth system models, establish flagship pilot studies and address issues related to high-impact regional climate features and extremes. Such regional coordination and joint scientific efforts were presented to the global community during ICRC-CORDEX 2019.

With the support of APN and other funding agencies, ICRC-CORDEX 2019 provided a platform to engage scientists, end-users, and other stakeholders from various disciplines of global change science. To further facilitate the direct involvement of Asia-Pacific early-career scientists (ECSs) in such a high-level global scientific event, as well as facilitate future collaboration among the international regional climate science and adaptation research communities, a project proposal, "ICRC CORDEX 2019: Promoting Involvement of Early-Career Scientists from the Asia-Pacific Region in Regional Integrated and Sustainable Development through Active Participation and Networking", was submitted to APN and awarded.

The objectives of this APN project were to provide a platform to advance capacity development, education, and knowledge exchange at multiple levels. It was particularly aimed at providing support for ECSs and students from APN member states and developing countries, so they could be offered the opportunity to exchange experiences with their peers on topics such as generating regional climate scenarios and applying climate information for effective adaptation planning. The ECSs event, a major component of ICRC-CORDEX 2019, was successfully held with the support of APN. The project also contributed to strengthening connections among the Asia-Pacific CORDEX domains—namely, East Asia, Southeast Asia, South Asia, Central Asia, and CORDEX Australasia. Communication with CORDEX initiatives in the Asia-Pacific region, as well as with global change programmes and initiatives such as WCRP/CLIVAR, WCRP/GEWEX and IPCC, was also established. Given the emphasis on cooperation within the Asia-Pacific region among global regions and between various disciplines of regional climate change, the project fell well in line with APN's scientific goals and agendas. Through the successful completion of ICRC-CORDEX 2019, APN and WCRP CORDEX's shared vision of boosting the coordination of research and applications of climate science in the Asia-Pacific region through global partnerships was promoted.

2. METHODOLOGY

One of the priorities of CORDEX is to enhance regional capacity building and networking, especially for the next generation of climate experts. Therefore, ICRC-CORDEX 2019 put considerable effort into ensuring the attendance of ECSs and students. As APN also lists capacity development as a priority mission, the organisation committee of ICRC-CORDEX 2019 proposed a project to APN with a focus on encouraging ECSs from the Asia-Pacific region to participate in ICRC-CORDEX 2019 and to be actively involved in the conference's activities.

Alongside WCRP CORDEX, IAP/CAS, and APN, many other institutions and funding agencies endeavoured to offer financial and other support for ECSs around the globe to join the conference. With this combined effort, ECSs were provided with a great opportunity to exchange their perspectives and experiences with their peers, established scientists and policymakers while gaining insight into future challenges in the development of physical climate science and its communication and communication application in the sense of sustainability. There was also an expectation that these ECSs would build connections and partnerships during the conference for future collaboration on joint proposals, research initiatives, or research papers. Of all applicants supported by APN, 21 ECSs and PhD students were granted, based on an evaluation of their scientific background and the scientific quality and relevance of submitted abstracts. The evaluation was conducted by scientists from the CORDEX Science Advisory Team and CORDEX domains, who are experts in regional climate modelling, analysis and data application.

A networking event for ECSs was funded by APN and organised to facilitate the younger generation to communicate and socialise with their peers, established scientists, and climate information users. The event was entitled "Let's focus on the users: CORDEX datasets for climate projections and applications". The event discussed the suitability of CORDEX products in a wide range of studies, as well as the prospects and scientific challenges, especially for the future. One particular aspect of the event involved inviting ECSs to highlight their perspectives on certain topics. The intention was to inspire the next generation of climate experts to engage in regional sustainability activities.

Capacity development among Asia-Pacific CORDEX teams was enhanced during and after ICRC-CODEX. For example, after face-to-face exchanges regarding the latest progress, the CORDEX Southeast Asia and East Asia teams discussed the possibility of jointly applying new projects based on common interests, including the simulation of climate extremes with high-resolution models and the assessment of climate change impacts on urban environments and human health, amongst other ideas. With their shared vision to support regional sustainable development, CORDEX Asia teams and MAIRS-FE, a Future Earth core project focusing on regional sustainability, planned to set up a new joint research initiative for a regional framework that would identify the most urgent climate–environment–sustainability challenges in the Asia-Pacific region and motivate responsive research and action through down-to-earth regional interdisciplinary collaboration.

3. RESULTS AND DISCUSSION

More than 300 participants from 44 countries and regions attended the 22 sessions of ICRC-CORDEX 2019, one side-event on risks hosted by Future Earth, and an APN-supported event for ECSs.

At the opening ceremony of ICRC-CORDEX 2019, Prof. Pavel Kabat, the WMO's Chief Scientist and Director of WCRP/WMO Research set out the challenges of the changing climate that we will face in the coming decades. Professor Panmao Zhai, Co-chair of the First Working Group of the IPCC, addressed the importance of regional climate research in the IPCC reports. Professor Ailikun, Assistant Executive Director of the Alliance of International Scientific Organisations in the Belt and Road Region (ANSO), emphasised the benefit and motivation of continuous collaboration between physical and social scientists to implement sustainable development. Two invited speakers, Profs. Congbin Fu and Filippo Giorgi gave talks on the history and development of regional climate modelling in Asia and around the globe over the past 30 years. Representatives from WCRP Core Projects, including GEWEX, SPARC, CLIVAR, CORA, and the CMIPs impressed the audience with their latest progress and offered opportunities for cross-programme interactions with CORDEX and regional climate science.

In the following two days, four parallel sessions were dedicated to presentations and discussions on the advances in regional downscaling techniques, as well as scientific understanding and development in coupled regional earth system modelling and climate change impacts. On the evening of the second day, the APN-supported event for ECSs entitled "Let's focus on the users: CORDEX datasets for climate projections and applications" was held. The event began with an expert presentation, followed by short reflections from selected ECSs. Ending with an interactive dialogue with the audience, the event highlighted the challenges and opportunities that ECSs face in regional climate science and VIA activities. On the third day, a side-event named "Future Risk, Future Earth" was jointly hosted by two Asian Future Earth core projects and CORDEX. Held in the form of a face-to-face dialogue, this side-event was designed to raise awareness of regional climate extreme–related risk and disasters, as well as the challenges in regional sustainability research. Afterwards, a new collaboration on Asian climate change–related risk and regional sustainability was proposed based on the on-site discussion.

The three-day conference and related events showcased recent achievements in applying regional climate downscaling and associated benefits, as well as progress in developing and refining regional earth system models and advancements made in recently developed downscaling techniques such as convection-permitting modelling. It also acted as a platform to share knowledge, vision, and support for VIA and capacity development. Furthermore, researchers and teams from various CORDEX regional domains and different scientific backgrounds were able to work on networking and the communication of potential new future collaborations.

3.1. APN-supported event for ECSs

The event for ECSs entitled "Let's focus on the users: CORDEX datasets for climate projections and applications" was financially supported by APN and locally coordinated by Nanjing University and the Young Earth System Scientists community (YESS). The event focused on the suitability of climate information and modeller–user interaction; that is, how to customise CORDEX outputs and accompanying information to facilitate users' needs.

Prof. Ailikun, an expert in integrated regional studies and crosscutting research between natural and social sciences, opened the event by sharing her experience and vision on how to move forward to bring the relevant aspects of regional climate science into society. The reliability, prominence and legitimacy of climate information require the support of robust climate change data and information products. One of the main challenges to consider in the future is how to incorporate human factors into regional climate models. To tailor climate information to end-users, Prof. Ailikun emphasised the need for a co-production and co-design approach. This could help toward a better understanding of the needs of users and obtaining useful climate information on a continuous, iterative basis to support climate change mitigation and adaptation.

Four ECSs presented a brief discussion on the challenges and opportunities in applying CORDEX data and interacting with users. Ester Salimun stated that users should be made more aware of what data are available and what to do with these data. Moreover, open access to data should be improved for the impact and vulnerability communities. Anubhav Choudhary and Dhirendra Kumar discussed how to ensure that users understand the biases and uncertainties in future projections and how to recognise user needs in user-oriented workshops. Miriam Murambadoro emphasised that a better understanding is needed of exactly who the end-user is. She also elaborated on the need for continued involvement and the integration of participatory approaches into knowledge production. After the presentations, the audience engaged in an interactive dialogue with the presenters on a wide range of topics. The discussion highlighted the need for engaging user interactions to further develop regional climate science as well as the challenge of fostering the next generation of ECSs with a user-aware scope while maintaining a solid disciplinary foundation of science. Particular emphasis was also placed on the need for capacity building and interaction platforms for users of CORDEX products.

The event for ECSs was an excellent occasion for ECSs from the Asia-Pacific region and beyond to share their perspectives and experiences. The discussion was carried out on topics relating to how to interact with potential users and accommodate their needs so as to explore the feasibility of applying CORDEX downscaling results in future research by ECSs.

In addition to attending this event, the APN-supported ECSs were encouraged to actively engage with the conference's academic activities and interact with the other participants. Selected ECSs were committed to coordinating conference sessions and events for ECSs, acting as assistant session rapporteurs and coordinators alongside the regular ones. Their reports contributed to the conference session summary and final reports. Through the proposed activities, the project's motivation to initiate partnerships and leadership in the research of ECSs to solve the challenges in regional climate science and regional development was fulfilled. By being actively involved in the conference's scientific and social events, ECSs were able to tune in to the highest level of regional climate science in theory, practice and application.

The WCRP, CORDEX Asia teams, and YESS were committed to continuing their joint efforts in increasing the visibility and engagement of Asian ECSs in the global science community with the completion of the ICRC-CODEX 2019 and the APN project. As a result, APN-supported ECSs can continuously contribute to networking in the climate change community and produce a sustained impact on worldwide CORDEX regions.

3.2. Continuation of CORDEX efforts in supporting regional sustainability

One of the objectives of APN's activities in ICRC-CORDEX 2019 was to raise awareness of the scientific and social challenges unique to the Asia-Pacific region, which include (but are not limited to) how the changing climate and air quality affect human health, the occurrence of climate extremes, and the support of natural resources to renewable energy in a changing climate. ICRC-CORDEX 2019 presented recent progress and achievements related to Asia-Pacific coordinated efforts in promoting, understanding and simulating regional earth system processes; plus, it hosted a side event to boost dialogue between climate and social scientists, thereby enhancing bilateral collaboration on climate change–related risks, disasters, and interactions between human and natural components. Nonetheless, the topics that are essential for the sustainable development of the Asia-Pacific region, e.g., those related to natural resources (e.g., water, ecosystem security, the regional cryosphere) and socioeconomic development (e.g., the ever-growing trend of urbanisation and other manmade land-cover changes, industrial restructuring to reduce greenhouse and aerosol emissions, the rapid development and application of renewable energy), were not fully presented and discussed at the conference. We realised that such issues need to be more thoroughly investigated and integrated into future regional climate change projections. We considered that it might point to a future way forward and a basis for regional collaboration between CORDEX Asia teams and application sectors (e.g., energy industries and urban development planning sections).

One of the key challenges that face scientists and scientific programmes is to fully integrate natural and anthropogenic fine-scale forcings in their climate research. CORDEX provides the solution so as to keep developing and applying high-resolution regional earth system models, which could address regional physical and biogeochemical processes in more detail (e.g., regional ocean, biomass emissions, ecosystem management). In its next stage of globally coordinated high-resolution downscaling activities (~10 km), CORDEX will not only provide reliable datasets to assess the regional natural resources but also offer opportunities to carry out crosscutting studies, e.g., the interaction between the fine-scale climatic-environmental change and the rapid development of clean-energy industries. Another big challenge is to establish effective collaboration with social sectors and policymakers by delivering applicable measures to society. Under such circumstances, CORDEX considers that closer collaboration with the Asian global change research programmes, including APN, Future Earth-Asia projects and ANSO, is crucial to identify regional issues, implement its objective to advance and coordinate the science and application of regional climate downscaling, and finally serve regional sustainability and development.

4. CONCLUSION

By presenting the Asia-Pacific region's and the international community's accomplishments in developing and applying regional climate downscaling and by enhancing the level of communication with users and stakeholders, ICRC-CORDEX 2019 achieved its objectives and exhibited CORDEX's vision to advance regional climate science and promote engagement in VIA practices with globally coordinated and region-based research (ICRC-CORDEX, 2019). The conference presented frontiers of regional climate science and techniques and showcased the knowledge-sharing of VIA practices and capacity development. Meanwhile, the conference demonstrated the globally and regionally coordinated efforts to address the processes and regional-scale driving forces that are most relevant to the Asia-Pacific region, such as the fine-scale changes of the Tibetan Plateau and their impact on Asian climate, the effects of climate change on land-surface conditions and atmospheric composition, and natural climate variability of the regional ocean and monsoon system. Special attention was paid to the challenges of emergent risks from climate extremes and weather events in regional sustainability. The success of the conference reflected APN's mission in developing scientific capabilities so as to support regional policymaking by providing reliable and actionable climate change information and by strengthening the communication and interaction between scientists and policymakers (APN, 2021) .

ICRC-CORDEX 2019 promoted intra- and cross-regional connections and networking among researchers, teams, and scientific communities. It also acted as a platform to discuss future collaborations on joint projects and scientific papers. In particular, the support of the APN grantee, the completion of the conference, and rendered the ECSs from the Asia-Pacific region to exchange their research and experiences with the global science community, thereby broadening their vision and resources. Consequently, the ICRC-CORDEX 2019 and the project entitled "Promoting Involvement of Early Career Scientists from the Asia-Pacific Region in Regional Integrated and Sustainable Development through Active Participation and Networking" have increased the global visibility of both APN and CORDEX. In addition, they have contributed to APN's scientific scope and mission in promoting effective and responsive regional collaboration to address the urgent issues for sustainable development in the Asia-Pacific region (APN, 2021; Solman et al., 2021). As the event directly involved other global and regional organisations, including the WCRP core projects, Future Earth community, ANSO, and local universities and institutions, ICRC-CORDEX 2019 also made contributions to APN's goal of enhancing regional networking and supporting joint research for the sustainable development of the Asia-Pacific region (APN, 2021).

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Review

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Strengthening adaptive capacity of rural farming communities in Southeast Asia: Experiences, best practices and lessons for scaling-up

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ABSTRACT

This article highlights the experiences, contributions, and lessons generated from the ten selected APN capacity development programmes implemented from 2011-2019 and focused on enhancing the resilience and adaptive capacity of rural farming communities in Southeast Asia. These capacity development projects employed varying strategies and approaches. Some projects centred on training and building the technical capabilities of service providers, while others have directly trained and built the capacities of the farming communities. Some projects emphasised the promotion of nature-based and sustainable farming techniques such as agroforestry, conservation farming, rainwater harvesting, and indigenous agricultural practices that helped farming communities cope and adapt to climate change impacts. At the core of these capacity development programmes are collaboration and partnerships that were built and institutionalised among different sectors, such as academia, local government units, and the farming communities. These multisectoral collaborations hastened the project implementation and generation of project outputs and gave way to the sustainability of the project initiatives. These projects have generated numerous outputs that paved the way for enhanced social and human capital development of various stakeholders, science-based decision-making by policymakers; adoption of sustainable farming techniques and technologies; and knowledge generation and advancement of science. More importantly, these projects have developed a model for enhancing the adaptive capacity and resilience of rural farming communities in Southeast Asia.

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KEYWORDS

Collaboration, lessons, capacity development, sustainable farming techniques, sustainability

HIGHLIGHTS

- Ten APN capacity development projects centred on enhancing community resilience and adaptive capacity for climate change adaptation of rural farming communities in Southeast Asia were reviewed and synthesised, and whose lessons and best practices were distilled for scaling-up in the region.
- These capacity development projects employed various approaches and strategies such as technical capability-building of service providers such as the local government units and the academia, promotion of sustainable farming practices through demonstration plots, and training of farming communities.
- Multisectoral collaboration is at the core of the APN capacity development projects, with academia/universities taking the lead role.
- The APN capacity development projects have developed a model and framework for enhancing adaptive capacity and resilience of rural farming communities in Southeast Asia, which could serve as a reference for replication and scaling-up.

1. INTRODUCTION

With more than 10% contribution to the gross domestic product and creating jobs for more than one-third of the working population in the region (Zhai & Zhuang, 2009), agriculture plays a vital role in the economy of Southeast Asia. As noted by Zhai and Zhuang (2009), nearly three-quarters of the poor in the region reside in rural areas, with agriculture as their main economic activity. An estimated 100 million smallholder farmers are actively producing staple crops (i.e., maise, rice, and wheat) and other high-value crops such as cacao and coffee (Mikolajczyk, Mikulcak, Thompson, & Long, 2021). But agriculture in general and smallholder farmers, in particular, are vulnerable to numerous challenges such as natural disasters (Israel & Briones, 2013) market and policy uncertainties, climate change (ADB & IFPRI, 2009; Tolentino & Landicho, 2013; Landicho, Cabahug, Baliton, & Gonzales, 2021; Ho, Ha, Luu, & Dong, 2019; Cruz, Carandang, Galapia, Carandang, & De Luna, 2014; Pulhin et al., 2020; Visco, Wulandari, & Huy, 2014; Diana, Zulkepli, Siwar, & Zainol, 2022); and the recent COVID-19 pandemic (Sleet, 2020; Kim, Kim, & Park, 2020; FAO, 2021)

With the crucial role of agriculture in the economy and its vulnerability to climate change impacts and other stressors, numerous studies point out the need to invest in measures that would build and enhance the adaptive capacity and resilience of rural farming communities (Silici, Rowe, Suppiramaniam, & Knox, 2021; Landicho et al., 2021; Lasco, Habito, Delfino, Pulhin, & Concepcion, 2011). Adaptive capacity is the ability of a system to adjust to climate change by moderating potential damages, taking advantage of opportunities, or coping with the consequences (IPCC, 2007). On a broader scope, Armitage (2005) defines adaptive capacity as a "critical aspect of resource management which reflects learning and an ability to experiment and foster innovative solutions in complex social and ecological circumstances". Lasco et al. (2011) also contend that a system with high adaptive capacity will be more resilient to climate change impacts.

In their study, De Fiesta and Rapera (2014) argued that households in Dumangas, Iloilo, Philippines, with higher adaptive capacity, employed more adaptation strategies. This finding is validated in the study of Landicho, Van, and Ximenes (2018), which emphasises that the level of adaptive capacity determines farmers' decisions to adopt climate change adaptation strategies in selected countries in Southeast Asia such as Vietnam, Philippines and Timor-Leste.

There have been numerous efforts that would help enhance the adaptive capacity of rural farming communities. These include, among others, the promotion of climate-smart agriculture (Sebastian & Bernardo, 2019; Nkumulwa & Pauline, 2021; Scherr, Shames, & Friedman, 2012); agroforestry (Baliton et al., 2017; Landicho et al., 2016, 2021); conservation farming techniques (Cruz et al., 2016; De Luna, 2018); rainwater harvesting (Landicho et al., 2021), and, training, awareness-building and capability-building programmes (Carandang, Huy, Wulandari, Visco, & Vilayphone, 2015; Landicho et al., 2019).

This article highlights the lessons and best practices of selected APN capacity development projects that were implemented to help improve the adaptive capacity of rural farming communities in various countries in Southeast Asia.

2. METHODOLOGY

From the 16 APN capacity development projects in Southeast Asia that focused on enhancing climate change adaptation of institutions and communities, the authors selected ten projects centred on building rural farming communities' capacity and resilience from 2011-2019. The collaborators' willingness to highlight their projects in the webinar and publication was the primary consideration in forming the list of the pre-selected capacity development projects.

The project reports submitted by the project collaborators to APN served as the basis for distilling the salient features of the project, as well as the significant experiences, lessons, and best practices. A webinar was conducted to validate the data and information gathered from the project reports. More importantly, the webinar allowed the project collaborators to communicate and share the lessons and experiences of their capacity development projects with a broader audience.

3. RESULTS AND DISCUSSION

3.1. Variants of capacity development programmes for enhancing adaptive capacity of rural farming communities

APN capacity development projects have varying strategies and approaches. Some projects centred on training and building the technical capabilities of the service providers, particularly the local governments, state colleges, and universities, as in the case of the projects that (a) trained students and farmers to become local climate change communicators; (b) equipped the local government units to develop climate change action plans; (c) enhanced the knowledge and skills of state colleges and universities and local government units in exploring basket of climate change adaptation strategies; and d) trained people's organisations in effective irrigation water management. In general, capacity building is always an essential component of climate change adaptation programmes (Climate ADAPT, 2019). Landicho et al. (2021) highlighted that farmers' training, policy forum, climate change awareness programme, and information dissemination activities are valuable ways of promoting climate change adaptation strategies towards enhancing the adaptive capacity of farmers.

Other projects emphasise promoting nature-based and sustainable farming techniques that help farming communities cope and adapt to climate change impacts. These projects did not only provide training activities but, more importantly, set up demonstration plots and model farms to showcase the workability and viability of these technologies, as follows:

a) *Conservation farming techniques* via the Conservation Farming Village (CFV) programme provided enabling conditions for the engagement of upland farming communities in the Philippines in sustainable and resilient agroforestry-based livelihoods that promote the economic productivity of upland farmers and the stability of the ecosystem. Cruz et al. (2014) stressed that CFV is a strategy for transforming mindsets and skills and for building on the assets of the upland farmers for the sustainable use of land and other natural resources.

b) *Agroforestry*. Agroforestry Learning Laboratories in selected upland farming communities in Indonesia, the Philippines and Malaysia showcase viable and workable agroforestry systems and soil and water conservation measures. Numerous literature cites the relevance of agroforestry as a key strategy for climate change adaptation (Tolentino, Landicho, De Luna, & Cabahug, 2010), food security, and environmental rehabilitation.

c) *Renewable energy from livestock* in the form of biogas raised awareness among stakeholders, particularly livestock producers, about opportunities for tapping biogas for climate change adaptation. Awareness-raising was undertaken through policy forums, information dissemination and training of stakeholders.

d) *Indigenous agricultural practices in the mountainous region of Vietnam*, such as planting of green mungbean, a drought-resistant crop often used in traditional dishes; raising of cold-resistant H'mong black-boned chicken that are less susceptible to diseases and that produce high-quality meat; and intercropping of local banana varieties with khoi tia (*Ardisia silvestris Pitard*). The local variety of bananas require less maintenance and are appropriate for sloping lands. Further, the medicinal plant khoi tia's leaves are a source of tannins and glycosides for pharmacology. Khoi tia is also a traditional medicine used for abdominal ailments (Ho et al., 2019).

e) *Rainwater harvesting*, which showcased a model of addressing water scarcity in the upland farming communities in the Philippines through the establishment of 11 rainwater harvesting ponds, utilising the collective action of the local communities. Han (2006) argues the need for a new paradigm in managing rainwater as the weather becomes more severe and unpredictable due to climate change. Hence, Contreras, Sandoval, and Tejada (2013) stressed that rainwater harvesting through small water impounding ponds (SWIPs) addresses unbalanced rainfall distribution by collecting and storing direct rainfall and surface run-off for future use. SWIPs play an important role in enhancing the multifunctionality of agriculture, particularly in the uplands (Concepcion et al., 2006).

Some projects utilised digital technology for more proactive solutions to agricultural uncertainties brought about by climate change, as emphasised in the Saung-Iklim project in Indonesia. This project trained various stakeholder groups on managing climate risks that affect their crop production through crop simulation models such as Aqua Crop and DSSAT to identify the potential impacts of climate fluctuation on rice productivity.

3.2. Forms of partnerships and collaboration established by the capacity development projects

While the ten capacity development projects vary in scope, approaches and intervention, it is worth noting that all of these projects emphasise collaboration and partnership at the core of their projects. The collaboration was established between the project collaborators, local government units, farming communities and local universities in building the capabilities of local climate change communicators in the Philippines, Lao People's Democratic Republic, Indonesia and Vietnam (Carandang et al., 2015); communicating and operationalising site-specific climate change adaptation strategies (Visco et al., 2014); establishment of model farms showcasing conservation farming practices and capacity development of farmer-volunteers (Cruz et al., 2014); establishment of agroforestry learning laboratories in Indonesia, Philippines and Vietnam (Comia, Landicho, Wulandari, & Huy, 2016); rainwater harvesting (Landicho et al., 2021); tapping renewable energy from livestock (Do, Nguyen, Dinh, Khanitchaidecha, & Le, 2021); and promoting indigenous farming practices in the mountainous regions in Vietnam (Ho et al., 2019). Meanwhile, the partnership between the project collaborators and the local government units was highlighted in the preparation of local climate change action plans in Aurora, Philippines (Pulhin et al., 2020), and the capacity building of Saung-Iklim in Indonesia (Perdinan et al., 2021). Penalba et al. (2012), meanwhile, have established a direct partnership with people's organisations to enhance the latter's capacity for irrigation water management.

At the forefront of these partnerships are agricultural and forestry universities as the source of technical expertise and catalysts of development efforts. The local government units are a significant component of the collaboration as they have the capacity to execute and institutionalise local policies and provide basic social services to the community. Meanwhile, the farming communities and people's organisations were the direct beneficiaries of the capacity development programmes. The multisectoral collaboration worked in many community-based development projects and sustainable development initiatives (Landicho & Dizon, 2020; Landicho, Cabahug, & De Luna, 2008; Cruz et al., 2016; Elauria, Manilay, Abrigo, Medina, & De Los Reyes, 2017). As argued by Jones, Ludi, and Levine (2010), communities with well-developed social institutions are typically better able to respond to a changing environment than those with less effective institutional arrangements.

3.3. Best practices and significant contributions of the capacity development programmes

Developed stakeholders' awareness about climate change and climate change adaptation strategies

The capacity development projects conducted policy forums, training, awareness programmes, information materials development and dissemination. These strategies provided an opportunity to inform and educate the different stakeholders, particularly the local government units, universities, farming communities and students, about the issue of climate change, its impacts, and the potential strategies and measures for climate change adaptation. As such, these stakeholders have become aware of the issue and potential solutions.

Promoted capacity development of young researchers and lecturers

Some projects have encouraged the participation of young researchers and lecturers as trainees (Tolentino, Huy, Kheowvongsri, Vilayphone, & Ghani, 2012; Carandang et al., 2015) but also involved them as collaborators or technical support in project implementation (Visco et al., 2014; Cruz et al., 2014; Landicho & Dizon, 2020; Comia et al., 2016). The provision of research grants encouraged young researchers in Vietnam to focus their research on indigenous knowledge systems (Ho et al., 2019). These strategies promoted mentoring and capacity development of early-career scientists.

Enhanced the knowledge and skills of farmers, people's organisations and local government units in planning for climate change adaptation and on the different nature-based and sustainable farming practices

The project of Carandang et al. (2015) trained about 60 farmers and agricultural technicians in upland communities in Indonesia, Lao PDR, Vietnam, and the Philippines, not only on the issues and impacts of climate change adaptation strategies but also on building their communication and presentation skills as communicators and disseminators of various aspects of climate change. Pulhin et al. (2020) enhanced the capacity of local government units (LGUs) to acquire data, implement research, conduct land capability classification, and assess vulnerability and risks associated with future climate scenarios. This project harnessed the active engagement of LGU personnel in assessing the vulnerability and risks of their respective municipalities, which served as the basis for the formulation of the local climate change action plan. Farmers' knowledge and skills were further enhanced through cross-farm visits and the establishment of agroforestry learning laboratories (Comia et al., 2016) and community projects (Visco et al., 2014). The capacity development project of Cruz et al. (2014) built the technical capabilities and appreciation of 272 LGU technicians and upland farmers in agroforestry, conservation farming and sloping land management. Perdinan et al. (2021) equipped the LGUs, extension workers, farmer groups and universities with the proper tools to enhance the farmers' capacity to utilise climate information in managing their farm activities. Meanwhile, farmers' groups were trained on effective water management (Penalba et al., 2012) and rainwater harvesting (Landicho et al., 2021).

Established multisectoral partnerships at various levels

APN capacity development projects undertaken by the Southeast Asian Network for Agroforestry Education (SEANAFE), such as that of Tolentino et al. (2012), Cruz et al. (2014), Visco et al. (2014) and Comia et al. (2016) enhanced regional collaboration. SEANAFE member universities could capitalise on this partnership for future collaborative research and development projects. Meanwhile, transboundary collaboration of universities in Japan, Thailand and Vietnam was harnessed in building public awareness about the potential of livestock waste as a renewable energy source in Vietnam (Do et al., 2021).

At the local level, the CFV Programme has strengthened the partnership among the five state colleges and universities (i.e. University of the Philippines Los Baños, Ifugao State University, University of Southeastern Philippines and the Bicol University College of Agriculture and Forestry) to work towards the replication of CFV in other provinces and share their technical expertise, as well. The partnerships of local state colleges, farming communities and local government units were strengthened and institutionalised in the different APN capacity development projects in the Philippines (Carandang et al., 2015; Visco et al., 2014; Tolentino et al., 2012; Landicho et al., 2021; Cruz et al., 2014; Comia et al., 2016).

Established demonstration plots showcasing nature-based and sustainable farming practices for climate change adaptation

Five APN capacity development projects have put up demonstration plots that showcase sustainable farming practices for climate change adaptation, such as agroforestry systems (Cruz et al., 2014; Comia et al., 2016); conservation farming practices (Cruz et al., 2014; Comia et al., 2016; Visco et al., 2014); indigenous agricultural practices involving intercropping of local crops (Ho et al., 2019); and rainwater harvesting ponds (Landicho et al., 2021). These demonstration plots served as models for the adoption of smallholder farmers within the project sites and for scaling up in other communities.

Developed policy briefs as instruments for lobbying and linking with the policymakers

From the science-based evidence, some capacity development projects were able to produce policy briefs that provide a science-policy linkage. The policy brief developed by Carandang et al. (2015) served as the instrument of the collaborators in the Philippines, Vietnam, Lao PDR and Indonesia in lobbying with their local and national policymakers about mainstreaming climate change adaptation in their local and national development programmes, respectively. The role of agroforestry in climate change mitigation and adaptation and the urgent need to mainstream agroforestry in local governments' local climate change adaptation programmes were highlighted in the policy brief produced by Tolentino et al. (2012). Do et al. (2021) provided science-based evidence that would help policymakers in making sound decisions on tapping livestock waste as a renewable energy source.

Provided a model for enhancing adaptive capacity of rural farming communities in Southeast Asia

The APN capacity development projects vary in terms of implementation strategies, scope and approach but were conceived with a common goal of enhancing the adaptive capacity and resilience of rural farming communities in Southeast Asia. Indeed, these capacity development projects have generated a number of tangible outputs: numerous farmers, LGU personnel and junior researchers and lecturers were trained on various aspects related to climate change adaptation and mitigation (agroforestry, climate change adaptation strategies, indigenous agricultural practices, tapping biogas, CDRA, development of local climate change action plans, and effective irrigation management); developed policy briefs; developed model farms and demonstration plots; and contributed to the advancement of science through paper presentations and scientific journal articles.

These outputs paved the way for an enhanced social and human capital development of different stakeholders and science-based decision-making by policymakers, as highlighted by the testimonies of the local chief executive in Aurora Province, Philippines and, hence, strengthening the policy-science linkage. Furthermore, the outputs have led to the adoption of sustainable farming techniques and technologies, as reflected in the testimonies of the farmers in Albay Province, Philippines and Vietnam, as well as knowledge generation and advancement of science as mentioned by local partner universities in the Philippines and Indonesia. As shown in Figure 1, these outcomes would certainly contribute to attaining the potential impact of enhanced adaptive capacity and resilience of rural farming communities in Southeast Asia. The model developed by APN capacity development projects could be used as a reference in replicating these projects in other communities in the region.

3.4. Lessons Learned from capacity development programmes

Important lessons were distilled from the different experiences and best practices of APN capacity development projects. These lessons could guide other universities and development organisations whose work aligns with enhancing adaptive capacity and building the resilience of rural farming communities.

1. Essence of collaboration in facilitating smooth project implementation, achieving project goals and objectives, and sustaining project initiatives.

The APN capacity development projects confirmed that emphasising collaboration facilitates effective and efficient project implementation as this strategy promotes sharing of expertise and resources and the integration of efforts from all the collaborating institutions. The importance of collaboration and partnerships at various levels and sectors is highlighted in a number of community-based development projects across Asia (Landicho & Dizon, 2020; Tolentino et al., 2010; Cruz et al., 2014; Kim, Youn, & Park, 2018; Frimadani & Yonariza, 2018; Pinthukas, 2018; Tuan, 2018).

2. Addressing the needs of farmers and local communities is of utmost importance

The genuine and sincere participation of the local communities is harnessed when the development programmes are centred on their felt needs. It also develops their sense of ownership in all of the project undertakings. This was observed by Landicho and Dizon (2020) in the establishment of rainwater harvesting facilities in selected upland farming communities in the Philippines. Since the farming communities were in dire need of water to irrigate their crops, the need for these facilities was expressed by the farmers themselves. As such, they have actively participated in the project even during the height of the pandemic. They were able to manage the facilities sustainably and have expanded their crop production.

3. Promoting policy-science linkage facilitates the institution of local policies that are supportive of the initiatives of the capacity development programmes. This could lead to the sustainability and scaling-up of the project initiatives.

Developing science-based evidence and organising policy forums and consultations are strategies used to raise policymakers' awareness of issues and problems, encouraging them to take action that could help address these problems. All ten APN-capacity development projects sought the partnership of local government units and made the latter aware of the climate-related problems upland farming communities face and the potential solutions.

4. Awareness-raising among the different stakeholders is an essential component of any capacity development programme

Various forms of public awareness programmes such as stakeholders' orientation, seminars, training, and policy forum were organised by the project

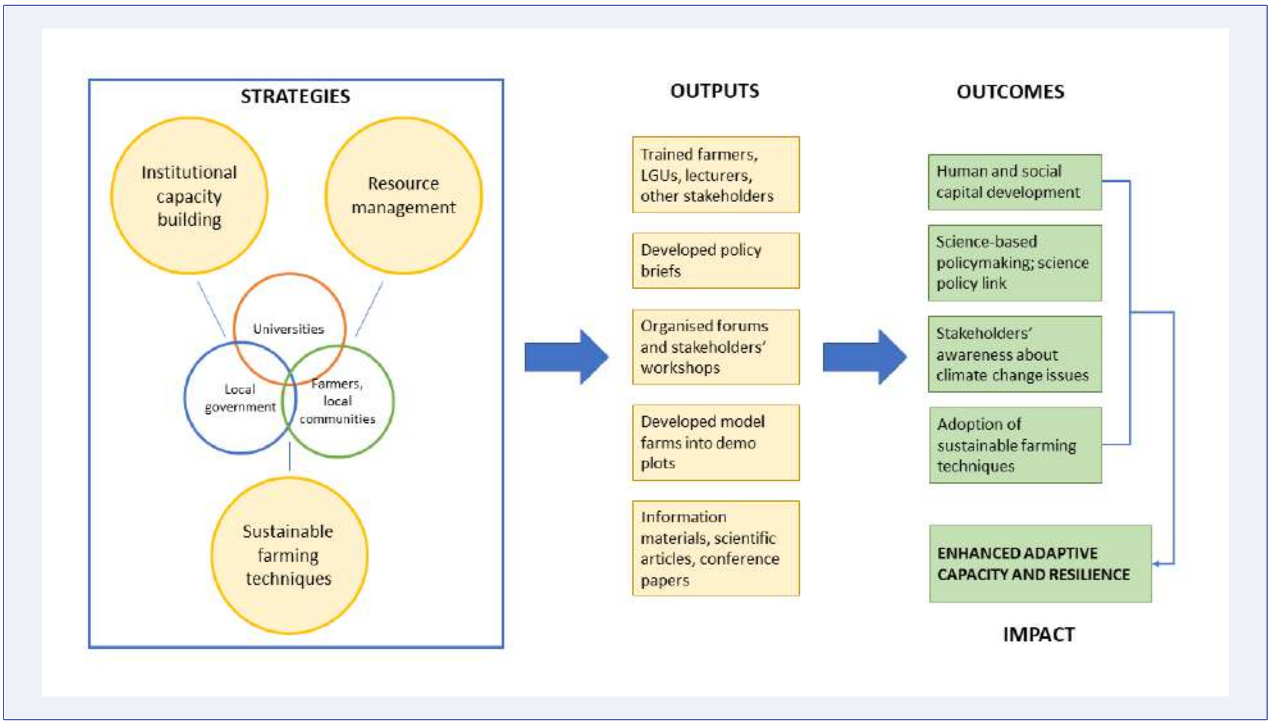

FIGURE 1. Model for enhancing adaptive capacity of rural farming communities in Southeast Asia: Experiences, lessons and best practices from APN capacity development projects.

collaborators to ensure that the concerned stakeholders are aware not only about their respective projects but, more importantly, of the issues and problems that are being faced as a result of climate change. Making stakeholders aware of the issues and problems brought about by climate change and other stressors, as well as opportunities that could be tapped to address the impacts, would prompt them to take action. Otherwise, concerned stakeholders may "do nothing" about the issue or problem.

5. Building model farms and demonstration plots showcase the workability and viability of agricultural technologies and innovations, which could serve as vehicles for technology adoption.

As we all know, farmers and practitioners would only adopt a particular technology or innovation if they see for themselves the viability of these technologies. Demonstration plots can be an effective means to create awareness among farmers about modern technologies and can motivate them to apply these technologies to their own farming practices (Khan, Pervaiz, Khan, Ahmad, & Nigar, 2009).

6. Local government units should be an integral component of any capacity development programme and an active player in multisectoral collaboration.

In multisectoral partnerships, the active role of LGUs should be harnessed to ensure the sustainability of project initiatives. Local governments have become active partners of project teams in the ten capacity development projects. Literature has pointed out the crucial role of LGUs in promoting sustainable natural resources management in the Philippines (Landicho & Dizon, 2020; Cruz et al., 2016; De Luna, 2018)

7. Active engagement of the local communities and partners helps ensure the sustainability of project implementation and project initiatives.

The initiatives of some of the capacity development projects, such as that of Visco et al. (2014); Cruz et al. (2014); Landicho and Dizon (2020); Ho et al. (2019) ; and Do et al. (2021), among others, were sustained by the LGUs and the farming communities. As argued by Conde and Lonsdale (2006), in the process of engaging the stakeholders, their adaptive capacity is being developed because people are given the time to strengthen networks, knowledge, resources, and the willingness to find solutions (Catacutan & Tanui, 2007).

4. CONCLUSION

Southeast Asia is one of the regions reportedly vulnerable to the impacts of climate change. The APN capacity development projects featured in the present paper are just a few of many APN projects focussing on climate change adaptation and mitigation and building community resilience in Southeast Asia.

It is worth noting that all of the capacity development projects highlighted in this publication considered collaboration and partnership at the core of their projects. Agricultural and forestry universities are at the forefront of these partnerships as the source of technical expertise. These capacity development projects have varying strategies and approaches.

Indeed, these capacity development projects have generated a number of tangible outputs based on project reports: numerous farmers, LGU personnel, and junior researchers and lecturers trained on various aspects related to climate change adaptation and mitigation (agroforestry, climate change adaptation strategies, indigenous agricultural practices, tapping biogas, CDRA, development of local climate change action plans, and effective irrigation management); developed policy briefs; developed model farms and demonstration plots; and contributed to the advancement of science through paper presentations and scientific journal articles.

These outputs paved the way for an enhanced social and human capital development of different stakeholders and science-based decision-making by policymakers and strengthening the policy-science linkage. Furthermore, the outputs have led to the adoption of sustainable farming techniques and technologies, as well as knowledge generation and advancement of science. These outcomes would certainly contribute to attaining the potential impact of an enhanced adaptive capacity and resilience of rural farming communities in Southeast Asia.

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Finally, the project collaborators would like to thank the Asia-Pacific Network for Global Change Research (APN) for providing the funds to implement the project activities, such as the webinar and developing knowledge products and communication materials, such as the video of different APN projects in Southeast Asia.

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Original article

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Tracking influences of Asian urban greenhouse gas emissions for sustainability policies: Preliminary report

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ABSTRACT

While nations have made commitments to address climate change, scholars estimate that even if these commitments are met, there remains an emissions gap between where we are and where we want to be to keep the globe under 1.5°C. Cities around the world are working to reduce this gap. Asian cities are large greenhouse gas (GHG) emitters and will be so over the next few decades. It is therefore urgent to identify ways in which the region's cities can become more efficient and less polluting. This study is an APN research project that examines the GHG emissions at the sub-city level across 5 Asian cities (Tokyo, Beijing, Taipei, Seoul and Bangkok) as well as in New York City. The attempt is to identify potential strategies for low-carbon pathways. The research demonstrates that, in most cases, national and urban emissions are increasing, although the APN research teams identified stable emissions over the past few years in Beijing and Tokyo. However, the emissions profiles are different. Therefore, reducing emissions will require different strategies across the region's cities. The study identifies some general policy priorities for cities based on the results of case studies.

KEYWORDS

Asia, urban energy use, greenhouse gas emissions, low carbon policies

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HIGHLIGHTS

- Asian cities are significant contributors to global GHG emissions.
- The influence on GHG emissions from cities varies.
- Reduction strategies must fit individual cities and will vary across the region.

1. INTRODUCTION

Through the Paris Agreement of COP 21, 12 December 2015, a legally binding international treaty on climate change signed by 196 world leaders representing the various parties, the international community recognised the importance of climate change and committed their economies, through Nationally Determined Contributions (NDCs), to address anthropogenic causes. The agreement reflects concern over current dramatic changes in planetary systems resulting in violent weather-related extreme events (fires, heat waves, typhoons, storm surges), rising seas, glacier melt, changes in precipitation patterns and other impacts. Furthermore, findings from the Intergovernmental Panel on Climate Change (IPCC) indicate that the net damage costs of climate change are likely to be significant and will increase over time if nothing is done to change emissions levels (IPCC, 2022).

Despite national commitments, however, there remains a significant "emissions gap", which is the difference in the total greenhouse gas (GHG) emissions projected by 2030 and the level that is necessary to keep global warming limited to 2°C (or under 1.5°C) and those under the current trajectory. The necessary trends in GHG emissions have been estimated by the IPCC and published in a Special Report on Global Warming of 1.5°C (IPCC, 2018) and its underlying studies. Estimates suggest that the gap for GHG levels by 2030 under the NDCs is approximately 15 Gt CO_2e (range: 12–19 Gt CO_2e) for below 2°C scenarios and about 32 Gt CO_2e (range: 29–36 Gt CO_2e) for below the 1.5°C scenarios (UNEP, 2020).

As the world continues to urbanise, cities have become the focus of concern for the emissions gap as well as the potential solution to emissions reductions. This is because urban areas are responsible for around 70% of global CO_2 emissions. The high total share of CO_2 emissions from cities is due to a number of factors, including, inter alia, the large number of urban residents, the higher wealth found in cities compared to national non-urban counterparts and the fossil fuel use-related activities found largely in and around cities (i.e., transportation). Among the entire urban population, those living in the largest cities and wealthiest cities are responsible for the largest share of total GHG emissions (Seto et al., 2014).

At the same time, spatially organising societies around dense settlements can help to address climate change as urban residents in wealthy nations are typically more energy efficient than their suburban and rural counterparts; they have lower carbon footprints (Marcotullio, Sarzynski, Albrecht, Schulz, & Garcia, 2013). This is due to, inter alia, sharing housing stock (i.e., living in apartment buildings), using less transportation energy and working in commercial rather than industrial sectors. Some suggest that this results in an increasing energy efficiency potential with the size of cities (Bettencourt & West, 2010).

Moreover, governance of urban areas can respond more quickly to climate change demands than national political units (Bulkeley & Kern, 2006). Scholars are placing much hope in implementing effective mitigation policies to promote low-carbon cities (Wiedmann & Allen, 2021). These hopes have been supported by evidence, as within the past few decades, there has been an uptick in city or municipality-level climate action, with cities coming up with their own policies to mitigate their emissions (Gouldson et al., 2016).

Given the importance of cities in climate change mitigation, many eyes are on the Asian region, as it is undergoing rapid urbansation and economic restructuring. China has emerged as the largest global GHG contributor, accounting for approximately 30% of annual emissions (Gouldson et al., 2016). The entire Asian region, as defined by the UN, contributes over 57% of annual emissions (Andrew & Peters, 2020). According to the World Bank, fast-growing cities in the East Asia and Pacific region will define the region's energy future and its GHG footprint (Ostojic, Bose, Krambeck, Lim, & Zhang, 2013). As the region urbanises, Asian urban residents can take advantage of the lessons learned in other countries and avoid locking into energy-intensive infrastructure and behaviours (Gouldson et al., 2016). There are significant opportunities for low-carbon energy futures for Asian cities, but measures need to be taken immediately.

This paper briefly reviews studies of urban GHG emissions studies in the Asian region and provides the results of a recent APN-funded study that examines drivers of GHG emissions and potential low-carbon strategies. The review findings suggest that studies have moved from examining the city as a black box to examining specific sectors and geographic locations within cities. The APN-funded studies presented in this paper continue this trend by examining the complex drivers of urban GHG emissions at the sub-urban scale and identify pathways for low-carbon urban futures. The results provide leverage for low-carbon actions to meet the Paris Agreement.

The first part of this paper presents an overview of Asian urban GHG emissions research. The next section briefly reviews the methods used in the different urban studies of the APN project. The fourth section summarises the results from each study team and the last section discusses the results. The paper concludes by providing key themes identified across Asian cities.

2. LITERATURE REVIEW

2.1. Asian GHG regional urban emissions studies

Due to local data limitations, many urban analysts perform urban GHG analysis at the provincial or larger geographic regional levels (Long et al., 2020) . Regional studies have applied similar protocols across a limited number of different cities. For example, Marcotullio, Sarzynski, Albrecht, and Schulz (2012) estimated urban GHG emissions in the Asian region using a top-down approach with data from the Emission Database for Global Atmospheric Research (EDGAR) and a consistent method. A more recent study created a globally consistent, top-down, gridded global model of city footprints (GGMCF) by downscaling national carbon footprints (CFs) into 250 m gridded cells and included Asian cities (Moran et al., 2018). From the data made available by Moran et al. (2018), we can see that the largest and wealthier cities in the region are responsible for the most GHG emissions Figure 1. Using their template for Asian cities, it is also evident is that per capita emissions vary among urban emitters Figure 2.

2.2. Asian GHG local urban emissions studies

Local Asian urban GHG inventories have largely been generated for megacities or provincial capital cities, particularly in China (Huang, Zhang, & Liu, 2018; Zhao & Li, 2016). Many city governments implement GHG inventories to help determine how to mitigate emissions and which policies might be most effective. Though some governments have a long-standing record of their annual GHG emissions, other localities neither have the time nor resources (and particularly the data) to build a fully-fledged inventory. Therefore, most of the local GHG inventories are from the major metropolitan centres in the region.

The Seoul Metropolitan Government (SMG) reports that 2019's total emissions were approximately 46.3 Mt CO_2e. Energy-related activities made up 90% of emissions (Seoul Metropolitan Government, 2021). For 2020, SMG

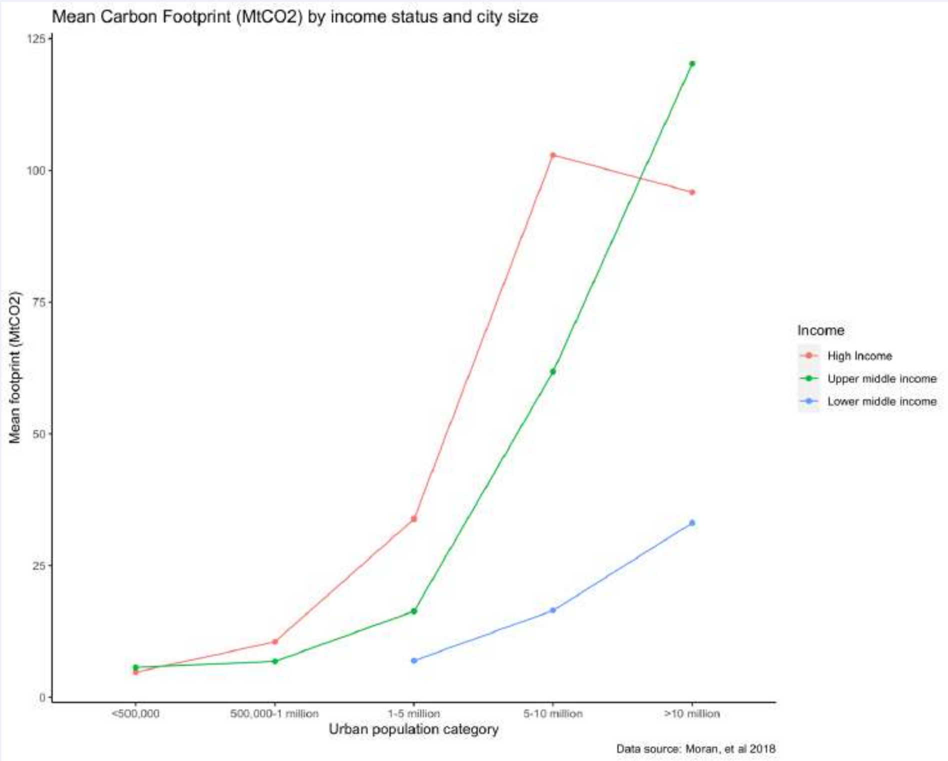

FIGURE 1. Mean carbon footprints of Asian cities. The mean carbon footprints were calculated by averaging total carbon emissions for each class of city.

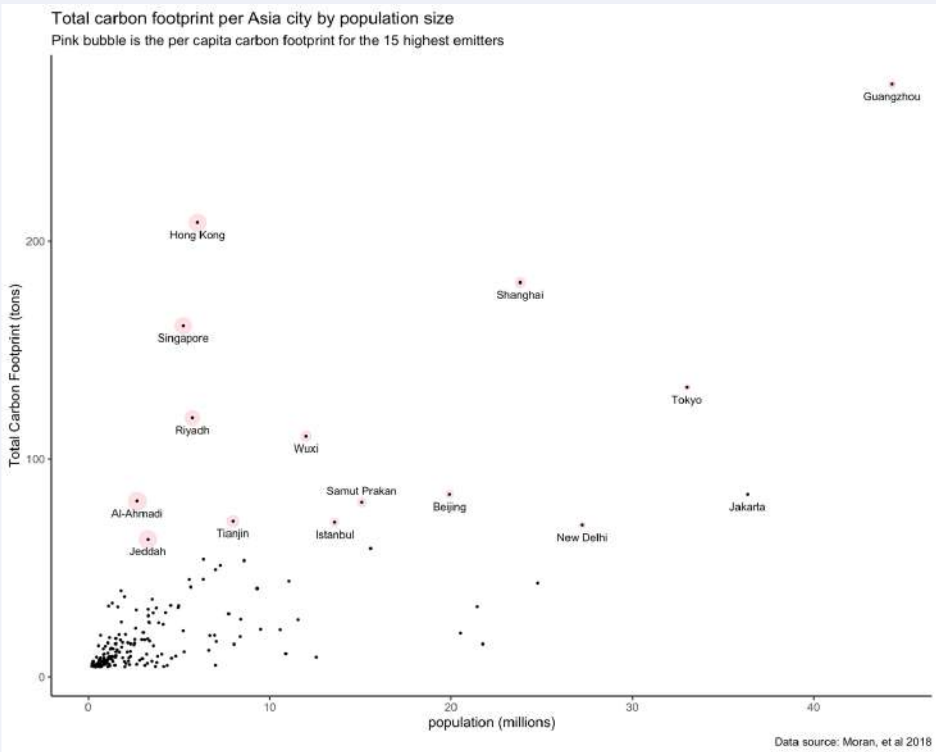

FIGURE 2. Population distribution and total carbon footprint of Asian cities. Note the top 15 largest urban carbon emitters in the Asian region have variable per capita emissions.

reports that total GHG emissions were 45.2 tons. The inventory includes details for different sectors. For example, the building sector, which accounts for the largest share of GHG emissions, accounted for 68.9%, which is similar to 2019 (68.8% estimated). Within the building sector, GHG emissions from households have been increasing (1.4% year-on-year between 2019 and 2020), while emissions from the commercial sector have been decreasing (1.2% year-on-year, between 2019 and 2020) (Seoul Metropolitan Government, 2021). Research confirms the importance of the building sector's contribution to Seoul's GHG emissions. Kim and Jeong (2018) estimated around 25.0–26.0 Mt CO_2e for Seoul in 2015.

The Tokyo Metropolitan Government (TMG) has made its inventories accessible since 2012. In 2018, Tokyo's total GHG emissions were approximately 63.9 Mt CO_2e and have demonstrated a declining trend since 2012 (Tokyo Metropolitan Government Bureau of Environment, 2021). Tokyo's commercial and residential sector emissions continued to increase while transportation and industrial decreased. The share of commercial and residential emissions in Tokyo is larger than that of Japan overall, demonstrating the importance of the buildings sector in Asian cities. Using a city-scale multi-regional input-output table, Long and Yoshida (2018) examined the difference in direct and indirect emissions for Tokyo. They point out that the transportation sector accounts for the largest share of direct emissions in Tokyo, while the energy supply, construction and private service sectors account for the largest share of indirect emissions.

In their climate action plan, the city of New Taipei announced that they emitted approximately 18 Mt CO_2e in 2014, with 72.6% from stationary energy sources and 24.9% from transportation, 1.96% from waste, 0.02% from industrial processes and 0.06% from agriculture, forestry and land use (New Taipei City Government, 2015). The residential, commercial and institutional building sectors have the highest share of emissions, with 7.4 Mt CO_2e, accounting for 56.0% of the emissions of the stationary energy sector.

The Government of the Hong Kong Special Administrative Region reports that their 2018 emissions totalled 40.6 Mt CO_2e, with electricity generation and town gas production making up 65.6% of the total (Hong Kong Environment and Ecology Bureau, 2021). Zhou, Shan, Liu, and Guan (2018) use the IPCC territorial emission accounting approach to estimate 2016 emissions for the Guangzhou-Hong Kong-Macao Bay Area. They suggest that Hong Kong's emissions are 47 Mt CO_2. Guangzhou emissions are higher at 66 Mt CO_2. As landfill area is becoming scarce in Hong Kong, Dong, An, Yan, and Yi (2017) focus specifically on the waste sector, reporting that in 2013 emissions were about 2.0 Mt CO_2e from this sector or over 4% of total emissions. The Hong Kong transportation sector emissions levels are estimated by To (2015) at 35.8 Mt CO_2e. Electricity consumption is approximately 30.8 Mt CO_2e (To & Lee, 2017).

The Singapore National Climate Change Secretariat, in their 2020 report, stated that Singapore's GHG emissions in 2017 totalled 52 Mt CO_2e, which is a 34.8% increase from 2000 levels (National Environment Agency, 2020). Primary emissions came mainly from the industry sector (46% of the total), followed by the power sector (39% of the total). Singapore stands out for its high share of industrial emissions compared to other large Asian metropolitan centres of medium to high income.

In Bangkok and Ho Chi Minh City (HCMC), The Japan International Cooperation Agency (JICA) has helped to create a GHG inventory. The Bangkok Metropolitan Administration (BMA) estimates that its year 2013 emissions suggest that the energy sector is the highest source of GHG emissions energy (25.6 Mt CO_2e), followed by transportation (13.8 Mt CO_2e), waste and wastewater (4.55 Mt CO_2e), and green urban planning (-0.045 Mt CO_2e). Total emissions are 43.9 Mt CO_2e (Bangkok Metropolitan Administration, 2015). In a more recent review, the BMA reported for 2016 that emissions for energy are 25.8 Mt CO_2e, while transportation emissions have decreased to 12.4 Mt CO_2e. Waste and wastewater remain at approximately 4.5 Mt CO_2e, and green urban planning is -0.045 Mt CO_2e (Bangkok Metropolitan Administration, 2017). According to a research report, however, the BMA is underestimating the importance of the waste sector. For example, Thitanuwat, Polprasert, and Englande (2017) suggest that this sector is emitting 7.1 Mt CO_2e annually. The CO_2 emissions for HCMC's stationary energy and transportation sectors are approximately 17 Mt CO_2e (Bangkok Metropolitan Administration, 2017). Together these sectors' emissions comprise 91% of total emissions and removals from the city. The total GHG emissions are 38.5 Mt CO_2e per year. As in many major metropolitan centres, emissions from HCMC account for a disproportionate share of national emissions. While HCMC's population share is 9% of the total national population, emissions from the city account for 16% of national GHG emissions.

In South Asia, Gouldson et al. (2016) estimate that 2014 emissions for Kolkata are between 23 and 24 Mt CO_2e, with the residential sector contributing most to the total emissions. These estimates include energy use and emissions from the metropolitan area, using direct consumption of fuels and waste facilities (Scope 1 emissions) and those produced while generating the electricity consumed within the city (Scope 2 emissions). Using the GAINS model, Majumdar et al. (2020) report that in 2015, the Kolkata Metropolitan City (KMC) emitted approximately 20.3 Mt of CO_2, 74.8 kt of N_2O, and 25.2 kt of CH_4. The power plant sector contributed the largest share (66%) of CO_2 emissions, followed by light- and heavy-duty vehicle exhaust (15%) and residential combustion (10%). The agriculture sector contributed the majority of N_2O and CH_4 emissions, 97% and 87%, respectively.

Sharma and Dikshit (2016) calculated Delhi's 2014 GHG emissions load to be 37.9 Mt CO_2e, with electricity generation/consumption contributing 43% and vehicles contributing 32% of the total. Nagar, Sharma, Gupta, and Singh (2019) estimate 2014 emissions to be at 41.6 Mt, with major contributions from power plants (46.8%), vehicles (29.7%), municipal solid waste burning (7.6%) and domestic cooking (6%). Transportation emissions in Delhi and Bangalore contribute the largest share of total emissions (32% and 43.5%, respectively), and the domestic sector emissions are most important in Mumbai and Kolkata (32.7% and 42.78%, respectively).

2.3. Asian intra-urban emissions levels

While it is well documented that the major metropolitan centres of nations, particularly those in Asia, are responsible for a large part of the emissions for their country, the distribution of these emissions by source, sector and urban location are less understood. Specifically, the spatial layout of a city, the fuels as part of the primary supply, the energy-consuming industrial processes as well as other characteristics, which are responsible for varying levels of emissions within the city, require further exploration. Few previous studies have examined urban emissions at the sub-city scale and, particularly spatially, even fewer distinguish among spatial emissions by sector. Indeed, research in these areas is only beginning to be published (Yang, Wang, Sun, Wang, & Zheng, 2018; Zhu et al., 2019). For example, examining 38 Beijing residential communities, Yang et al. (2018) estimate residential and transportation emission levels for each community, separating out the levels into electricity, cooking and heating emissions for residential emissions and private car and taxi for transportation emissions. Wang, Shi, Fang, and Feng (2019) analysed CO_2 emissions for the manufacturing industry, transportation, service industry and housing sectors, as well as the total emissions for the entirety of the metropolitan area using a downscaling analysis.

Increasingly, satellite remote sensing is used to detect atmospheric CO_2 concentration, with the advantage of enabling a stable, continuous and large-scale observation (Goldberg et al., 2019; Park, Jeong, Park, Yun, & Liu, 2021). Zhu et al. (2019) used a high-resolution carbon emission spatially gridded (1 km^2) dataset for Shanghai from 2010 to 2015 to generate fossil fuel emissions. Pan, Li, Zhu, and Dang (2017) used a similar method to study CO_2 emissions in Shanghai by energy type, usage type, and facilities. Sun et al. (2021) also used a 1km^{2}resolution CO_2 emission gridded data for a number of Asian megacities: Seoul, Busan, Incheon, Daegu, Tokyo, Kyoto, Osaka, Chiba, Beijing, Tianjin, Shanghai and Chongqing.

3. REVIEW OF METHODS

The present research examined the drivers of GHG emissions at the sub-city scale and different ways to promote low-carbon futures. Each team picked a different focus, method and used different data. The study was not intended to compare GHG emission results, which typically are different, but rather to identify areas where Asian cities could enhance low-carbon pathways. In this section, we briefly review the different methods used to help identify drivers of GHG emissions.

3.1. Bangkok

Thailand developed its first national GHG inventory report in 1994, followed by subsequent inventory reports in 2000 and 2011. However, comprehensive sub-city level inventories have only started to be explored (Ali, Pumijumnong, & Cui, 2018). The Bangkok team developed a historical inventory of GHG emissions at the sub-city level with a focus on the residential, commercial, industrial and transportation sectors. The team used secondary data to calculate the associated sectoral emissions from 2008 to 2016 by province. It is important to note that the study has estimated only electricity-based emissions from residential and commercial sectors (due to data limitations) and only focused on CO_2 emissions. The team used fuel consumption, the net calorific value of the fuel and emission factors to calculate emissions. For electric use, the method was to multiply the electric consumption by the local emission factor. For all sectors except electricity, calorific values and emissions factors for fuels were collected from the IPCC 2006 guidelines. The factor for power generation was collected from the Thailand Energy Policy and Planning Office.

3.2. Beijing

The Beijing team developed comprehensive indexes using the stochastic frontier parametric approach (SFA) to measure relative carbon emission reduction efficiency (Feizabadi, Bagherian, & Moghadam, 2019) in order to study the carbon emission performance and mitigation potential of 39 industrial sectors in the Beijing city, Tianjin city and Hebei Province (BTH) region, China. According to data from the National Bureau of Statistics of China, the BTH region covers an area of 0.22 million km^2, with a population of more than 110 million persons in 2017 (21.3 million persons in Beijing, 15.6 million persons in Tianjin and 75.2 million persons in Hebei), accounting for 8.06% of the total population of China. In 2017, the GDP was approximately 8.06 trillion Chinese Yuan (CNY), accounting for 9.74% of the nation's total. Industrial development has been an important part of regional economic growth in recent years and, by 2017, accounted for 30.9% of the regional GDP. In Hebei, in 2017, the industrial share of GDP exceeded 40%.

Variables for the analyses included capital, labour, energy use, GDP (desirable outputs) and CO_2 emissions (undesirable outputs) (Guo, Liu, & Wang, 2013; Lin & Wang, 2015). The inputs were classified as belonging to 1 of 39 sectors. The original data was derived from the Beijing Statistical Yearbook, the Tianjin Statistical Yearbook, the Hebei Economic Yearbook and the China Statistical Yearbook (2011–2017). The economic data from each sector was converted to 2010 price levels, including capital and GDP. Estimates of the capital stock for each sector were based on the perpetual inventory method. Energy consumption was converted into standard coal equivalents (Tce). The carbon emissions were calculated according to the IPCC method (Wang, Zhan, Li, Zhang, & Zhang, 2019). The team captured the total factor carbon emission performance (TFCP) and carbon emission mitigation potential (CMP) for 39 industrial sectors in each of the three sub-regions from 2010 to 2016. The study also calculated the carbon emissions from residential consumption in the BTH region and analysed the influence of impact factors on the indirect residential carbon emissions. Details of the methods can be found in Wang, Zhan, Bai, Chu, and Zhang (2019) and Wang et al. (2019) .

3.3. Seoul

The Seoul team evaluated the progress of green growth policy in Seoul and the Republic of Korea with suggested methods for improving the effectiveness and enforcement of policies that respond to climate change. The team first conducted an analysis of the CO_2 emissions in the building sector, focussing on socioeconomic driving forces. Energy consumption is calculated per year per building from natural gas use. The emissions were spatialised using a kernel density function. The spatial distribution of emissions data was then compared visually to the spatial distribution of population, number of buildings (houses), number of businesses, local GDP, and other factors. The team then reviewed national and local plans for low carbon development for the province and city, including actions by sector for energy production, air quality, transportation, resource recycling, water use, local ecology, and urban agriculture. The team analysed the focus of policy and the related emissions to identify ways to enhance the low-carbon development of the city.

3.4. Taipei

The Taipei team identified the CO_2 emissions within the building stock of the city using emergy analysis to calculate embodied energy (Brown & Buranakarn, 2003). Emergy is an accounting technique that quantifies all forms of energy in terms of their equivalent ability to do work when used in the system of which they are a part. This includes natural factors (rain, wind, sunlight, etc.) as well as anthropogenic energy (primary fuels, electricity, heat). Emergy is typically expressed in solar emjoules (sej). The Taipei team divided all buildings in the city into five types classified in accordance with the building materials used and the years the structures were built (red brick buildings – before 1945, 1-5 story buildings 1946-1974, 6-12 story buildings 1975-1995, and 12-24 story and 25 story and above buildings 1996 to present). They calculated densities of emergy storage (sej/m^2) and CO_2 emissions for the different building types through an analysis of the raw construction materials. Estimates were developed based on the "Building Material Production and Transportation CO_2 Emission Chart" issued by the Architecture and Building Research Institute of Taiwan's Ministry of the Interior (MOCA), delineating the building types of high and low CO_2 emissions. In order to analyse the spatial distribution of emergy storage and building CO_2 emissions in Taipei City, this study used both district and neighbourhood scale mappings. Presenting results from the different scales allowed for the identification of distinctions between daily consumption CO_2 emission and urban development intensity. Complete details of the study can be found in Huang, Huang, and Marcotullio (2019).

3.5. Tokyo

The Tokyo team examined the change in energy use, GHG emissions from 2000 to the present, and national and local energy-related policies during that period (20 different energy-related mitigation policies). The analysis used data obtained at various levels, including local emissions levels published by the Tokyo Metropolitan Government (TMG) for different fuels (gasoline, fuel oil, LPG, city gas, electricity) and sectors (industrial, commercial, residential and transport). The focus was on evaluating the differences in policies at different levels of government, particularly after the 2011 earthquake, and to assess the effect of these policies on energy use and emissions. This was performed through a historical analysis of changes in energy use and GHG emissions, given the timing of implementation and enforcement of specific policies. Details of the methods can be found in Aleksejeva, Voulgaris, Long, and Gasparatos (in press).

3.6. New York City

The New York City team used a variety of online data sets at the national level to generate a historical spatialised map of residential energy use from 1993 to 2009 for the New York metropolitan area, as defined by the Regional Plan Association (RPA) (34 counties in and around New York City). The analysis of the data included three major steps, including developing regression equations for the four different residential energy end uses (space heating, water heating, cooling and appliance use), spatialising the outputs of these regressions using census data and then generating emissions based upon fuel use (using national conversion factors). The spatialised residential energy use was then aggregated into different urban units (core, inner suburban, outer suburban and exurb) and compared. The results were validated by comparing the total energy use and GHG emissions data to state databases. Details of the methods can be found in Rio, Lu, and Marcotullio (in press).

4. REVIEW OF RESULTS

4.1. Bangkok

The Bangkok team identified five major findings for GHG emissions and four suggested drivers for lower emissions levels. The first major finding is that for the BMA overall, there is a trend of total CO_2 emissions increase from 2008 to 2016 at a rate of 0.94% per annum. The second finding is that the transportation sector had the highest levels of emissions, followed by the industrial sector, then the commercial sector and finally, the residential sector. Transportation accounted for 43% of total emissions in the Bangkok Metropolitan region and within the transportation sector, the largest fuel source was diesel. The third finding is that there was a significant decrease in energy use and emissions during 2011, which was due to flooding experienced across the country but largely experienced within the Bangkok region. This flooding was most severe in the Ayutthaya and Pathumthani provinces. As a result of the flooding, electricity-related emissions dropped significantly. Finally, the rate of increase in electricity consumption was higher (3% increase for buildings) than the rate of increase in electricity-related emissions (approximately 1% increase in emissions) from 2008 to 2016. This suggests an energy and or carbon intensity efficiency during this period. From these results, the team suggested that the drivers for future low-carbon actions are to increase the share of renewable energy in power generation, increase energy efficiencies, particularly in the buildings sector, continue to develop mass transit to encourage less private vehicle use and promote electric vehicles.

4.2. Beijing

The major findings of the Beijing team include identifying the trend of total carbon emissions in the BTH region, which increased from 542 Mt CO_2 in 2010 to 649 Mt CO_2 in 2016. Carbon emissions in Hebei increased from 439 Mt CO_2 in 2010 to 565 Mt CO_2 in 2016 and contributed the largest proportion (87%) of the increase during this period. Carbon emissions in Tianjin increased slightly from 44 Mt CO_2 in 2010 to 48 Mt CO_2 in 2016, while those in Beijing decreased slightly from 59 Mt CO_2 in 2010 to 36 Mt CO_2 in 2016.

The sub-regional CMP of most industrial sectors decreased from 2010 to 2016. Processing of Food from Agricultural Products, Manufacture of Foods, Manufacture of Beverages, Manufacture of Nonmetallic Mineral Products, Smelting and Pressing of Ferrous Metals, Manufacture of Transport Equipment, Production and Distribution of Electric Power and Heat Power in Beijing have the greatest potential for reducing carbon emissions. The total residential carbon emissions increased from 257.50 Mt CO_2 in 2002 to 673.34 Mt CO_2 in 2012 in the BTH region, reflecting an increase of more than 150%. In addition, carbon emissions in Hebei were 3.86 times that of Beijing and 10.58 times that of Tianjin in 2012. Residential carbon emissions from urban areas were far higher than that from rural areas, with urban carbon emissions being 1.51 times higher in 2002, 2.66 times higher in 2007, and 2.79 times higher in 2012. Moreover, indirect carbon emissions were higher than direct ones. The contribution of indirect emissions to total emissions comprised more than 60% in Beijing and Tianjin, and more than 70% in Hebei. Three impact factors exhibited positive effects on the growth of indirect emissions in the three sub-regions; intermediate demand, consumption, and population size.

4.3. Seoul

The Seoul team suggest that the Seoul Metropolitan Government's green growth policies were developed before the national policies, demonstrating that Seoul leads the country in low carbon mitigation strategies. Moreover, the Seoul Metropolitan Government supplemented its existing green policies, seeking to facilitate citizen participation, and to divide action plans between citizens, companies and the government. However, the achievement was not found to be inclusive.

From the GHG emissions analysis, the team identified a number of potential policies for low carbon futures. First, the city must establish a spatially organised system that connects differences across space, the environment, energy and resource cycling. Green growth plans need to reflect differences in socioeconomic and physical factors across the city. Plans must be specialised to take advance of physical spaces, environment, energy, resource cycling, transportation, infrastructure and climate change. Second, policy must focus on urban restoration. For example, the decline of the old downtown area of Seoul had been a persistent problem which was addressed by the Cheonggyecheon Stream project, which subsequently led to the revitalisation of central Seoul. The authors suggest that when selecting green-city-model target areas, urban revitalisation areas must be a priority, and the sites need to reflect various examples of applied planning elements. Third, low-carbon green policy must focus on spatial planning for local energy. Local energy plans can help to identify the current conditions of energy consumption and GHG emissions status. This requires a local energy consumption inventory and enhanced demand estimations. Finally, policy must enhance governance systems, which start with guidelines to provide solutions by forming consultative groups that are inclusive of stakeholders.

4.4. Taipei

The Taipei team found that among the five building types studied, 13 to 24 story steel-reinforced, concrete buildings have the highest emergy density (7.59E+15 sej/m^2) and brick buildings (the oldest building type) have the lowest emergy density (1.25E+15 sej/m^2). The results show a correlation between emergy densities of different building types and the density and height of the buildings. Using emergy density, the growth of the city is evident, which brick buildings located close to Tamsui River and higher emergy density buildings located in consecutive circles, moving east from the river. Buildings with higher emergy density and stories tend to use greater amounts of construction materials with higher unit emergy value UEVs (transformity values) (i.e., reinforced, concrete and steel), which results in higher emergy density. These results suggest that the building types with higher emergy densities are also responsible for higher building–CO_2 emissions.

The total CO_2 emissions embedded in buildings in the city surpasses 1.47 Mt CO_2, of which approximately 71% is embedded in the building structure, while approximately 20% is embedded in the foundations. They also note that given the newer building have higher emergy density and CO_2 emissions, further building can rapidly increase total embedded CO_2 emissions. This suggests the importance of building re-use, particularly for newer developed structures.

The team also argued that by calculating the correlation between the emergy of different building types and the building-CO_2 emissions during the construction process, the team was able to identify the positive correlation between accumulated emergy storage and CO_2 emissions. They conclude that emergy synthesis can effectively assess CO_2 emissions derived from building construction.

4.5. Tokyo

The Tokyo team found that the Tokyo Metropolitan Government has been a clear frontrunner in energy consumption and GHG emission reduction efforts within Japan, possibly even influencing the agenda of the national government towards the adoption of more ambitious targets and individual initiatives. Apart from consistently setting more ambitious emission reduction targets than the national government, the Tokyo Metropolitan Government has enacted some truly innovative policies and initiatives ahead of the rest of the country. Some examples include the local Cap-and-Trade program, the rapid switch to LEDs, and the energy-labelling scheme, among others. These policies have helped to reduce energy use and emissions in the city.

Given the results of the study, the authors suggest that in some cases, city governments can be more ambitious and proactive in emission reduction targets than national governments, even in the wake of unanticipated events. They also argue that despite good intentions and clear efforts, many of the factors affecting the effectiveness of energy consumption and emission reduction policies are beyond the reach of city governments. That is, localities need to cooperate with national governments to provide effective mitigation strategies. Both of the findings have major ramifications for managing energy consumption and meeting emissions reduction targets both at the national and city levels.

4.6. New York City

The New York team identified a number of findings. First, the tri-state region's total residential energy use was about the same from the start to the end of the period (although there were fluctuations), but there were dramatic changes in energy services. For example, the residential energy for space heating dropped by approximately 16.4% from over 1.06 quad to 880 trillion BTU. At the same time, residential energy for cooling increased from 840 billion to 21 trillion BTU or by over 2400%. Energy for appliance use also increased by 80% from 160 trillion to 289 trillion BTU during the period. Second, total energy use shifted by geographic region. Residential space heating energy dropped across all geographic areas. At the same time, residential energy for water heating, cooling and appliances all increased. Residential energy for cooling increased by the greatest amount relatively across sectors. The greatest absolute total increase in residential energy end use was for cooling in the outer suburbs, which increased from 720 billion to 15.8 trillion BTU. Energy for appliance use also increased differentially across geographies during the period. The greatest increases were experienced by the inner and outer suburban areas, where appliance energy use increased by 80.5% and 85.6%, respectively. Finally, the energy use per household also changed over time, demonstrating differences across space. In terms of household residential energy, the only geographic area that didn't change was the outer suburban metropolitan areas. All other regions experienced drops in average total household energy use. The authors argue that emissions reduction strategies should include a geographic component, as residential emissions are significantly different across metropolitan areas.

5. DISCUSSION AND CONCLUSION

5.1. Asian urban GHG emissions

From the review of the literature, we find that GHG emissions from the region are significant and the major metropolitan centres are large and growing contributors. In most cases, national and urban emissions are increasing, although the APN-funded research teams identified stable emissions over the past few years for Tokyo.

Although it is difficult to directly compare results of the different city research teams due to differences in research focus, methods and data used, there are some generalities that can be identified in terms of the drivers of emissions. First, confirming the literature review, in the rapidly developing cities and urbanising areas such as Bangkok and the BHT, China, important activities related to the growth of emissions include: 1) the building of cities and subsequent creation of concrete-related CO_2 emissions; 2) vehicle (passenger and freight) use; 3) industrial manufacturing energy use and industrial processes and 4) low but growing residential consumption. Within these urban areas, there is a significant difference among sub-city units. For example, the BHT industrial centres and new commercial centres have the highest emissions levels. This is probably due to the economic activities and demand for transportation. That is, industry and transportation are important sectors of GHG emissions in these types of Asian cities.

The Bangkok and BHT studies suggest that cities of rapid growth and industrial development require policies to regulate industries. Industrial development, particularly in cities that are industrial centres, is an important contributor to economic wealth, but emissions from industrial processes can be regulated to help reduce emissions. In this case, both urban planning and city regulations requiring lower emissions are possible. Enhancing laws that encourage energy efficiency in both energy use and industrial processes could help here.

Second, in the more developed cities (Seoul and Tokyo), large shares of emissions are largely from transportation and residential energy use and not from industry. Emissions from these cities are lower per capita than those of some rapidly developing cities. For example, Tokyo's per capita emissions are lower than those of Beijing.

The Taipei study is different in that the team examined embedded energy and CO_2 emissions. The findings, however, suggest the importance of embedded energy in the building sector. This translates into the importance of building re-use rather than demolition and construction of new structures as a means to reduce overall emissions levels. Importantly, the newer buildings have high embedded energy and CO_2 emissions and should be considered for re-use when their current uses are outdated.

Third, some of the major Asian metropolitan centres are leading national low-carbon efforts. The studies in this project identified Tokyo and Seoul as national leaders in carbon reduction strategies. Taipei and Bangkok are also implementing policies, although whether they are leading national efforts was not studied. Low-carbon policies across cities in the region vary, and rightly so. Certainly, all cities share the need to reduce emissions from growing passenger car use, but other priorities vary. Many Asian cities are already dense and compact, facilitating high transit and non-passenger car mobility. For those cities that can sprawl, such as Bangkok, other policy alternatives, such as the electrification of motor vehicles, as pointed out by the Bangkok team, are necessary.

In conclusion, Asia will remain the centre of industrial activity, population growth and increasing CO_2 emissions over the next few decades. It is therefore urgent to identify ways in which the region's cities can become more efficient and less polluting. There are both hopeful and threatening trends emerging. Whether cities in the region can leap-frog over the problems experienced by the developed world remains uncertain. Work on urban GHG emissions will continue to play an important role in helping to understand GHG trends and provide valuable assistance to policymakers.

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Factors influencing farmers' climate change adaptation in Southeast Asia: A comparative study from Vietnam, Laos, and Cambodia

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ABSTRACT

Southeast Asia is among the most climate-vulnerable regions in the world. Despite this, little is known about how climate change adaptation at the household level differs across countries in this geographic region. This cross-country study investigated factors influencing adopting three adaptation practices: growing climate-tolerant crops, intercropping, and switching to cash crops in some selected provinces in Vietnam, Laos, and Cambodia. Based on the survey data from 1017 farm households in these three countries, the paper found that surveyed households in Laos and Cambodia were less likely to adopt the three practices than those in Vietnam. Perception about the impacts of climate change and perceived usefulness of climate change adaptation consistently influenced the adoption likelihood of those practices. Information on climate change shaped farmers' decision to select climate-tolerant varieties and diversify crops. Policy implications aiming at fostering farmers' adoption of adaptation practices are discussed.

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KEYWORDS

Southeast Asia, farm households, cross-country analysis, adaptation likelihood, adaptive capacity, climate change adaptations

HIGHLIGHTS

- We focus on three adaptation practices: using climate tolerant crops, intercropping, growing cash crops.
- Surveyed farmers in Laos and Cambodia were less likely to adopt the adaptation practices.
- Perception of climate change impacts decreased the adoption likelihood of Vietnamese, Laotian, and Cambodian surveyed farmers.
- Perceived usefulness of adaptation facilitated adoption likelihood.
- Information acquisition positively influenced the decision to select climate-tolerant varieties and diversify crops.

1. INTRODUCTION

Southeast Asia is among the most climate vulnerable regions in the world (IPCC, 2022). In recent years, the regions have faced the increased frequency and intensity of extreme climate events (IPCC, 2022). Surveys conducted in this region documented that a large proportion of households have reported yield reduction due to climate change (Waibel, Pahlisch, & Völker, 2018). It is projected that increased floods and droughts, along with heat stress will negatively affect food availability and prices, resulting in increased undernourishment in the region (IPCC, 2022). Vietnam, Laos, and Cambodia, three developing countries in Southeast Asia are also vulnerable to climate change, but at varying degrees: Vietnam is the least vulnerable while Cambodia is the most vulnerable to climate change (Kuntiyawichai, Plermkamon, Jayakumar, & VanDau, 2015). At the national level, discrepancies in climate change adaptation among the three countries are well-documented (Waibel et al., 2018). However, research that compares the differences in climate change adaptation at the farm level across the three countries is limited, even though agriculture is the most climate-vulnerable sector. This leads to our incomplete understanding of farmers' adaptation at a larger scale, which is beyond the border of a single country in Southeast Asia.

Adaptation in human systems responds to climatic stimuli to reduce negative impacts or take beneficial opportunities (IPCC, 2014). Adaptations have been made at different levels, from the global to the national and farm level. In developing countries, since limited resources constrain these countries' public funding for climate change adaptation, farm-level adaptation is necessary to complement governmental efforts (Reidsma, Ewert, Lansink, & Leemans, 2010). Small-scale farmers in Southeast Asia have adopted a wide range of adaptation measures such as tolerant varieties, crop diversification, irrigation, and adjustment of seasonal calendars have been reported (Phuong, Biesbroek, Sen, & Wals, 2018; Shaffril, Krauss, & Samsuddin, 2018). However, it is worth noting that all measures above are autonomic adaptation, which is informal in its development and implementation process, reflecting the lack of relevant services (McDowell, Stephenson, & Ford, 2016).

At the farm level, adopting an adaptation practice is a result from the households' decision-making process, with multiple internal and external factors involved. Empirical studies outside Southeast Asia showed that internal factors include knowledge and perception of climate change (Asrat & Simane, 2018), gender and other demographic characteristics (Ngigi, Mueller, & Birner, 2017), and production factors (e.g., access to land) (Gezie, 2019). External factors are agricultural and climate policies (Aryal et al., 2020), and the prevalence of broader support networks from the government and/or communities (Harmer & Rahman, 2014). Empirical evidence on the determinants of farmers' adoption of climate change adaptation practices is not lacking in Southeast Asia (Bairagi, Mishra, & Durand-Morat, 2020; Trinh, Rañola, Camacho, & Simelton, 2018). However, most of them focus on a single country, leading to a narrow view of farmers' adaptation in the region. To address this gap, the study investigates the determinants of farmers' adoption of three adaptation practices: growing tolerant-climate crops, intercropping, and growing cash crops in Laos, Cambodia, and Vietnam. We found cross-country differences in farmers' adaptation, the consistent influence of perception of climate change and perceived usefulness on the decision to implement the three practices. This way, this study contributes to existing adaptation literature and provides useful information to assist the development of adaptation policies in Southeast Asia.

2. MATERIALS AND METHODOLOGY

2.1. Farmer survey

Four provinces, including Son La (Vietnam), Xaysomboun and Vientiane (Laos), and Oddar Meanchey (Cambodia), were selected for the farmer survey. These provinces have faced extreme climate events in the past five years, including intensified cold air, cold spells, heat waves, droughts, floods, and storms. In chosen provinces above, we selected districts that are highly vulnerable to climate change. They include Yen Chau and Van Ho (Son La), Anouvong (Xaysomboun), Naxaythong (Vientiane), and Banteay Ampil (Odda Meanchey). Common cropping systems in Yen Chau and Van Ho districts are paddy rice, upland rice, maize, fruit and vegetables. In Anouvong and Naxaythong districts, popular crops include paddy rice, upland rice, vegetables, and fruits. Farmers in Banteay Ampil mainly grow upland rice, cassava, vegetables, and fruits.

We used the convenience sampling method to recruit farmers. In each chosen district, we collaborated with village leaders to send oral invitations to farm households. Only one representative of each household which agreed to participate in our survey was recruited. The survey was conducted from June 2021 to November 2021 and we received 1017 complete replies from farm household representatives (417 from Vietnam, 299 from Laos and 303 from Cambodia). The characteristics of surveyed farmers and their households are presented in Table 1. The distribution of male and female respondents is relatively equal, with 52% of the surveyed participants being men. Noticeably, respondents' education level was relatively low; about 60% of them either had no schooling or only had elementary education (result not shown). Respondents' mean age is 42; on average, their households had five to six members. 32% of surveyed households were self-reported as poor, and the agricultural land per household was about 3.1 ha on average.

2.2. Variable description and data analysis

Table 1 shows descriptive statistics of variables used in this study. Dependent variables are the adoption of three adaptation practices, including (1) using climate-tolerant varieties (e.g., drought-tolerant varieties), (2) intercropping, and (3) growing cash crops. Previous research shows that rice farmers in Vietnam and Cambodia have used climate-tolerant varieties to respond to climate change (Bairagi et al., 2020; Phuong et al., 2018). Crop diversification including intercropping has the potential to increase smallholder farmers' income while being climate resilient in Southeast Asia (Phuong et al., 2018; van Noordwijk et al., 2020). Transitions toward cash crop production that are market-oriented improve Southeast Asian farmers' income (Burra et al., 2021), and thus strengthen their adaptive capacity. Here, we define cash crops are high value crops such as coffee and tea.

Variable	Mean (Standard Deviation) or %			
	Whole sample (n=1017)	Vietnam (n=417)	Laos (n=299)	Cambodia (n=303)
Use Tolerant Crop: % of farmers using tolerant climate crops, =1 if use, =0 otherwise	44.94	91.566 ^{a}	9.365 ^{b}	16.172 ^{c}
Intercropping: % of farmers intercropping, =1 if intercrop, =0 otherwise	32.25	57.590 ^{a}	14.381^{b}	15.12 ^{bc}
Use Cash Crop: % of farmers growing cash crops, =1 if growing cash crops, =0 otherwise	33.92	65.542 ^{a}	16.388 ^{b}	7.921^{c}
Gender: % of male respondents, =1 if being male	52.02	51.807	56.856	47.525
Age	41.99 (13.11)	37.764^{a} (10.450)	41.452^{b} (13.782)	48.293^{c} (13.287)
Education: From 0 (no schooling) to 6 (Postgraduates)	1.43 (1.29)	1.627^{a} (1.237)	1.712^{ab} (1.472)	0.888^{c} (0.956)
Household Size: Number of people	5.54 (2.45)	4.928^{a} (1.565)	7.542^{b} (2.960)	4.403 ^{c} (1.547)
Income: Annual household income, USD	3252.318 (2512.361)	3529.099 ^{a} (2867.041)	2849.848^{b} (3852.145)	3270^{c} (2111.113)
AgriLand: Agricultural landholding, hectares	3.13 (5.867)	1.670^{a} (1.96)	3.276^{b} (5.770)	4.991^{c} (8.436)
Perceived Climate Impact : Perceived impact of climate change on crop production from 1 (not at all) to 5 (very much)	3.77 (1.14)	4.248^{a} (0.889)	3.184^{b} (1.131)	3.706^{c} (1.172)
Perceived Climate Change: Perceived the frequency of extreme climate events, from 1 (very low) to 5 (very high)	3.57 (1.01)	3.723^{a} (0.806)	2.993^{b} (0.909)	3.941^{c} (1.105)
AdaptationInform: Acquisition of adaptation information, from 1 (very little) to 5 (very much)	2.13 (1.34)	2.251^{a} (0.887)	2.154^{ab} (2.019)	1.954^{bc} (0.937)
UsefulnessTolerantCrop: Perceived usefulness of using tolerant crops, from 1 (very little) to 5 (very much)	2.76 (1.01)	3.161^{a} (0.762)	2.528^{b} (1.171)	2.426^{bc} (0.960)
UsefulnessIntercropping: Perceived usefulness of intercropping, from 1 (very little) to 5 (very much)	2.53 (0.99P)	2.863^{a} (0.785)	2.234^{b} (1.209)	2.367^{bc} (0.862)
UsefullnessCashCrop: Perceived usefulness of switching to cash crops, from 1 (very little) to 5 (very much)	2.66 (1.120)	3.084^{a} (0.935)	2.505^{b} (1.273)	2.241^{c} (0.976)

^{a,b,c}Note: Scores in one row with a different superscript are significantly different at $p < 0.05$ using oneway ANOVA and post hoc Tukey test.

TABLE 1. **Descriptive statistic of variables**

Independent variables include farmers' demographics (country, age, gender, education), farms' characteristics (household size, land area, annual income), and perception. The variable "country" (not shown in Table 1) was coded as 1, 2, or 3 for Vietnamese, Laotian, or Cambodian respondents, respectively. To measure the perception of climate change, respondents were asked to evaluate the frequency of extreme climate events, on a 5-point Likert scale ranged from 1 (very low) to 5 (very high). Perceived climate impact refers to the impact on farmers' crop production. There were three items on perceived usefulness for three corresponding adaptation practices. The responses for all perception-related items were on 5-point Likert Scale, ranging from 1 to 5, with higher scores reflecting a higher frequency, impact, or usefulness. To measure the acquisition of adaptation information, respondents were asked how well they were informed about recommended adaptation strategies at the farm level.

Since the adoption of the three adaptation practices, the dependent variable, is in the form of binary data, we used logit regression to predict the probability a farmer adopts a specific practice. Each crop production practice is associated with a separate logit model, making three regression models in total. For simplicity, for each regression model, we used pooled data, which combines data from all studied countries. The multicollinearity assumption was satisfied, as evidenced by the absence of coefficient correlations less than 0.5.

3. RESULTS AND DISCUSSION

3.1. Perception of climate change and climate change impact

There is a statistically significant difference in perception of climate change and climate change impact among surveyed farmers in Vietnam, Laos and Cambodia (oneway ANOVA and post hoc Tukey test results, Table 1). Cambodian respondents perceived the highest frequency of extreme climate events, while Vietnamese farmers also reported a high frequency but to a lesser extent, and Laotian respondents perceived the lowest. Vietnamese respondents expressed the highest impact of climate change and Laotian respondents indicated the lowest impact.

Perception of climate change might be influenced by actual extreme climate events that occurred in relatively recent time. Venkatappa, Sasaki, Han, and Abe (2021) reported that among the three countries, the relative frequency of moderate and extreme droughts was the highest in Cambodia from 2015 to 2019.Our group discussions with surveyed farmers in Cambodia also show that farmers had experienced severe drought in 2021 before our survey. Group discussions participants in Vietnam also reported a severe drought and heat waves in the surveyed area in 2021. Participants said that droughts, floods, and landslides have become more frequent in the past five years. Vientiane province (Cambodia) has often been flooded during the rainy season, while Xaysomboun province experienced a water shortage during upland rice plantations in 2021. In all surveyed districts, farmers reported decreased rice yield due to extreme climate events. In general, there was a link between farmers' perception of climate change and actual climate change, as shown by Hasan and Kumar (2019).

3.2. Factors associated with the adoption of climate change adaptation practices

Table 2 shows a number of factors associated with farmers' adoption of adaptation strategies. Surveyed Laotian and Cambodian farmers were less likely to use climate-tolerant varieties, have integrated cropping systems, and change cash crops compared to Vietnamese farmers. It is evidenced by negative and significant coefficients associated with the variable "Laos" and "Cambodia" in all regression models. Descriptive statistics also confirm this result: the percentage of surveyed farmers adopting all three practices is the highest in Vietnam (Table 1). Previous literature shows that adaptation strategies vary across countries and are context-dependent. A comparative study between Cambodia and Myanmar reported that changing new crop species were more common in Myanmar, while changing cropping calendars was more popular in Cambodia (Shrestha, Raut, Swe, & Tieng, 2018). The differences in the adoption of studied adaptation strategies among Vietnamese, Laotian, and Cambodian surveyed farmers might be attributable to the heterogeneity in adaptive capacity across the three countries (Yusuf & Francisco, 2009). Vietnamese farmers might benefit from a higher level of economic development in Vietnam, as evidenced by their higher income level (Table 1). Therefore, they are more capable of adapting and this might explain their higher adoption rate of adaptation practices as compared to Laotian and Cambodian farmers.

Farmers' characteristics did not play an important role in influencing adoption likelihood. The effect of gender and education was non-significant in all regression models. Age is the only demographic variable that had a significant effect, but only in "growing cash crops". This means older farmers were more likely to produce cash crops. Older farmers are likely to have more farming experience (Prokopy et al., 2019) and better resources for agricultural production (Wang, Jin, Fan, Obembe, & Li, 2021). These might explain the positive association between age and the likelihood to grow cash crops.

Noticeably, regarding households' characteristics, income exerted a significant effect, but only in the "growing cash crops" model. This result suggests that shifting to cash crops might contribute to improved income. This result also implies that producing cash crops is costly, so farmers with a lower income are less interested in cash crop production. As such, limited income or resources can be seen as a barrier to cash crop production. Moreover, agricultural landholding only determined intercropping adoption. Famers with larger landholding were more likely to intercrop.

Information about recommended adaptation strategies influenced farmers' decision to use adaptive crop varieties and diversify crops. In other words, farmers, who are better informed about available adaptation measures were more likely to adopt intercropping and use drought tolerant varieties. This finding aligns with the study by Etwire, Koomson, and Martey (2022), which reported that access to information was positively associated with adaptation decisions. This result suggests that the improvement of information provision on adaptation measures, for example, via extension service, will facilitate the adoption of adaptation practices. However, the association between information and the decision to switch to cash crops was non-significant. This result implies that farmers might not consider changing to cash crops as an adaptation strategy.

The perception of climate change significantly affected the decision to grow climate-tolerant crops. Previous studies provide mixed results on the association between the perception of climate change and adaptation. For instance, Hasan and Kumar (2019) reported a positive correlation between the perception of climate change and the number of adopted adaptation practices in Bangladesh. In contrast, Marie, Yirga, Haile, and Tquabo (2020) found that climate change perception did not determine adaptation strategies in Ethiopia. Similarly, the current paper found that perception of climate change did not influence the decision to intercrop and grow cash crops. Farmers might not view these two practices as adaptation strategies and, therefore, not relate them to climate change.

Given the drastic impact of climate change in the survey provinces, farmers' high perception of climate impact is expected. However, the negative association between perception about the impact of climate change and adaption likelihood was surprising. This result can be explained in two ways. Farmers who perceive high climate change impacts might not be aware that intercropping, producing cash crops or using climate-tolerant crops are strategies to combat climate risks. As such, they would be more reluctant to adopt the three practices. There might be another way to explain this result. Farmers who have already adopted the three practices have been able to reduce the impacts of climate change and thus perceive fewer conse-

	Use Climate Tolerant Crops		Intercropping		Growing Cash Crops	
	Coefficient (SE)	Marginal effect (SE)	Coefficient (SE)	Marginal effect (SE)	Coefficient (SE)	Marginal effect (SE)
Vietnam	Base level		Base level		Base level	
Lao	-5.030 *** (0.375)	-0.784 *** (0.031)	-2.574 *** (0.293)	-0.385 *** (0.034)	-3.029 *** (0.305)	-0.462 *** (0.035)
Cambodia	-3.934 *** (0.293)	-0.667 *** (0.038)	-1.827 *** (0.238)	-0.306 *** (0.037)	-3.045 *** (0.294)	-0.463 *** (0.036)
Gender	-0.320 (0.228)	-0.028 (0.020)	-0.066 (0.177)	-0.009 (0.025)	-0.269 (0.189)	-0.034 (0.024)
Age	-0.003 (0.010)	-0.000 (0.001)	0.003 (0.008)	0.000 (0.001)	0.015 * (0.008)	0.002 * (0.010)
Education	0.075 (0.101)	0.006 (0.009)	0.097 (0.076)	0.014 (0.011)	0.037 (0.083)	0.005 (0.010)
Household size	0.039 (0.053)	0.003 (0.005)	0.034 (0.043)	0.005 (0.006)	0.016 (0.045)	0.002 (0.006)
Log_Income	0.062 (0.088)	0.005 (0.008)	0.023 (0.069)	0.003 (0.010)	0.232 ** (0.117)	0.029 ** (0.015)
Log_AgriLand	-0.001 (0.008)	-0.000 (0.001)	0.024 ** (0.010)	0.003 * (0.001)	0.012 (0.010)	0.001 (0.001)
Perceived ClimatChange	0.360 *** (0.121)	0.031 *** (0.010)	-0.138 (0.094)	-0.019 (0.013)	-0.057 (0.103)	-0.007 (0.013)
Perceived ClimateImpact	-0.367 *** (0.113)	-0.032 ***(0.010)	-0.395 *** (0.091)	-0.056 *** (0.012)	-0.542 *** (0.100)	-0.068 *** (0.012)
Adaptation Inform	0.362 *** (0.117)	0.031 *** (0.010)	0.257 *** (0.097)	0.036 *** (0.014)	-0.083 (0.099)	-0.010 (0.012)
Usefulness TolerantCrop	0.931 *** (0.135)	0.080 *** (0.011)				
Usefulness Intercropping			1.236 *** (0.125)	0.175 *** (0.015)		
UsefulnessCash Crop					1.196*** (0.117)	0.150*** (0.012)
Cons	-1.394 (1.029)		-2.128 *** (0.810)		-2.562** (1.009)	
Pseudo R^2	0.568		0.312		0.393	
Count R^2	0.893		0.792		0.832	

Note: Log_income, Log_Agriland denote the logarit transformation of income in USD and agricultural landholding in ha. ***, **, and * indicate significant level at 0.01, 0.05, and 0.1, respectively.

TABLE 2. **Logit regression results**

quences of climate change.

The perceived usefulness of specific adaptation practices is positively associated with adopting these practices. Previous studies indicated that adaptation strategies were used because of their perceived usefulness or benefits. Arunrat, Wang, Pumijumnong, Sereenonchai, and Cai (2017) revealed that perceived importance and usefulness positively influenced farmers' decision to apply adaptation strategies against drought and flood in Thailand. Farmers, including those not adaptation-orientated, can view the usefulness of action from diverse angles. For example, while farmers in Pakistan perceived crop diversification as an adaptive practice (Abid, Scheffran, Schneider, & Elahi, 2019), producers from Uganda viewed coffee-banana intercropping as an income-generation activity (Jassogne, vanAsten, Wanyama, & Baret, 2013).

4. CONCLUSION AND POLICY IMPLICATIONS

This paper is among the few cross-country studies in Southeast Asia investigating households' adoption of adaptation practices. Our focus practices are using climate-tolerant crops, intercropping, and growing cash crops. The paper found that surveyed households in Laos and Cambodia were less likely to adopt the three practices above than those in Vietnam. This result might reflect the weaker adaptive capacity at the farm level in Laos and Cambodia. More efforts are needed to enhance farmer adaptive capacity in these two countries.

In this study, farms' and farmers' characteristics are unimportant determinants of adaptation decisions. Age and income are the two significant predictors, but only in "growing cash crops" model. The transition to high value cash crops can boost farm income. However, our finding shows that households with a lower income level were less likely to grow cash crops. Policy instruments aiming to improve loan access are crucial to support these farmers. Moreover, agricultural landholding only influenced intercropping adoption.

Perceived impact of climate change, perceived usefulness, and information acquisition on adaptation strategies are important determinants of adaptation decisions. The negative relationship between the perception of climate change impact and the adoption likelihood of the three studied adaptation practices might be attributable to farmers' limited awareness about how these practices can enable climate change adaptation. Since perceived usefulness increased the adoption likelihood of all three concerning adaptation practices, communication that aims at improving farmers' awareness about the benefits of these practices is essential. Furthermore, because information acquisition on adaptation positively influenced intercrop adoption and the use of drought tolerant crops, providing farmers with more information on effective adaptation measures via agricultural extension programs will motivate adaption decisions.

This study has some limitations including the convenience sampling method and a non-national representative sample. Given these limitations, our research findings are unable to generalize to all geographical regions of studied countries.

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6. AUTHOR'S CREDIT STATEMENT

Thanh Mai Ha managed data collection and took the lead in writing this paper. Sayvisene and Fu Yang conducted data collection in Laos and were involved in writing the Result and Discussion sections. Pisidh Voe led data collection in Cambodia. Cong Duan Dao analyzed the data. Other remaining authors were involved in designing the survey, collecting data, and/or commenting on the manuscript.

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Potential of agroforestry for climate change adaptation in the Northwest mountainous region of Vietnam

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ABSTRACT

The literature on the impacts of climate change on the Northwest mountainous region of Vietnam was assessed in this article. Additionally, the project team conducted regional interviews and visits to gather information on the same topic. The findings indicate that climate change has had a significantly negative impact on the region's agriculture, the primary income source for the local population. Furthermore, the local communities have a limited understanding of the subject matter. However, the existing agroforestry system in the region may prove to be an effective measure for adapting to the impacts of climate change. In addition to increasing local awareness and understanding of climate change, further efforts are necessary to improve the agroforestry system in the region. These efforts should consider the region's diverse population and terrain characteristics.

KEYWORDS

Da River headwater, Vietnamese northwest mountainous region, agro-forestry, climate change

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HIGHLIGHTS

- The Northwest region of Vietnam's local community is highly susceptible to the adverse effects of climate change, particularly given the region's socioeconomic characteristics. Nevertheless, the community's knowledge and understanding of this matter remain insufficient.
- In order to achieve sustainable food security for the region under a changing climate, farmers and policy planners need to consider certain climate change adaption and mitigation measures.
- Agroforestry practices can be promoted as a climate change adaptation measure for the region, built upon existing agroforestry models practised in the region.

1. INTRODUCTION

The climate has been changing more rapidly and its negative impacts have become even more widespread in the last few decades (IPCC, 2022). The best estimate of temperature increase is approximately 1.8–4 °C in 2090–2099 compared to 1980–1999, with the specific increase depending on future greenhouse gases (GHGs) emitted into the atmosphere (IPCC, 2007). The impacts of climate change are localised – different regions would suffer from heat, drought or flooding events at different times. These increasingly frequent and extreme climate events are resulting in catastrophic consequences, particularly for agriculture and food security (IPCC, 2022).

Mountainous agricultural areas, as well as the communities whose livelihoods depend on them, are highly vulnerable to the impacts of climate change (IPCC, 2022; Bandara et al., 2021). The impact on specific locations would vary depending on many factors, such as topographic and social structures, land use, level of soil erosion and farming traditions. To develop the capability and acceptance of climate-intelligent technologies and practices among farmers in specific regions, gaining insights into their understanding of climate change is crucial. Planning and programs for agriculture in these areas should also take into account the impacts of climate change and associated issues, such as the risks posed, the long-term effects, technologies that communities can adopt and attitudes toward changing farming practices.

Among the land use practices that have been promoted as adaption strategies for climate change, agroforestry has the potential to be one of the most suitable systems for the region which is the subject of this study – the mountainous Northwest region of Vietnam. The World Agroforestry Centre (which used to be The International Centre for Research in Agroforestry, as cited in Nair (1993)) defined agroforestry as follows: "*Agroforestry is a collective name for land-use systems and technologies where woody perennials (trees, shrubs, palms, etc.) are deliberately used on the same land-management unit as agricultural crops and/or animals, either on the same form of spatial arrangement or temporal sequence. In agroforestry system there are both ecological and economical interactions between the different components.*" Agroforestry, which involves the integration of woody perennials and crops or animals on the same land management unit, has been practised in the region for a significant period of time as a strategy to enhance land use management and boost income generation (Martin et al., 2020). With necessary adjustments, the practice can also be employed to help local communities

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impacted by the negative effects of climate change and support their agriculture production (Charles, Nzunda, & Munishi, 2014; Tschora & Cherubini, 2020; Udawatta & Jose, 2021). There is a need for more research and adoption of the most suitable agroforestry models for the region's climate and population.

The present paper begins by introducing the characteristics of the Vietnamese Northwest region, specifically the Da River upstream catchment, in Section 1. Section 2 provides an overview of the intricate relationship between mountainous farming systems and climate change in Northwest Vietnam. In Section 3, we present some results from our work with local communities on issues related to climate change and discuss which farming models should be adopted to adapt to the changing local weather patterns.

2. METHODOLOGY

We conducted a comprehensive review of peer-reviewed articles and scientific reports on climate change and extreme weather events in the Da River upland area and the Northwest region of Vietnam in both Vietnamese and English. Our search was based on keywords such as "climate change," "Vietnamese northwest mountainous," "Da river upland," "climate change adaptation," and "agroforestry." We extracted relevant information, including meteorological monitoring data, to compare the recent climate regime (2010-2020) with the climate regimes of the past 30-50 years.

We used a random stratified sampling technique to select our samples for our study. Specifically, we chose three districts, Mu Cang Chai, Tram Tau, and Muong La, which are significantly exposed to extreme climatic events, as our study sites (Figure 1). From each district, we selected one commune that represents the typical topographic, ethnic and land use characteristics of the area (Figure 2).

During our project, we conducted group discussions in each commune with 15 participants, including both men and women of mature age who had been living in the area for at least five years. The questions posed during these discussions were:

1. Have there been any changes in climate characteristics in the areas?
2. If yes, what were these changes?
3. How have these changes affected your household farming activities?
4. How have these changes affected natural resources (e.g., soil, water, forest, wildlife) which related to your everyday life & farming activities?

The results of these discussions confirmed the findings in the literature.

3. RESULTS AND DISCUSSION

3.1. Characteristics of the Vietnamese Northwest region

The Da River, also known as the Black River, runs through China, Laos and Vietnam. Half of the basin originated from the river (Da River basin) in Vietnam's territory in the Northwest. The Northwest region, including Hoa Binh, Son La, Lai Chau, Dien Bien, and the western part of Yen Bai and Lao Cai provinces, also lies within Da River Basin. The river serves as the main water supply for agriculture in 25 provinces and cities in Vietnam and is the primary source of drinking water for a population of more than 30 million people (Vietnamese Government, 2010).

The river is also the major water supply for about 40 small and large hydroelectric power plants, including Vietnam's three largest hydroelectric power plants (Son La, Hoa Binh, Lai Chau). These power plants also serve as reservoirs for flood control, making them critical for the region's rural development. Thus, any impact of climate change on this area will have long-lasting and far-reaching consequences for the local population and surrounding regions.

The dominant annual crops across the Northwest provinces are maize, rice and cassava (Vietnam General Statistics Office [GSO], 2022a; Zimmer, Thi, Lo, Baynes, and Nichols, 2017). (Figure 2) Common agriculture practices include shifting cultivation with very short fallow periods (3 years maximum), monoculture cultivation of annual crops and agro-

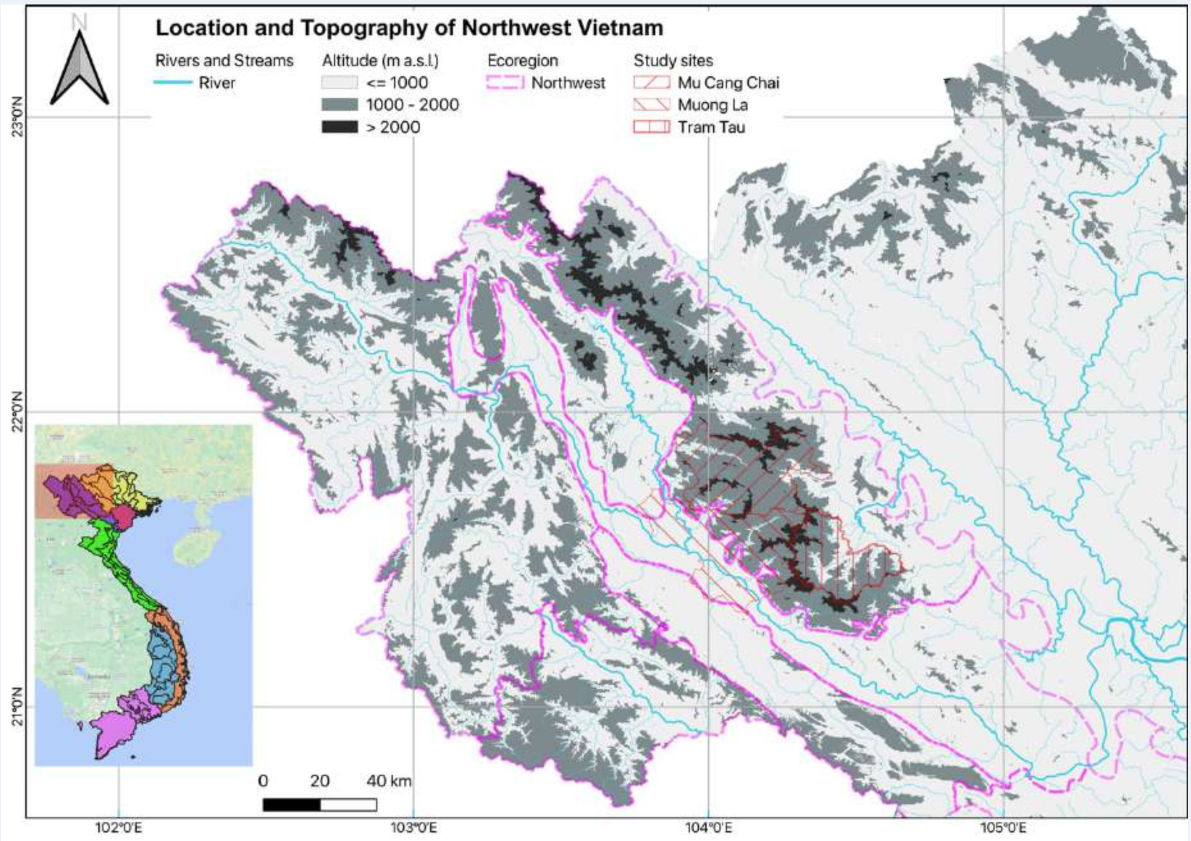

FIGURE 1. Location and topographic of Northwest Vietnam. Ecoregion border was adopted from Vũ Tấn Phương et al. (2012).

FIGURE 2. A typical landscapeof highland Northwest Vietnam (Photo by Ha Do).

forestry in the form of homegardens. Intensive agricultural practices resulting from population growth and government policies can lead to problems such as decreased production and soil erosion (Zimmer et al., 2017; Nguyen, Whelan, & Nichols, 2022). For several years, according to the poverty and multidimensional poverty index, the region has recorded the highest rates of poverty among households (Table 1).

In addition, the diverse ethnicity of the region makes it more vulnerable to climate change. Seventy percent of the population of the region belongs to an ethnic minority (in Vietnam, the ethnic majority is "Kinh") (World Bank, 2009). The main ethnic groups are Muong, Hmong and Thai. Hmong people mostly live in the higher elevation section of the mountains, while Thai and Muong people usually live in the lower sections. The majority of these communities face significant challenges due to low incomes and inadequate access to essential services (GSO, 2022b). As a result of inadequate infrastructure, outdated farming methods, and natural disasters like floods and landslides, these communities have frequently suffered from severe food shortages and low-quality food. Much research has emphasised the difficulties of breaking the vicious cycle of population growth, leading to pressure on the environment and increasing poverty (Le & Tran, 1995). Overall, local agriculture activities depend largely on weather conditions. Due to a lack of knowledge about climate change, the local communities are failing to adapt and mitigate its impacts (Isabel, 2010).

3.2. Climate change's impacts on the region

We interviewed three groups of people from the local communities in Nam Pam (Muong La District, Son La Province), La Pan Tan (Mu Cang Chai District, Yen Bai Province) and Ban Mu (Tram Tau District, Yen Bai Province). The group in Nam Pam commune consisted of Thai and Hmong people. The two remaining groups were Hmong people.

The interviews focussed on how much local people know about "climate change" ("*Biến đổi khí hậu*" in Vietnamese; "*Phạ lét lôm piến máư*" in Thai; "*Lub ntxug ib ntxhaav*" in Hmong). Overall, most respondents did not know about the concept of climate change. However, they have observed many changes in the local weather recently, including:

- longer summers, shorter winters;
- annual temperatures have increased with hotter summers, warmer winters;
- unpredictable rainfall – larger amounts of rainfall for longer periods, resulting in flash floods and landslides at unprecedented levels;
- extreme/severe drought; and
- other extreme weather events such as cold spells, ice freezing in winters (Figure 3) and dry spells have all occurred with higher frequencies, increased magnitude and longer duration.

In their opinion, the weather becomes more and more unpredictable, leading to significant changes in plant phenology, such as multiple flowering in the years but no or little fruiting for perennial plants (e.g., peach, plum), earlier flowering for annual plants.

Such experience was also confirmed in climate data from meteorology stations across the region (Table 1; MONRE, 2016; 2021). The effects of climate change in Vietnam are most evident in the characteristics of the number and frequency of storms and tropical depressions hitting the region (MONRE, 2021). Only in Yen Bai province, in 2015, there were 23 storms and tropical depressions; in 2018, there were particularly, storms and tropical depressions from 2008 to 2020 had unusually greater frequencies and unpredictable characteristics, thus making it very difficult to prevent and respond. These storms and tropical depressions occurred in high mountain areas such as Mu Cang Chai, Tram Tau and Muong La, causing a number of severe flash floods and landslide occurrences in the seasons. Such occurrences were considered as typical and tangible evidence of climate change (MONRE, 2021).

Changes in rainfall regime are one of the factors that accelerates erosion. (Figure 3) A study on one stream basin of Da river in Hat Lot commune,

Region	Province	Year				
		2016	2017	2018	2019	2020
Vietnam		**9.20**	**7.90**	**6.80**	**5.65**	**4.80**
Northern Midland and Mountainous regions		**23.00**	**21.00**	**18.40**	**16.43**	**14.38**
Northeast	Ha Giang	39.80	36.90	32.60	29.11	26.98
	Cao Bang	37.30	34.90	31.50	28.53	25.97
	Bac Kan	29.70	27.70	25.10	22.53	21.47
	Tuyen Quang	22.00	19.60	17.50	15.11	12.90
	Thai Nguyen	7.80	7.40	6.00	5.09	4.09
	Lang Son	23.50	20.60	18.40	15.90	12.26
	Bac Giang	6.40	5.40	3.80	3.29	2.81
	Phu Tho	10.30	9.20	7.50	6.53	5.84
Northwest	Lao Cai	26.40	23.90	20.50	17.24	15.38
	Yen Bai	26.10	23.60	20.30	17.47	15.06
	Dien Bien	53.90	50.20	44.50	39.85	36.74
	Lai Chau	44.30	41.60	37.10	33.04	30.83
	Son La	42.80	41.00	36.30	33.01	30.53
	Hoa Binh	17.80	15.40	12.70	10.50	9.09

Source: GSO, 2022

TABLE 1. The poverty and multidimensional poverty index of northwest provinces from 2016-2020.

	Period	Vietnam			Northwest region		
		Average	Max	Min	Average	Max	Min
Total hot days per year	1961-2018	21(0÷85)	50(0÷148)	5(0÷36)	15(0÷42)	43(0÷129)	3(0÷18)
	1981-2010	21(0÷86)	42(0÷148)	7(0÷46)	15(0÷41)	31(0÷85)	6(0÷21)
	1999-2008	19(0÷79)	31(0÷105)	10(0÷51)	13(0÷38)	22(0÷60)	6(0÷21)
	2009-2018	27(0÷89)	47(0÷129)	14(0÷62)	19(0÷57)	41(0÷129)	7(0÷33)
Total extreme cold days per year	1961-2018	46(0÷182)	9(0÷117)	25(0÷145)	45 (13÷128)	73 (35÷150)	17 (0÷78)
	1981-2010	44(0÷162)	12(0÷117)	24(0÷145)	43 (13÷126)	69 (30÷149)	23 (1÷107)
	1999-2008	37(0÷160)	15(0÷129)	22(0÷144)	42 (13÷120)	61 (23÷136)	31(3÷107)
	2009-2018	38(0÷182)	12(0÷122)	22(0÷140)	39 (9÷114)	61 (15÷138)	24(2÷97)
Total extreme heavy rain days per year	1961-2018	0 (2,6÷28)	0 (7÷43)	0(0÷14)	6.1 (2,6÷11)	14 (9÷25)	0.9 (0÷4)
	1981-2010	0 (2,6÷27)	0 (7÷43)	0(0÷14)	5.9 (2,6÷11)	13.3 (7÷25)	1 (0÷4)
	1999-2008	0 (3,4÷27)	0(7÷37)	0(0÷20)	6.7 (3,4÷14)	12.6 (7÷25)	2.1 (0÷8)
	2009-2018	0 (2,4÷25)	0(5÷34)	0(0÷17)	6 (2.4÷11)	11.1 (7÷15)	1.9 (0÷7)

Source: MONRE, 2021.

TABLE 2. Statistics of changes in weather characteristics.

Mai Son District, Son La Province (Nguyen et al., 2022) concluded that soil erosion was caused by the practice of fallow farming and increasing deforestation. On the other hand, farming with adequate technology in uncultivated land might help prevent soil loss. The authors did not analyse the contribution of climate regime changes that led to more susceptibility to soil erosion in Mai Son. The Revised Universal Soil Loss Equation (RUSLE) estimates soil erosion by taking into account several factors, including rainfall, slope length, slope steepness, soil cover, erosion control practices and the soil's erodibility factor. Together with conversion of forest land to cropland (cover factor), climate change likely contributes to the change of rainfall cycles, leading to the increase of soil erodibility (rainfall increased in the rain season), longer dry season, wetter and more extreme rainfall in the rain season.

FIGURE 3. Figure 3. Photo of soil erosion in Thuan Chau, Son La (left, middle). Cardamom plants died because of extreme cold in Mu Cang Chai in 2021 (right). (Photo by Ha Do).

In the future (2021–2100), using a dynamical downscaling model for greenhouse gas concentration scenario RCP4.5 for the Da river basin, rainfalls were predicted to become more frequent and in larger amounts in some provinces (Son La and Lao Cai) while become lighter in some others (Lai Chau and Yen Bai) (Hồ, Trịnh, Đỗ, & Nguyễn, 2019). A study (Huong, Bo, & Fahad, 2019) explored the possible connection between the changes in rainfall and temperature and the net income of the local population in Northwest Vietnam. It was found that an increase in temperature and the amount of rainfall may have a negative impact on household net income. Particularly in the dry season, when temperature and rainfall increased, the household income declined and was projected to continue to decline by 17.7% and 21.28% in 2050 and 2100, respectively, if no climate change adaptation measures were employed.

3.3. Adaptive farming systems across the landscape

As discussed above, agriculture is the main economic activity and the main source of income for the Vietnamese Northwest mountainous region (ILRI, 2014). Climate change poses one of the biggest challenges to the agriculture sector of the region, as well as a significant barrier to sustainable agricultural production and food safety for the local communities. To achieve sustainable food security under a changing climate, farmers and policy planners need to consider certain climate change adaption and mitigation measures.

Climate smart agriculture (CSA) comprises a series of farming practices that have the potential to address challenges caused by climate change (FAO, 2013). These include water shortages for irrigation systems, soil loss, weeds and pests, among others. CSA practices include recycling of water, rotation of crops, farming diversification, agroforestry, among others (Bai et al., 2019).

Agroforestry is the combination of various types of woody vegetation, such as trees and shrubs, with crops or livestock at the same location. This system intends to diversify production sources for the owners, and the interaction between different elements should bring about various environmental, social, economic and financial benefits. Different combinations constitute different types of agroforestry, including agrosilvipasture (trees, crops and livestock), forest farming (crop or livestock and trees), urban agroforestry, i.e., homegardens (trees with crops close to homestead), among others.

Agroforestry was first deemed a promising approach for 'land sparing', soil conservation and resource-use efficiency. The practice itself is not new, having been employed by the local communities in the Vietnamese highland regions for decades through various traditional forms such as a combination of livestock–fishpond–garden–forest or fruit–forest plantings. The practice has been promoted to improve economic activities and income for small households (FAO, 2013). In the age of climate change, an agroforestry system that consists of trees and crops in the same area may serve as a sustainable CSA initiative that enhances the climate resilience of farms, reduces GHG emissions and increases productivity.

Applying suitable agroforestry models in an area of land or a landscape is key to sustainable development in rural highland Vietnam. Many national and international programs have been conducted in northwest Vietnam to promote agroforestry systems suitable for the sites (Mulia et al., 2020). In the context of climate change, suitable systems should be climatic and topographically resilient (such as plant species/varieties), resilient to drought, colder and hotter weather, as well as well adapted to changes brought about by the new climate regime, resistant to floods or able to prevent landslide or soil erosion (Crowther, Zimmer, Thi, Quang, & Nichols, 2020; van Noordwijk et al., 2021).

Increasing the cultivation system's resilience will make the household and local economy more stable and take less time to recover from natural disasters. Diversifying crops agroforestry is a farming technique that has the potential to enhance both carbon sequestration and crop yields. Various studies (Vernooy, 2015; van Noordwijk et al., 2021; Simelton, Dam, & Catacutan, 2015) found positive results for households that employed crop diversification. Such households recovered quicker from disastrous weather events with better yields than those who employed monoculture farming. Their crops also show more resilience to changes in the climate.

Many different agroforestry systems/models were adopted in Vietnam (Thang, Dung, & Hoang, 2013; Mulia & Nguyen, 2021). The difference in models reflects the difference in topographic locations, weather conditions, regional and local markets, and skills and traditions of communities and households. In general, the cultivation system is topographic driven - terrace cultivation.

Agroforestry practices can be promoted as a climate change adaptation measure for the Northwest region of Vietnam. Agroforestry models are naturally localised and could be flexibly up-scaled or down-scaled with spatially and temporally diverse methods applied for different purposes. In this region, agroforestry already exists and is currently built upon traditional local products of rice, casava, maize, homegardens with tropical and subtropical fruit trees, and industrial trees and shrubs, such as tea, coffee, avocado, plum, peach, pear, and native forest fruit trees. Taungya systems with timber trees and staple crops were popular. In the Northwest highland region, *Docynia indica* (also known as *Son tra* or *Tao meo* in Vietnam, Assam apple/wild apple in India, In-sein in Myanmar and Douyi in China (Muchugi et al., 2021)) has been domesticated and considered as one of the most important and common species in agroforestry systems for decades (Mulia & Nguyen, 2021).

At the three sites that the project team visited, there were terrace rice fields where people could manage water resources, then dry rice fields, maize or casava was usually at the middle of the hills/mountains; natural forest or plantation was usually on the tops. The most common agroforestry system at the local/household scales in our sites were homegarden fruit trees, vegetables, spices, medicinal plants and flowers. However, homegardens differed among Thai and Hmong groups in terms of area, plant species and purpose. Usually, Thai people have larger gardens and plant more spices, medicinal and vegetables than Hmong people. Hmong people plant fruit trees or timber with forage grass in their gardens. On the field, Hmong people usually plant upland rice, maize, casava with shan tea/peach/*D. indica* or with pine and *F. hoginsii*, a valuable timber and used traditionally by Hmong people (Appendix A.1., A.3., A.4.), while Thai people plant maize, casava and plum/mango/longan/coffee or Magnoliaceae species used for timber (*Michelia mediocris, Magnolia baillonii. M. balansae, M. conifera*) (Appendix A.2., A.5., A.6.).

It is recommended that further studies be conducted to evaluate the effectiveness of existing agroforestry models in the region. This will help promote and expand models that are adaptable and resilient to climate change while identifying areas for necessary changes and adjustments. Additionally, it is important to provide continued training and education for the local communities on climate change and appropriate measures for mitigating and adapting to its impacts.

4. CONCLUSION

Based on the literature, surveys and site visits, it is evident that climate change is significantly impacting the Northwest mountainous region of Vietnam. The region is already facing numerous challenges, such as poverty and lack of education and infrastructure, and climate change is exacerbating these problems. Therefore, urgent action is needed to identify and implement adaptation measures to ensure food security and improve the livelihoods of the local communities.

Agroforestry is a promising solution for the region, as it has been practised for a long time and has shown potential to improve land use management and increase income capacity. However, further research is needed to determine the effectiveness of current agroforestry models and identify suitable and resilient practices that can withstand the impacts of climate change. Additionally, education and training on climate change and adaptive measures should be provided to the local communities to increase their capacity to adapt to a changing climate.

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Original article

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How to measure urban water security? An introduction to the Water Security Assessment Tool (WATSAT)

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ABSTRACT

The objective of the project was to develop a web-based digital tool called the Water Security Assessment Tool (WATSAT) to help city authorities and decision-makers make an objective evaluation of the water security situation in the city. It uses an indicator-based methodology that measures five distinct dimensions (broad elements) of water security: "Water supply and sanitation", "Water productivity", "Water-related disasters", "Water environment", and "Water governance", which together culminate into a Water Security Index (WSI). The tool is developed based on the water security assessment framework developed by Babel, Dang, Sharma, and Shinde (2015). WATSAT results in a quantitative assessment of water security in a city, wherein the WSI provides an overall picture of the water security situation in a city, while the evaluation of the various dimensions helps identify areas of concern. WATSAT aids city authorities in having a holistic understanding of water security and interconnections of various factors affecting it and assists them in informed decision-making to arrive at system-based interventions to tackle water security threats in the cities.

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KEYWORDS

Decision-support tool, indicator-based methodology, water security assessment, water security index, WATSAT

HIGHLIGHTS

- A web-based digital tool named WATSAT to assess urban water security was developed.
- WATSAT measures five dimensions of water security, resulting in a Water Security Index.
- Users simply enter the data required and WATSAT does all the analysis at the backend.
- WATSAT aids in determining practical interventions for the enhancement of water security.
- It is a decision-support tool enabling city stakeholders to operationalise water security.

1. INTRODUCTION

Ensuring safe water and enhancing water security is a major concern in light of the effects of changing climate, increasing population and urbanisation, as well as intensive socioeconomic development and extensive land-use changes (Babel, Chapagain, Shinde, Prajamwong, & Apipattanavis, 2022). Initially viewed as a water scarcity issue, the concept of water security has evolved over time and is now looked at holistically, encompassing several dimensions (Cook & Bakker, 2012; Chapagain et al., 2022). A widely accepted definition of water security provided by UN-Water (2013) describes it as "*the capacity of a population to safeguard sustainable access to adequate quantities of and acceptable quality water for sustaining livelihoods, human well-being, and socioeconomic development, for ensuring protection against water-borne pollution and water-related disasters, and for preserving ecosystems in a climate of peace and political stability*". A precursor to achieving water security is measuring it, based on the adage by Peter Drucker, "*you cannot manage what you cannot measure*".

Water security assessment has received increasing attention from academicians, practitioners, planners, and policy- and decision-makers, with varieties of frameworks developed for different scales (Sullivan, 2002; Vörösmarty et al., 2010; Grey & Sadoff, 2007; Cook & Bakker, 2012; van Leeuwen & Chandy, 2013; UN-Water, 2013; Gerlak et al., 2018; Assefa, Babel, Sušnik, & Shinde, 2018; Krueger, Rao, & Borchardt, 2019; Jensen & Wu, 2018; Aboelnga, Ribbe, Frechen, & Saghir, 2019; Young et al., 2019; Chang & Zhu, 2020; Babel, Shinde, Sharma, & Dang, 2020; Khan, Guan, Khan, & Khan, 2020; Chang & Zhu, 2021; Zakeri, Mirnia, & Moradi, 2022; Chapagain et al., 2022; Babel et al., 2022; GWP, 2000; ADB, 2013, 2016; WEF, 2020). From an operationalisation point of view, the city scale is appropriate to take account of the spatial and social variation of water security assessment, which is often precluded in analyses carried out at the national scale (Babel et al., 2020). Cities are considered the engines of economic growth. As cities generate more than 80% of the world's gross domestic product (GDP) (Lall, Lebrand, Park, Sturm, & Venables, 2021), it is evident that human activities will lead to increased pressure on land and natural resources in the coming decades (Lall et al., 2021). Moreover, the gradual shift from rural to urban areas, along with fast-paced urbanisation, rapid population growth and changing climate, are making cities susceptible to rising water stress and water insecurity (Ray & Shaw, 2019). Thus, it is imperative that concepts related to enhancing water security, which usually require a "bottom-up" approach, be implemented at the local level, such as the city for sustainable growth and increased productivity (Babel et al., 2020).

It is to address this notion that the Asian Institute of Technology (AIT) and its partners developed a holistic water security assessment framework for cities (Babel, Dang, Sharma, & Shinde, 2015) consisting of five dimensions: (1) Water supply and sanitation, (2) water productivity, (3) water-related disasters, (4) water environment, and (5) water governance.

The five dimensions accurately reflect both the definition provided by UN-Water (2013) and the indicators of SDG6. This framework was applied successfully in three cities with diverse climates and socioeconomic conditions, namely, Bangkok (Thailand), Hanoi (Vietnam) and Jaipur (India). The framework is meant to help city authorities and decision-makers make objective evaluations of the water security situation in their city. It uses an indicator-based methodology that measures five distinct dimensions of water security, which together add up to a Water Security Index (WSI). The WSI provides an overall picture of the water security situation in the city, while the evaluation of the various dimensions helps identify specific areas of concern.

To improve the ease of convenience of using the water security assessment framework, the objective of this project was to develop a web-based digital water security assessment tool called "WATSAT" that is holistic in nature and can quantitatively assess the different aspects of water security. The tool is available in the public domain at (www.watsat.org). WATSAT has been developed by the Asian Institute of Technology (AIT) in collaboration with the National Institute of Urban Affairs (NIUA) and the Central University of Rajasthan (CURAJ) in India, the Thuyloi University (TLU) in Vietnam, and Tribhuvan University (TU) in Nepal.

2. METHODOLOGY

An overview of the methodology adopted for the development of the Water Security Assessment Tool (WATSAT) is summarised in Figure 1. It began with a review of the existing web-based tools for water security assessment, followed by the software development based on the existing water security assessment framework, and finally, the validation of the tool's applicability through an example of water security assessment in Bangkok city. The methodological steps are described in the following section.

2.1. Literature review

The authors first conducted a thorough literature review on the existing web-based water security assessment tools. We discovered that there are a limited number of tools developed for water security assessment. For example, the Global Water Scarcity Atlas tool developed by the Water & Development Research Group at Aalto University in Espoo, Finland, in collaboration with the Water Program at International Institute for Applied Systems Analysis (IIASA) in Laxenburg, Austria, showcases analyses of global water scarcity. However, the tool focuses only on the water availability dimension of water security. Similarly, the Aqueduct Water Risk Atlas developed by the World Resources Institute WRI (2019) evaluates water risks based on cutting-edge data and maps the current and future water risks across locations. Likewise, OurWater, a digital tool for resilient water governance developed by a collaborative effort between Arup, the Stockholm International Water Institute (SIWI), and the Organisation for Economic Co-operation and Development (OECD), funded by The Resilience Shift, is designed to address the need for collaborative governance by understanding the impact of shocks and stresses on natural and man-made water infrastructure and identifying the interaction among key stakeholders involved in urban water management (Saikia et al., 2020).

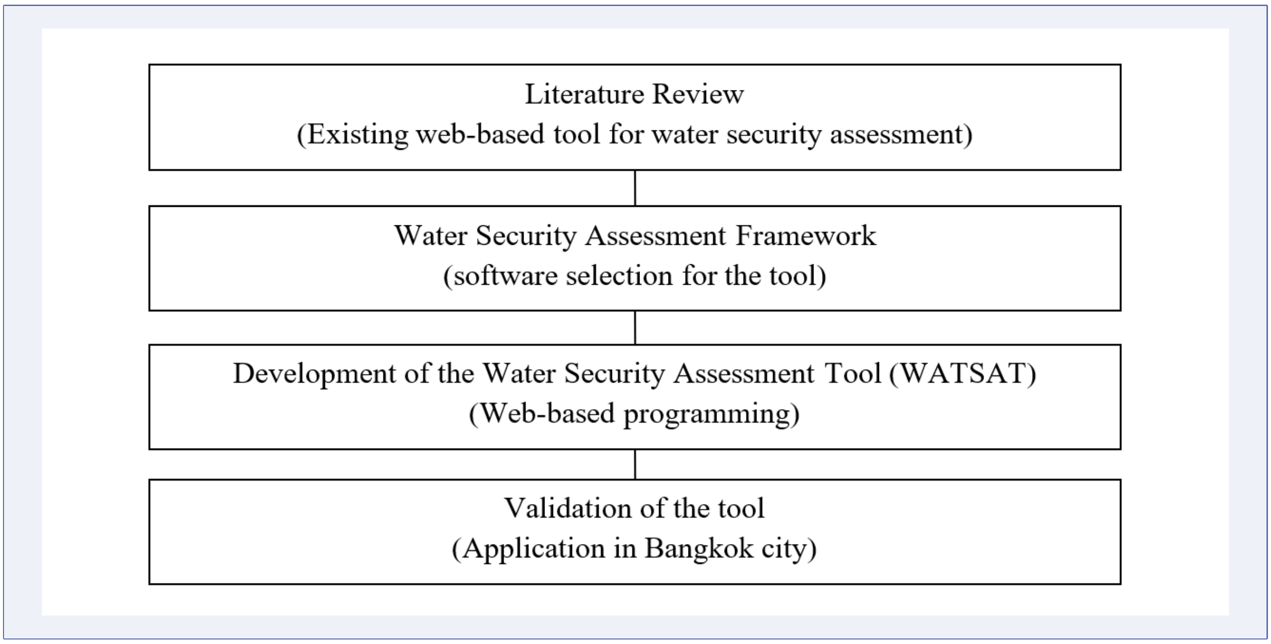

FIGURE 1. Methodology for WATSAT development

To our knowledge, there are no such digital tools that exist to facilitate users with a holistic assessment of the water security situation, specifically at the city scale.

2.2. Water security assessment framework

The architecture of WATSAT is based on the water security assessment framework developed by Babel et al. (2020). WATSAT comprises a three-layered structure—dimensions, indicators and variables—that ultimately results in the Water Security Index (WSI). It comprises five dimensions and twelve indicators and provides users with a long list of potential variables to choose from to reflect the indicators. From an operational viewpoint, the twelve indicators were selected to measure the five dimensions because they represent the areas of interest within the dimensions, are relatively easy to understand and comprehend, have better data availability and accessibility (World Bank and UN databases), are reflective of the SDG6 indicators and fosters generalisation of the water security assessment framework developed, making it universally applicable to cities across the globe.

The dimensions each capture a distinct aspect of water security, with minimal overlap between them (Babel et al., 2020). The five dimensions are: "Water supply and sanitation", "Water productivity", "Water-related disasters", "Water environment", and "Water governance". The dimensions are measured by one or more indicators, as shown in Figure 2. Each indicator is estimated using specific variables. The three-layered structure of the framework allows it to remain generic while still being able to identify site-specific issues and challenges related to water security (Babel et al., 2020). Hence, the dimensions and indicators are kept fixed in the framework. The selection of the variables is up to the users, depending upon what they think is relevant for their city and what data is available. WATSAT is flexible and robust to allow city authorities to choose the most relevant variables to reflect the local contexts. Thus, WATSAT can be applied to any spatial unit, such as part of a city (such as ward) or whole city, to capture its variability, provided the required data is available at the selected spatial unit. One fundamental principle of the framework is that all the potential variables contribute to the estimation of water security depending on the weightage given to them. The details of the city-scale water security assessment framework developed by Babel et al. (2020) are presented in Table 1.

Dimension	Indicator	Potential variables	Suggested ways to measure	Source
Water supply and sanitation	Water availability	1. Per capita water use (lpcd)	Total domestic water consumption/City population	
		2. People in the city using improved water sources (%)	(Population with improved water sources facilities/City population) × 100	UNESCO-WWAP (2006)
		3. Investment in water supply facilities (USD)	Self-explanatory	UNESCO-WWAP (2006)
		4. Percentage of imported water (%)	(Amount of water imported/Total water supplied to the city) × 100	
	Accessibility to water	1. Population access to piped water supply (%)	(Population access to piped water supply/City population) × 100	UNESCO-WWAP (2006)
		2. Service area coverage by piped water supply (%)	(Area covered by piped water supply/City area) × 100	
		3. Average distance travelled to fetch water from improved water sources (km)	Self-explanatory	
		4. Safe drinking water inaccessibility (%)	(The ratio of population without access to improved drinking water resources to the total population) × 100	Babel and Wahid (2008)
		5. Water supply service duration per day (h)	Self-explanatory	
	Quality of water supplied	1. Customer satisfaction with quality of water supplied (1:n)	No. of employees in water utility/No. of city customers	
		2. Type of water treatment employed (no unit)	Self-explanatory	
		3. Coliform count of supplied water (MPN/1000)	E.coli count	
		4. Residual chlorine (%)	Percentage of residual chlorine monitoring points satisfying the remnant requirement	
		5. Turbidity of water (NTU)	Self-explanatory	
		6. pH of supplied water (NTU)	Self-explanatory	
	Hygiene and sanitation	1. People in the city using improved sanitation facilities (%)	(Population with improved sanitation facilities/City population) × 100	UNESCO-WWAP (2006)
		2. Water-borne disease factor (%)	(Hospitalised cases of water-borne diseases/Total hospitalised cases) × 100	UNESCO-WWAP (2006)
		3. Investment in sanitation facilities (USD)	Self-explanatory	UNESCO-WWAP (2006)
		4. Proportion of customers connected to sewer line system (%)	(No. of customers connected to sewer line/City population) × 100	

Continued on next page

Table 1 continued

Water productivity	Economic value of water	1. Commercial water productivity (USD/m^3)	Commercial GDP of the city/Commercial water use in the city	
		2. Agricultural water productivity (USD/m^3)	Agricultural GDP of the city/Agricultural water use in the city	
		3. Water wealth (USD/m^3)	Total income of people/Water used	
		4. Water price (USD/m^3)	Self-explanatory	
Water-related disasters	Disaster mitigation	1. Disaster budget factor (%)	(Investment in disaster response mechanisms/Total city budget) × 100	
		2. Per capita GDP (USD)	Total GDP/City population	
		3. Flood damage (USD)	Economic damage caused by floods	
		4. Proportional area of flooding (%)	(Flooded area/Total city area) × 100	Xiao, Li, Xiao, and Liu (2008)
	Disaster preparedness	1. Drainage factor (%)	(Total open green space/Total city area) × 100	
		2. Disaster preparedness workshops with vulnerable communities (number)	Number of workshops conducted with vulnerable communities	
		3. Flood risk mapping (no unit)	Flood zoning	
Water environment	State of natural water bodies	1. Natural water quality factor (%)	(Dissolved Oxygen (DO) concentration/Minimum required standard for DO) × 100	
		2. Water Quality Index (no unit)	Country-specific	
		3. Biochemical oxygen demand in water bodies (mg/L)	BOD5 concentration	Mehr (2011)
	Effect of polluting factors	1. Wastewater treatment factor (%)	(Amount of treated wastewater/Total wastewater generated) × 100	
		2. Water pollution factor (%)	(Volume of the untreated wastewater to the total volume of water source) × 100	Babel and Wahid (2008)
		3. Industrial influent treatment factor (%)	(Amount of treated industrial effluent/Total industrial effluent generated) × 100	
Water governance	Overall management of the water sector	1. Institution factor (no unit)	Questionnaire	
	Potential to adapt to future changes	1. Adaptability factor (no unit)	Questionnaire	
	Citizen support for water security	1. Public support factor (no unit)	Questionnaire	

TABLE 1. Water security assessment framework for city scale (Babel et al., 2020)

To compute the WSI, the first step involves normalising all variables to a range of 1 to 5 using reference values. Reference values can be used to categorise variables based on their magnitudes, which can be assigned numerical scores on a scale of 1 to 5 (Babel et al., 2020). Although there are many reference values for various variables reported in the literature, it is crucial to consult with experts within the country to confirm or modify these values and scores to fit the local context (Babel et al., 2020).

After normalising all the variables that contribute to an indicator, their scores are aggregated and averaged to determine the indicator score. In the same way, the dimension score is determined by aggregating and averaging all the indicators that contribute to it. Finally, the WSI is determined by averaging all the dimension scores (Babel et al., 2020). Weights to be given to selected variables of an indicator, to various indicators of a dimension, and to various dimensions can be provided by the users; else the tool uses equal weights at all three levels. These weights can be established with inputs from various stakeholders or using techniques such as the Analytic Hierarchy Process (AHP) (Saaty, 1987). The WSI falls in the range of 1–5, with a score of less than 1.5 interpreted as "Poor Water Security" and a score greater than 4.5 interpreted as "Excellent Water Security".

2.3. Development of the water security assessment tool (WATSAT)

WATSAT is a web-based tool written in the C#.net programming language with the welcome page interface written in JavaScript and HTML.

The tool has been developed to make it as user-friendly as possible, keeping in mind that its actual design purpose is to facilitate city authorities and decision-makers to make an objective evaluation of the water security situation and foster practical solutions to improve water security in the city. In this regard, the selection of indicators reflecting areas of interest within the dimensions was a conscious decision, as well as keeping indicators to a minimum of 12 so that the tool can be relatively easily operationalised. Furthermore, the variables used to quantify the indicators are characterised by a relatively manageable degree of complexity in terms of data availability.

Similarly, data entry for selected variables in WATSAT is grouped into different categories in a fashion similar to how different organisations or governmental authorities store their data. For example, population-related data in WATSAT are categorised into demographic data, whereas GDP data are categorised into the socioeconomic data category. Additionally, the water governance dimension is measured through three subjective variables: "institutional factor", "adaptability factor" and "public support factor". These variables are quantified through questionnaires as formulated by Babel et al. (2020) and the responses to these questionnaires were scored on a scale of 1-5 using a 5-point Likert scale. For ease of data entry and computation purposes in WATSAT, these questionnaires have been presented in yes/no format. A remark is provided in the data entry menu instructing the users to enter the value "1" if their answer is yes and "0" if their answer is no to the question. By doing so, WATSAT facilitates users in systematic data collection and storage processes.

The reference values used to benchmark variables' scores on a 1-5 scale are kept fixed in WATSAT, thus enabling spatial and temporal comparison of water security status within and among cities. Similarly, the tool's flexibility in weightage provision at all levels (i.e., variables, indicators, and dimensions) serves to prioritise diverse water-related issues and challenges faced by different cities. Moreover, WATSAT also has a provision for validating the user's input data. The data validation in WATSAT functions to validate if there are any variables with missing values and if weights provided at all three levels—variables, indicators, and dimensions—are correct. In case the weights given at any of the three levels do not add up to 100%, users are informed of this discrepancy during the data validation process. WATSAT also has a provision for users to export the results to their personal computers in an Excel sheet format. This

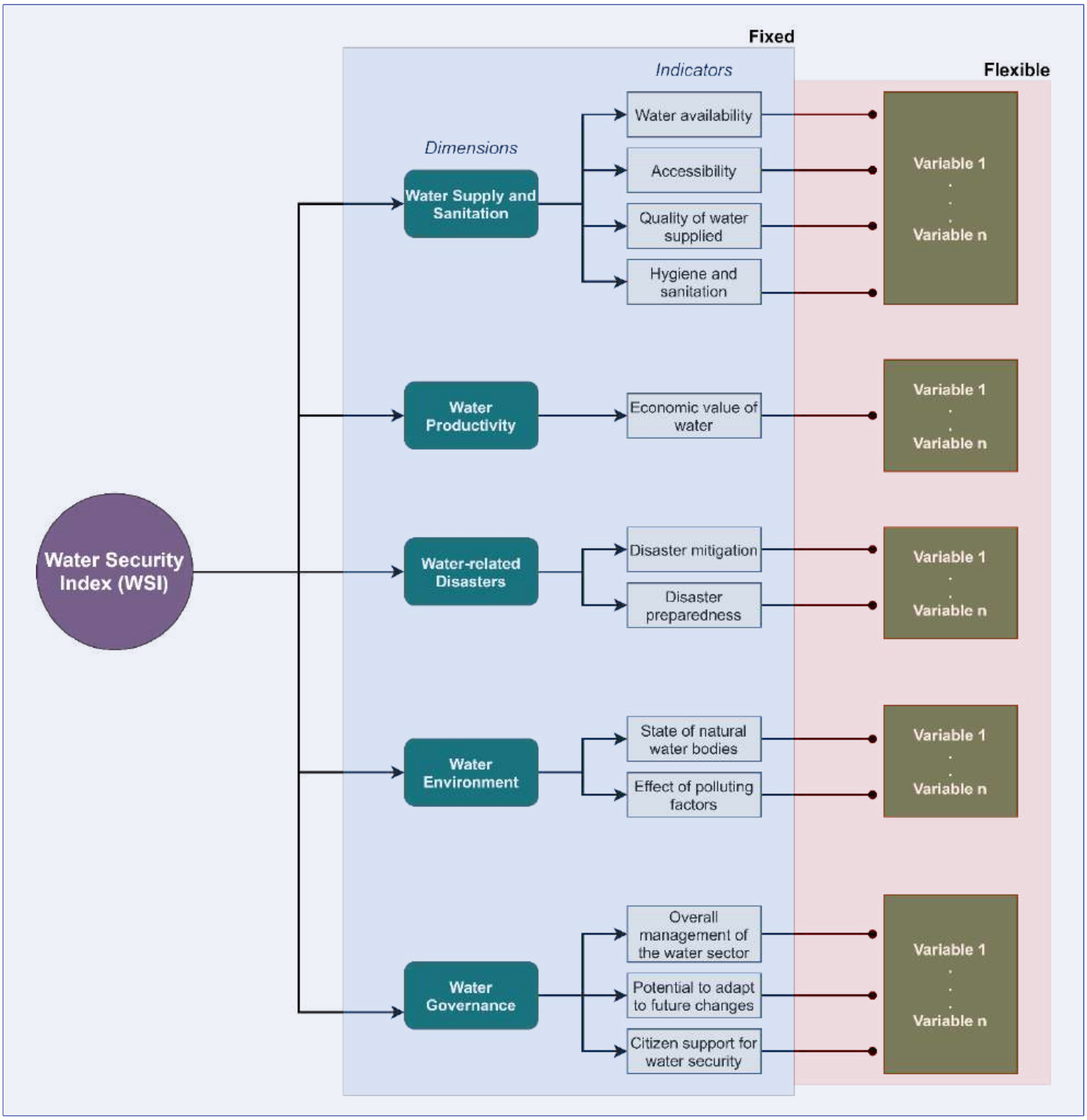

FIGURE 2. WATSAT framework for city-scale analysis

enables them to carry out further analysis, such as comparison within and among cities and developing graphical visualisation of results, among others. Finally, WATSAT also provides a guideline functionality which, as its name suggests, guides users through a step-by-step procedure to successfully carry out water security assessment for the city.

2.4. Validation of the tool

WATSAT was validated by testing its application to assess the water security of Bangkok city. The data for Bangkok city for the year 2017 was collected from various government agencies, as presented in Table 2.

3. RESULTS AND DISCUSSION

The developed water security assessment tool, "WATSAT", is a significant outcome of the project, which is available in the public domain <www.watsat.org>. The website directs users to the landing page, which consists of six menus, as shown in Figure 3. The "Home" and "How it Works" menus provide the user with background information on WATSAT, its structure, and its operating procedure. The

Sl. No	Data	Unit	Value
1	City population	persons	9,005,378
2	City area	km^2	1565.2
3	Green areas (open space)	km^2	378
4	Total city budget	USD/year	15,068,000,000
5	Commercial GPP	USD/year	129,481,385,699
6	Total water supplied	MCM/year	1,835
7	Population with access to piped water supply	persons	8,213,805
8	Amount of imported water	MCM/year	511
9	Total domestic water consumption	m^3/year	474,100,000
10	Commercial water use in the city	m^3/year	392,310,000
11	Number of residual chlorine monitoring points	Number	28
12	Number of residual chlorine monitoring points satisfying the remnant requirement	Number	26
13	Total cases of hospitalisation	Number	3,744,546
14	Hospitalised cases for water-borne diseases	Number	38,227
15	Investment in disaster response mechanisms	USD	451,465,800
16	Average Dissolved Oxygen (DO) concentration at all monitored locations	mg/L	1.74
17	Minimum required standard for Dissolved Oxygen (DO)	mg/L	2
18	Volume of wastewater generated	m^3/day	1,898,981
19	Volume of wastewater treated	m^3/day	1,106,013
20	Is public opinion sought when developing water-related plans for the city?		Yes
	Is there a provision for the public to register their grievance?		Yes
	Is there an official mechanism to monitor Non-Revenue Water (NRW)?		Yes
	Is there a provision to incentivise judicious water management?		Yes
	Does the organisation consult other water organisations during the development of annual or long-term plans?		Yes
	Does recycling and/or reuse of water take place in the city?		No
	Is there a centralised database for water-related information?		Yes
	Is there a system to forecast water availability and quality?		Yes
	Are future drivers of change (e.g., climate change) taken into consideration when developing long-term city master plans?		Yes
	Is there a mechanism for the organisational staff to upgrade water-related knowledge?		Yes
	Are citizens involved in water management through any mechanisms?		Yes
	Out of the total amount that the consumer has to pay as water fee, is at least 80% received every month?		Yes
	Do citizens generally comply with the rules and regulations set for water theft/ water malpractices? (generally may be taken as around 80-90% of the population)		Yes
	Do citizens generally comply with the rules and regulations set for unauthorised groundwater abstraction? (generally may be taken as around 80-90% of the population)		No
	Do citizens generally comply with the rules and regulations set for illegal pollution of water? (generally may be taken as around 80-90% of the population)		No

TABLE 2. Raw data for Bangkok City in 2017 (Babel et al., 2020)

"Example" menu demonstrates the application of WATSAT by considering the case study of Bangkok city.

The "Create Account" menu requires users to provide their basic information, email address, and organisation in order to create a user account for WATSAT. They also need to provide consent for allowing WATSAT developers to use an anonymised version of the data they enter into the tool for research purposes and further development of the tool. The "Contact Us" menu provides the contact information of developers for users to provide feedback and suggestions to further improve the tool. After creating an account, users can log in to WATSAT from the "Login" menu with their username and password.

A flow chart presenting each of the menus in WATSAT is shown in Figure 4. Two types of colour coding are used to describe the WATSAT menu. The grey-coloured boxes represent the fixed menus in the WATSAT system, where users can explore the menus and sub-menus but do not enter any data and are not allowed to make any changes or modifications. The green-coloured boxes represent the user-defined menus. As the name suggests, these menus and sub-menus are typically where the users can select the site-specific variables, input data values, assign weights, and estimate variable scores.

After the user logs into WATSAT, the tool consists of seven main menus. The "Home" menu is the first menu which outlines all the content in the seven menus of WATSAT. The second menu — Water Security Assessment Framework" — describes in detail the theoretical components of the WATSAT framework. It consists of six sub-menus: "Dimensions", "Indicators", "Variables", "Reference Values", "Raw Data Categories", and "WSI Interpretation". As mentioned before, the menu is solely for understanding purposes, and users are not required to enter any data and cannot modify these menus.

In the "City Profile" menu, users need to enter the city-related basic information to provide an overview of the city. City-related information includes the city's name, the country it is located in, the year of assessment for water security, urban area, climate zone, average annual temperature, maximum and minimum temperatures, average annual rainfall, population, population growth rate, annual income per capita, number of sub-cities or districts or wards, and source(s) of water supply (surface water, groundwater, or both). From the above mentioned information, users have to enter the city's name and year of assessment for water security, but the rest of the information is optional as these data are only to provide a context for the city and none of the data entered in this menu are taken for the purpose of analysis.

The fourth menu, "Data Entry and Computation", is the most important menu in WATSAT. It consists of three sub-menus: "Variable selection", "Input raw data values", and "Variable estimation and weightage". The variable selection sub-menu provides the users with a long list of potential variables and information about the data required to estimate these variables. This allows users to select specific variables that are relevant to their city's context. In the input raw data values sub-menu, users are required to input the raw data values for the variables they selected in the previous menu. Users are advised to be careful about the units of the data while entering the data values. After the users input the raw data values for the variables, the computation of the selected variables' scores is carried out in the variable estimation and weightage sub-menu. Users simply need to click on the "Compute all variable score" button in this sub-menu and WATSAT carries out all the computation at the backend and provides users with the estimated variable score. Likewise, users can also provide equal weights automatically to the selected variables by clicking on the "Equal weights" button or entering the weightage at all three levels: variables, indicators, and dimensions, in this sub-menu.

As mentioned earlier, WATSAT has a "Validation" menu to identify missing data or discrep-

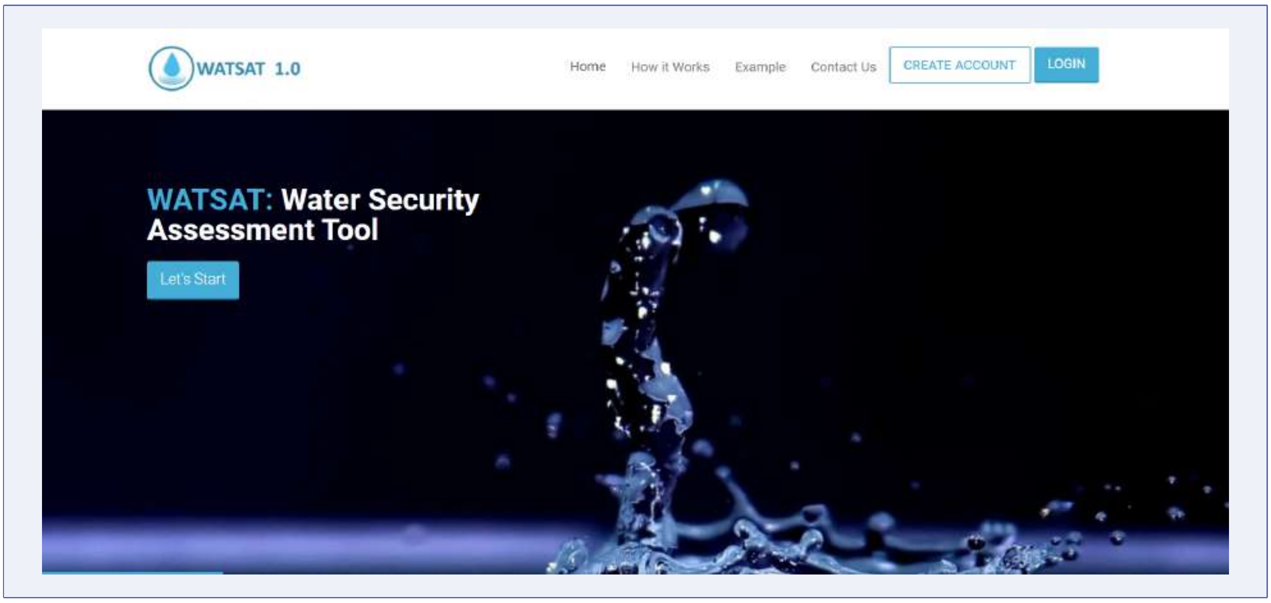

FIGURE 3. WATSAT landing page.

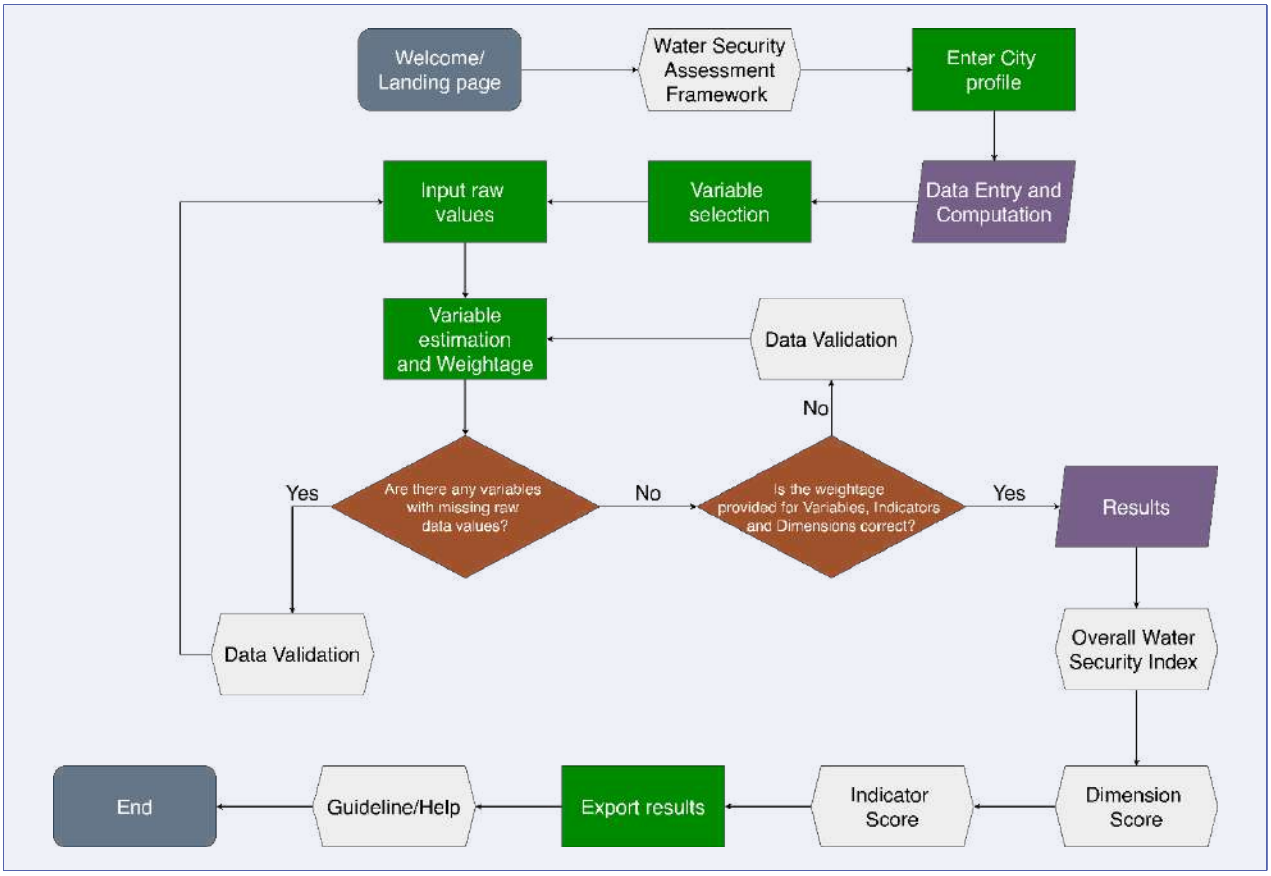

FIGURE 4. WATSAT flowchart for users.

ancies in assigned weights to variables, indicators, and dimensions. The menu consists of four sub-menus: "Dimensions with wrong weights", "Indicators with wrong weights", "Variables with wrong weights", and "Variables with missing value". As the name indicates, the first three sub-menus validate if the weights given to selected variables, indicators, and dimensions in the previous menus add up to 100% or not, while the last sub-menu checks if there are any selected variables that are not provided with data values in the tool. This menu is a vital one as it offers the user an opportunity to minimise errors. For example: in many cases, users tend to forget to balance the weights provided to the selected variable to 100%. This discrepancy is detected in the Variables with wrong weights sub-menu in WATSAT and users can modify the weights for the selected variables within this sub-menu as well. It is recommended that users must always go through all four sub-menus of the "Validation" menu.

After the validation, the "Results" menu consists of four sub-menus: "Overall Water Security Index", "Dimension Score", "Indicator Score", and "Export Variable Results". The overall water security index sub-menu provides users with a single aggregated value ranging from 1 to 5 that depicts the overall situation of water security in a city along with the interpretation of the score. The Dimension score sub-menu provides users with means to understand how the city performs in terms of the five dimensions of water security. Further fine-grained analysis at the indicator level is provided in the indicator score sub-menu. In all these sub-menus, an "Export" button is provided, which enables users to download an Excel sheet consisting of the results of the dimension score and indicator score. Likewise, users can also export an Excel sheet with results at the variable level from the Export variable results sub-menu. This consists of results of raw variable value, variable score, and weights provided to the selected variables. It is noteworthy that the indicators reflecting water productivity and water governance dimensions are incorporated in WATSAT, given that these dimensions are often overlooked in other frameworks and tools. Likewise, the water security analysis at three levels (i.e., overall water security index, dimension score and indicator score) aids city authorities in identifying the driving forces or root causes that influence water security and guide them in developing practical solutions to enhance water security in the city.

Finally, WATSAT also provides users with a "Guideline/Help" menu which consists of two sub-menus: "Guided Access" and "User Manual". The Guided access sub-menu guides users to go directly to any user-defined menu in a guided manner. The User manual menu provides a manual in PDF format that describes WATSAT in a step-by-step manner that is easy to comprehend and follow.

WATSAT was successfully applied to evaluate the water security situation for Bangkok City for the year 2017 based on the data presented in Table 2. Figure 5 , Figure 6, and Figure 7 show snippets of the results obtained in WATSAT for Bangkok city for the year 2017.

As indicated in Figure 5, the overall state of water security for Bangkok in 2017 was in a "very good" state. However, from the dimension's perspective, Bangkok still has considerable room for improvement in terms of water-related disasters and water environment dimensions, as shown in Figure 6. The analysis at the indicator level shows that significant efforts are needed to reduce the effect of water polluting factors, such as direct discharge of domestic wastewater into waterways, to improve the water environment in Bangkok city. Likewise, Bangkok needs to increase investment in both disaster mitigation and disaster preparedness to anticipate future water challenges related to extreme climate events.

4. RESEARCH PROSPECTS AND LIMITATIONS

In recent years, there have been rapid advances in research on water security which have led to an improved and holistic understanding and assessment of water security. For example, the water poverty index proposed by Sullivan (2002), as a means to determine sustainability of water

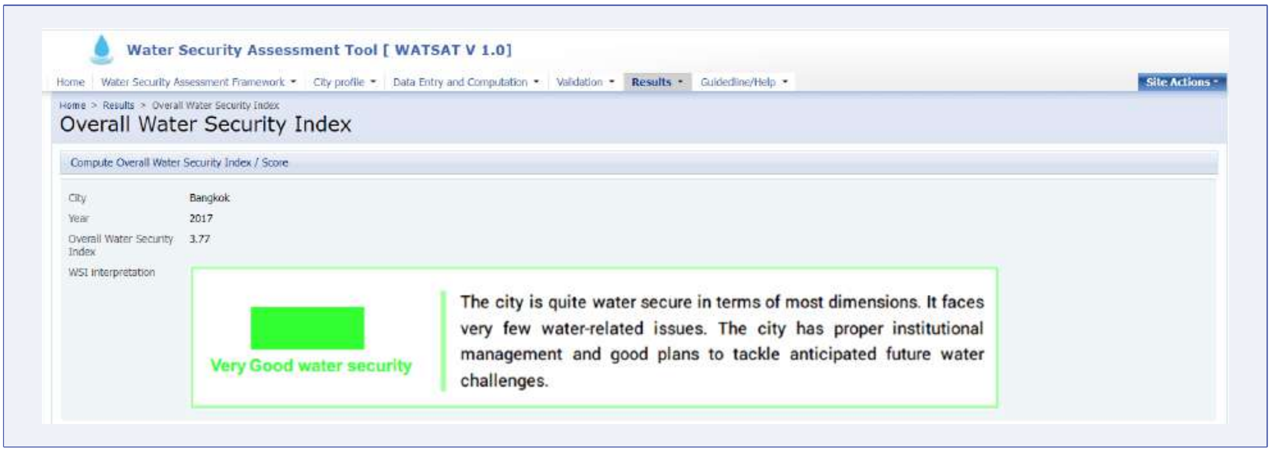

FIGURE 5. Water Security Index (WSI) for Bangkok city.

FIGURE 6. Dimension score for Bangkok city.

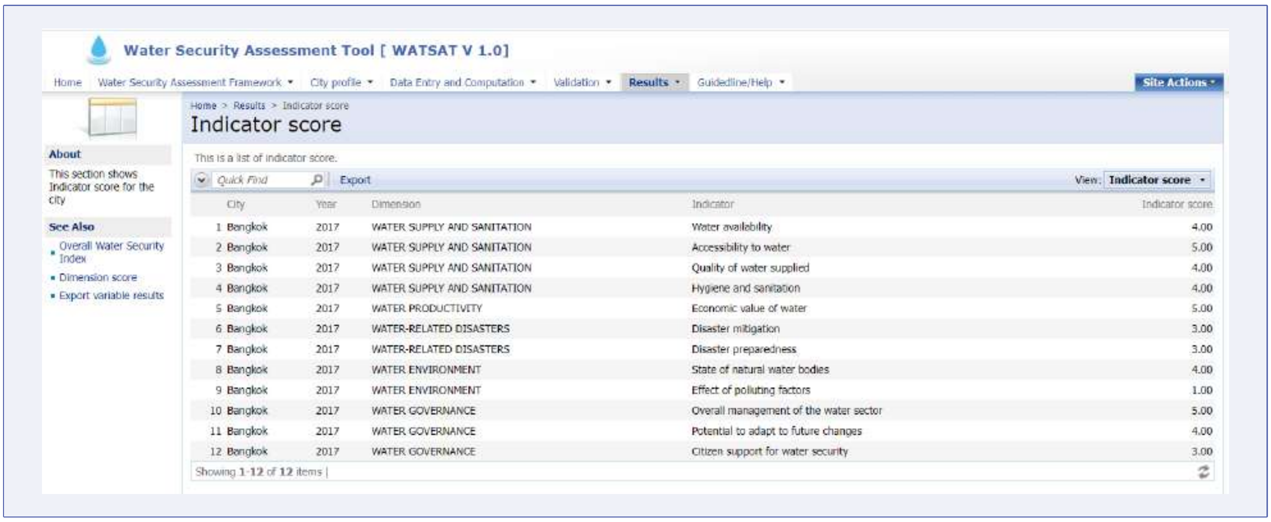

FIGURE 7. Indicator score for Bangkok city.

resources and their impacts on human populations, is a multi-dimensional index that reflects on five components: Resource (R), Access (A), Capacity (C), Use (U), and Environment (E). Although the WPI reflects on multiple dimensions of water security (Availability, Accessibility, Productivity, Quality), it does not effectively capture the water-related disasters and water governance aspects of water security, which are included in the present study. Similarly, Aboelnga et al. (2019) developed a framework with 27 indicators for urban water security assessment. The framework, although comprehensive, also disregards the water governance dimension of water security. Although the theoretical understanding and frameworks for water security assessment are robust, there is a great shift required to translate science into practice from an assessment framework to an action-based framework (Babel et al., 2022). In this regard, this work is an effort to bridge the science-policy gap by facilitating the transfer of existing science into practice by developing WATSAT, a digital tool which is publicly accessible and holistic in nature, enabling city authorities to carry out independent quantitative assessments of the water security situation in the city.

One of the prospects for future work on WATSAT is the inclusion of the socio-political dimensions in the existing framework to take account of social inequality aspects such as roles of gender, vulnerable and marginalised groups of people, power, and conflict in securing water in urban areas. Similarly, climate-reflective and adaptation-related indicators to measure water-related disasters could further improve the framework. Furthermore, the addition of integrated indicators that reflect on the interlinkages of water, energy, and food resources is another avenue to explore upon to enhance the framework (Hoff, 2011; Albrecht, Crootof, & Scott, 2018; Cai, Wallington, Shafiee-Jood, & Marston, 2018; Babel, Rahman, Budhathoki, & Chapagain, 2023). However, given the inherent complexity of the interaction associated with each resource, it is recommended that due consideration be given to ensure a comprehensive understanding of the nexus's indicators and data availability prior to their incorporation into the urban water security assessment framework.

From the tool perspective, a limitation of WATSAT is its inability to undertake a water security assessment for multiple cities simultaneously, which is often carried out for comparative assessment among cities with diverse climatic and socioeconomic conditions. However, WATSAT was preliminary designed to be used by city authorities and decision-makers to assess water security for their cities. Furthermore, there is an opportunity to enhance the representation of the results through the implementation of effective visualisation techniques (bar charts, heat maps, among others), which can lead to better understanding and generate additional insights about the city's water security situation. These improvements will be incorporated into the future versions of WATSAT.

5. CONCLUSIONS

This project has successfully developed a web-based digital tool called WATSAT (Water Security Assessment Tool) to help city stakeholders make a quantitative assessment of the water security situation in the city using five distinct dimensions. The tool is in the public domain (www.watsat.org). The findings and reflections that emerged out of the study are summarised as follows:

1. The tool is holistic in nature and robust to capture the elements of water security and thus can be applied to any city across the globe;
2. City stakeholders can make an objective assessment and have a holistic understanding of water security and interconnections of various factors affecting it and assist them in informed decision-making to arrive at system-based interventions to tackle water security threats in the cities; and
3. The validation of the tool is carried out with an example of the water security assessment

in Bangkok city. Results show that while the overall state of water security is good, there is considerable room for improvement in terms of water-related disasters and water environment dimensions of water security in Bangkok.

This project work is an effort to bridge the science-policy-society gap by facilitating the transfer of science into practice. Thus, it is expected that the tool will help build the capacity of city authorities, planners and decision-makers, practitioners, and academicians, among others, in an improved understanding of the holistic nature of water security and its assessment. Moreover, this will create an enabling environment for mainstreaming WATSAT as a policy and management instrument.

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Original article

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Strengthening adaptive capacities of small holding South Asian agrarian community through Climate Information Network -based decision support tool

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ABSTRACT

Marginal farmers in rain-fed agrarian systems can benefit immensely from real-time contingency planning and decision-making tools in the climate milieu. Long-term climate anomaly prediction of some selected locations was made. Forty-two Global Circulation Models (GCM) from the Coupled Model Intercomparison Project Phase 5 project (CMIP5) were used for the present work and Representative Concentration Pathway (RCP) 4.5 to prepare future projections. The effect of the climate anomaly on existing farming practices in two selected climate-vulnerable locations of Purulia, India, and Shyamnagar, Bangladesh, has been analysed. A participatory action research and Climate Information Network (CIN)-based crop calendar has been devised for the selected locations. An interactive Android bot in the form of a Decision-Making Cropping Support System (DMCSS) has been devised and field tested. This system can provide seasonal crop suggestions and suggest contingency management to farmers. The system also provides risk assessments on the basis of preparedness and categorical inputs that users provide on crop, climate and contrivances.

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KEYWORDS

Climate Information Network (CIN), Crop calendar, Participatory Action Research (PAR), Global Circulation Model (GCM), Coupled Model Intercomparison Project Phase 5 (CMIP5), Representative Concentration Pathway (RCP), Decision Making Cropping Support System

HIGHLIGHTS

- Long-term climate anomaly prediction and PAR (Participatory Action Research) based on existing crop practices and available climate information were made on two extremely climate-vulnerable locations in the Indian subcontinent of Purulia (India) and Shyamnagar (Bangladesh).
- Long-term climate anomaly prediction was made based on CMIP5 scenarios and RCP 4.5 projections.
- Alternative crop calendar, crop and cropping practices were developed based on probable climate emergencies.
- DMCSS involving crop, climate, contrivances and contingency (4C) has been developed as an Android based bot and field validated.

1. INTRODUCTION

Climate change is causing seasonal shifts resulting in various anomalies related to temperature, rainfall pattern and the number of dry and wet spells. These and other visible increments in extreme events have adversely impacted cropping patterns and crop productivity (Crane, Roncoli, & Hoogenboom, 2011). Climate change has triggered weather anomalies that can significantly impede achieving zero hunger sustainable development goals (UNDESA, n d; UNICEF, 2021). A widespread increase in high-temperature events in India has been highlighted, and thirty-fold higher than 2°C warming is predicted (Mishra, Mukherjee, Kumar, & Stone, 2017). Increased days with higher temperatures may decrease production by creating physiological stress on plants and causing sterility (Wang et al., 2020). Adaptation is the adjustment in natural or human systems in response to actual or expected climatic stimuli or their effects, which moderates harm or exploits beneficial opportunities (Parry, Canziani, Palutikof, & Van Der Linden, 2007). The potential impacts of climate change on agroecological systems have been addressed by various models (Lahsen, 2005; Olson et al., 2008; Hein, Metzger, & Leemans, 2009; Thornton, Jones, Alagarswamy, Andresen, & Herrero, 2010). Modelled climate practice scenarios often ignore farmers' adaptive capacities to climate trends in both the short- and long-term (Crane et al., 2011). Richards (1989, 2002) has emphasised that farmers' improvisational capacities are key elements in formulating agriculture performance. However, climate change impacts and risks are becoming increasingly complex and more difficult to manage (Pörtner et al., 2022). In this situation, integrated, multi-sectored solutions that address social inequities and differentiate responses based on climate risk and local situations may enhance food security and nutrition (Pörtner et al., 2022). The science of forecasting has emerged as "the key technology for visualising and anticipating the processes and impacts of climate change and climate variability on agricultural production systems" (Crane et al., 2011). The accuracy of these climate predictions is, however, limited by fundamental, irreducible uncertainties (Dessai, Hulme, Lempert, & Pielke, 2009). Prediction is only useful for farmers if the forecast is reliable and the uncertainty is understood (Mall, Bhatt, Sonkar, & Banerjee, 2014).

The weather prediction-based approach for advancing agriculture has been well implemented in developing countries. To the best of our knowledge, a climate-based approach for the long-term improvement of cropping patterns has been significantly overlooked. The major differences between weather-based and climate-based approaches are that weather-based approaches focus on improving short-term water usage efficiency in agricultural fields. In contrast, climate-based approaches focus on the low-risk selection of crops and varieties for long-term improved productivity. The weather-based agro-decision-making system depends upon numerical simulation of Weather Research and Forecasting (WRF) models at a high-resolution scale for five to seven days of forecasting using meteorological data from ground-based weather stations. The advantages include sowing/transplanting time selection during monsoonal crops, irrigation advisory at the critical plant growth time, and fertiliser application based on wind and rain-predicted conditions. On the other hand, the climate-based approach uses CMIP5 outputs that are statistically downscaled for a higher spatial resolution to predict the best possible future climatic conditions over an area. Outputs from the climate-based approach can be directly used to formulate strategies and decision-support tools for farmers through a micro-level crop calendar incorporating agricultural, economic and climate data.

A crop calendar tool has been developed to assist farming communities and stakeholders in facilitating the availability of quality seeds of specific crop varieties based on agroecological zone and climate conditions and can serve as an adaptive tool against changing weather patterns (FAO, nd). Business as usual cropping and crop calendar does not incorporate scientific adaptive measures. Adjusting crop calendars may present an effective adaptation measure to avoid crop yield loss and reduce water use in a changing climate (Wang et al., 2022), especially in rain-fed agrarian systems. Place-based and micro-level crop calendar is vital in assisting marginal farmers to adapt to changing climatic conditions with better and resilient crop and cropping practices. Adger, Huq, Brown, Conway, & Hulme (2003) and Kurukulasuriya et al. (2006) stated that adaptation is one of the policy options for reducing the negative impacts of climate change, while Mendelsohn, Nordhaus, & Shaw (1994) noted that farmers will be especially hard hit if they do not adjust to new climates. Including agro-meteorological information networking in planning for crop calendars over time and space is necessary. It is also essential to document the change and resilience of local marginal farmers on which their adaptive capacities need to be built. The present study has been undertaken to develop a Decision Making Cropping Support System (DMCSS) for climate vulnerability in Purulia, India and Shyamnagar, Bangladesh. This would act as a climate information network (CIN) based real-time contingency planning (RTCP) system. A system such as DMCSS can be a critical policy tool for ensuring food security and livelihood augmentation in the climate milieu in the Global South.

1.1. Objectives of the Study

1. Prepare Crop Inventory of Project Locality - contrivances, traditional practices and resource inputs

2. Undertake Participatory Action Research (PAR) at the grassroots level and long-term climate anomaly prediction based on global circulation models (GCMs) to develop a micro-level CIN-based Android based bot crop advisory system

3. Validate the crop calendar with at least two cropping cycles (Monsoon & Winter) to develop a decision support system for rain-fed agro-farming

4. Undertake capacity building of marginal farmers on the use of a CIN-based decision-making cropping support system using the Android based bot.

2. METHODOLOGY

2.1. Climate Information Network (CIN)

A Climate Information Network (CIN) has been established through an APN-funded cross-country collaborative project over Purulia, West Bengal, India (23.3N, 86.4E) and Shyamnagar, Bangladesh (22.3N, 89.1E) for the improvement of climate literacy among marginal farmers. Purulia is extremely arid and receives minimum rainfall, whereas Shyamnagar is located on the edge of the Bay of Bengal and is affected by climate extremes. The study collected meteorological data from various sources spanning 1960 to 2019, compared them with multiple GCM models and data from the IPCC Fifth Assessment Report (AR5), and identified the most appropriate model output for the study areas. Future projections were taken from the best-fit model output.

Past weather data was gathered from the following sources: (1) The gridded Climatic Research Unit (CRU) TS (time-series) 3.21 (CRU-TS3.21) monthly datasets with a resolution of 0.50×0.50 covering the period 1901-2012 prepared by CRU at the University of East Anglia (Harris, Jones, Osborn, & Lister, 2014); (2) Global Precipitation Climatology Centre (GPCC) V6.0 and a reanalysis of monthly land-surface rainfall data set with a temporal span of 110 years from 1901-2010 at a resolution of 0.50×0.50 (Schneider, Fuchs, Meyer-Christoffer, & Rudolf, 2008); (3) WorldClim version 2.1 monthly climate data for minimum, mean and maximum temperature, precipitation, solar radiation, wind speed, water vapour pressure, and for total precipitation gathered with climate data from 1970-2000 (Fick & Hijmans, 2017); and (4) Terra Climate, which is a dataset of monthly climate and climatic water balance for global terrestrial surfaces from1958-2019 (Abatzoglou, Dobrowski, Parks, & Hegewisch, 2018).

Forty-two GCMs from Coupled Model Intercomparison Project Phase 5 (CMIP5) were used for the present work and are among the group of GCMs outlined in the IPCC AR5 (Stocker, 2014) having monthly precipitation records from 1860-2100 in its experimental 'run-1'. The CMIP5 products are freely available at http://www.knmi.nl/. The GCMs used in the present study were also used by IPCC AR5 working group (WG) I and WGII (Field & Barros, 2014). The GCMs' performance was assessed by dividing the simulation period into two parts: 1960-2019 for evaluating the models and 2006-2100 for constructing future climate change scenario information. The 42 GCMs' performance was evaluated against observational data through rigorous statistical analysis. The best-performing models were selected for the prediction of future scenarios. For preparing future projections, RCP 4.5 was used.

The term climatic water deficit is quantified as the amount of water by which potential evapotranspiration (PET) exceeds actual evapotranspiration (AET) (Lutz, Wagtendonk, & Franklin, 2010). This term effectively integrates the combined effects of solar radiation, evapotranspiration, and air temperature on watershed conditions, given available soil moisture derived from precipitation. The Palmer Drought Severity Index (PDSI) (Palmer, 1965) uses readily available temperature and precipitation data to estimate relative dryness. It is a standardised index that generally spans from -10 (dry) to +10 (wet).

2.2. Participatory action research

Questionnaire-based stakeholder feedback was generated through an online system by utilising Survey Monkey. Crop calendars were developed based on PAR involving 4C (crop, climate, contrivances, contingency) and engaging farmer groups through PRA (Participatory Rural Appraisal). Contingency crop planning was undertaken according to Banerjee et al. (2019) and National Innovation in Climate Resilient Agriculture (NICRA).

An MS Excel-based gradation system of preparation level of farmers (>75%=A, 60-74%=B, 50-59%=C and <50%=D) was developed where higher grades or higher percentages signify higher resilience and lower risk. Here the farmers are categorised into various groups based on their available resources like land elevation, soil condition, tillage, water availability or irrigation, finance, land area, labour, market availability, seeds and fertilisers, among others. Based on preparedness or resource availability, the score range was established as 0-5, where 0 signifies the lowest score and 5 the highest regarding preparedness and resilience. By this logic, one (farmer or user) must accumulate a minimum score of 75% or more of the total cumulative score possible to qualify as grade A. Some standard logic sets were set up in the framework to arrive at the right score for a particular input. Farmers who adhered to agroecological practices such as minimal or zero tillage, utilisation of animal power in tillage, preservation of indigenous seed banks, reduced water waste in fields, and the use of natural ingredients for fertilizers and pesticides achieved significantly higher scores compared to farmers who transitioned to more equipment-based intensive farming. Similarly, lack of financial strength, non-availability of public or private credit, greater distance from the market, and consistently maintaining fallow land, among others, were designated lower scores in the 0-5 range. Then, decisions on the crop (grain, vegetable and pulses) and contingency suggestions are provided based on (1) the final accumulated grade of the farmer; (2) the sowing season, i.e., monsoon (*Kharif*) or winter (*Rabi*); and (3) rainfall pattern (normal, less than 75% or excessive).

2.3. Preparation of conditions based crop suggestion in the form of "Android based bot"

A cloud computing Android based bot was developed using a Gradation Based Cropping and Contingency Suggestion framework. The bot uses Android software development kit (SDK) Version 21 with Android 5.0 — A Lollipop software system, utilising NodeJs and MongoDB server, is designed to generate tailored outputs based on various inputs, including geolocation, weather, land and soil conditions, available resources and equipment, market and economic conditions. A flow chart of the system's functionality is given below (Figure 1).

The Android based bot was field validated with farmers at locations during different crop cycles and fined tuned accordingly.

3. RESULTS

3.1. Climate information

3.1.1. Purulia: Historical pattern

The historical weather pattern for Purulia indicates the aridness of the region. The yearly maximum temperature has regularly reached 40°C during the summer months since the 1960s (Fig. S1, Supplementary Material-Appendix 3). The annual temperature minimum always stays above 22°C. During winter (December-February), the minimum temperature remains at ~12°C and reaches ~42°C during summer (March-May). It is also clearly evident that the minimum and maximum temperature gradually increases over Purulia. The annual average rainfall for the study period 1960-2019 was 1267±182 mm, with a range varying from a maximum of 1920 mm to a minimum of 854 mm (Fig. S1, Supplementary Material-Appendix 3). Around 60% of the years, annual rainfall deficiency was observed during the study period and the skewness of the frequency distribution of annual rainfall inclined towards the left. Very high solar radiation (216±40 watt m^{-2}) over the study area indicates scorching heat and aridness (Fig. S1, Supplementary Material-Appendix 3). No significant trend was observed in solar radiation and wind speed during the entire study period.

3.1.2. Purulia: Precipitation and temperature anomaly

The precipitation and temperature anomalies were calculated for the last two decades (2000–2019) considering a baseline of 1958–1970 and represented in Fig. S2, Supplementary Material-Appendix 3. 55% of the time, rainfall deficiency was observed and 45% of the time, annual rainfall was found to be surplus. The decadal rainfall was analysed and no significant changes in decadal rainfall were observed. However, a significant error in the box plot for individual decades (25-75 percentile) indicates year-wise high variability. A significant positive trend was found while plotting the decadal variability as a function of rainfall anomaly, and it was observed that the variability increased during the last couple of decades. It was observed that

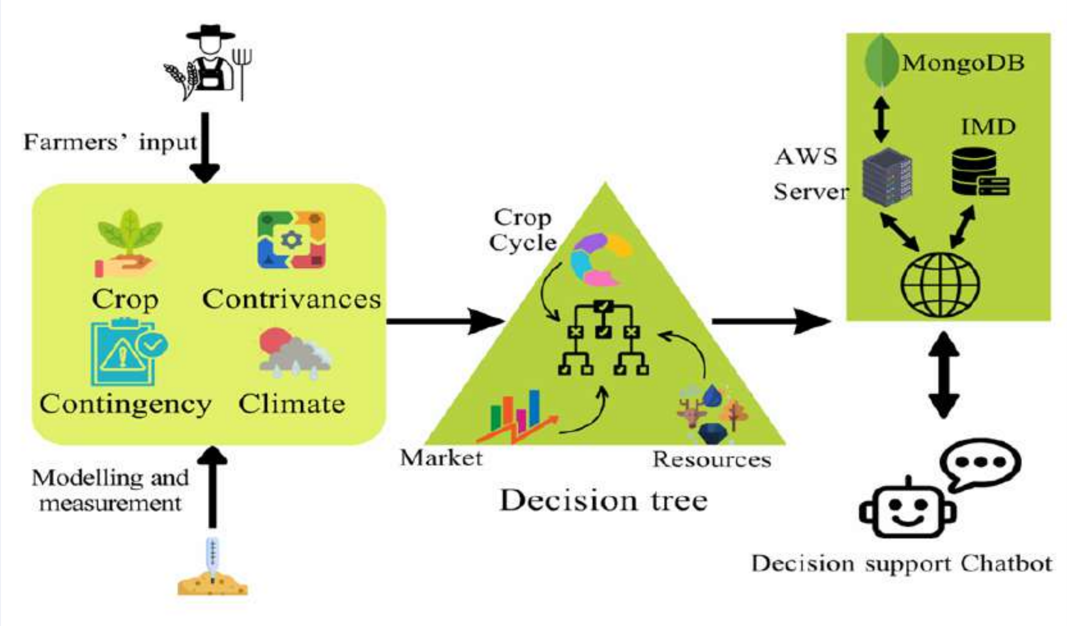

FIGURE 1. Flow chart of the functionality of the cloud computing "conditions-based crop suggestion" in the form of an Android based bot.

positive temperature anomalies exist for both maximum and minimum temperatures considering the baseline from 1958-1970 (Fig. S2, Supplementary Material-Appendix 3). It was found that the rate of increment for temperature minima was higher compared to temperature maxima.

The month-wise maximum temperature anomaly for the last decade (2010-2019) computed with respect to the 1958-1970 baseline is represented in Fig. S3 (Supplementary Material-Appendix 3). It reflects hotter summer and winter months compared to historical climatic patterns. The 70% positive climatic water deficit anomaly value in the last two decades for Purulia indicates drought-prone increments over the region. The PDSI values over Purulia specify that the region has been suffering from prolonged drought since the 1960s and becoming more regular and repetitive (Fig S3, Supplementary Material-Appendix 3).

3.1.3. Purulia: Future prediction and agronomic significance

The future projection of temperature for Purulia has been given in Fig. S9, Supplementary Material-Appendix 3. The projection indicates increments during both the summer and winter months. During the end of the upcoming decades, a certain probability exists to lower the mean temperature slightly. The maximum temperature during winter has been calculated and plotted as a histogram. It could be observed that the median range of maximum temperature increment is 1.5-2°C. The projection suggests that the monsoonal precipitation will increase during July and decrease during August. Winter precipitation will decrease in the upcoming decades (Fig. S9, Supplementary Material-Appendix 3). There is an expected increase in the frequency of flash flood events and longer periods of drought in the coming decades. During the decade's end, a significant monsoonal precipitation decrement is expected. Severe drought events might be observed during non-monsoonal months. Irrigation-dependent agriculture or low-water-consuming crops need to be promoted. Winter varieties might be highly affected as winter temperatures will increase. Increasing the number of flash floods will also elevate nutrition run-off from the soil.

3.1.4. Shyamnagar: Historical pattern

Compared to Purulia, the temperature over Shyamnagar is stable and less extreme (Fig. S4, Supplementary Material-Appendix 3). However, the minimum and maximum temperatures gradually increase over Shyamnagar, and the increment rate of minimum temperature is five-fold higher compared to the maximum temperature. Very high solar radiation (203±28 watt m^{-2}) was observed. However, unlike Purulia, substantial monthly variation was observed. Due to close proximity to the sea and convection activity during summer months, wind speed is much more elevated in Shyamnagar (3.6±0.3 m s^{-1}) compared to Purulia (Fig. S4, Supplementary Material-Appendix 3).

3.1.5. Shyamnagar: Precipitation and temperature anomaly

The precipitation anomaly was calculated for the last two decades (2000-2019) considering a baseline of 1958-1970 and represented in Fig. S6, Supplementary Material-Appendix 3. During the monsoon season, the anomaly was found to be more skewed towards the deficit, which implies that precipitation extremes have been higher over Shyamnagar compared to Purulia in recent times.

The decadal precipitation (1960-2019) has been plotted along with temperature anomalies over Shyamnagar (Fig. S6, Supplementary Material-Appendix 3). The quantile and central tendency for precipitation in recent decades is considerably lower compared to previous decades. It can be observed that, especially during the last decade, both maximum and minimum temperatures increased compared to historical climatic patterns, but temperature minima increases were higher compared to temperature maxima.

Two drought indices, climate water deficit anomaly and Palmer drought sensitivity index, are presented in Fig. S7 (Supplementary Material-Appendix 3). High precipitation and proximity to the sea help to overcome the climate water deficit over Shyamnagar. The Palmer drought sensitivity index also indicates that the impact of drought has been relatively low in the last decade.

3.1.6. Shyamnagar: Future prediction and agronomic significance

Both minimum and maximum temperature in Shyamnagar is expected to increase during the upcoming decades compared to the last decades (Fig. S10, Supplementary Material-Appendix 3). Dry spells will increase significantly, and up to an eight-to-nine-day increment in break-spell is expected compared to previous decades. An overall increment in monsoonal rainfall is expected in Shyamnagar (Fig. S11, Supplementary Material-Appendix 3). Similarly, the frequency of extreme precipitation events is expected to rise in comparison to previous decades, and there will be a gradual increase in the occurrence of warm spells. Precipitation extremes such as drought and flood are expected in the next decade.

It can be predicted that saltwater inundation and extreme cyclonic risk aggravate the difficulties of agrarian livelihoods in Shyamnagar. Low-water-consuming crops or salt-tolerant varieties need to be promoted. Conservation of rainwater and incorporating micro-irrigation may help reduce the dry physiological condition.

3.2. Stakeholder feedback

Significant numbers (85%) of stakeholders (n=85) were in favour of such an android mobile-based decision-making tool. In the climate milieu, real-time contingency planning in the form of an Android based bot which disburses implementable suggestions, including resilient crops, cropping techniques, risks etc., can be extremely critical in securing food and livelihoods. Fifteen percent of those surveyed were of the opinion that such a system would not be able to provide implementable adaptive measures if accurate information on local soil, weather and market trends were not available. The majority of respondents have opined that the most visible effect of climate change on agricultural farming systems is on two fronts: water scarcity and productivity. While this has been asked what would be the most niche-specific and pertinent ways to deal with the problem, the majority of answers hover over watershed management and the promotion of sustainable farming practices (Fig. S12 and Fig. S13, Supplementary Material-Appendix 3).

3.3. Crop Calendar

An alternative crop calendar (Supplementary Material-Appendix 1), including contingency management and recommendations, has been developed by involving farmer groups through PRA (Figure 2). The crop calendar includes average meteorological data, including monthly maximum and minimum temperature, monthly rainfall (mm), rainy days, relative humidity (RH%), solar days, among others. The CIN information has been included in the form of expected variations in rainfall and temperature regimes. Both common and alternative local crops are suggested, with probable days of sowing and harvesting. The management of pests and diseases should be conducted using natural and chemical-free methods, along with contingency plans to handle climate extremes.

The grade of preparation level of the farmer is based on real-time input of land/soil type, tillage, water and irrigation, finance, land availability, seeds, fertiliser, labour and market availability, and has been developed for both locations together with suitable contingency planning based on (1) crop season; (2) real-time weather conditions like normal or excessive rainfall, dry spell or drought; and (3) stage of cropping (Supplementary Material -Appendix 2).

3.4. Crop suggestions by the Android based bot

The Android based bot, which has been named *Borshamongol* (which means "Blessing of Rain" in the Bengali language), has been developed as a bilingual (Bengali and English) system which can provide crop suggestions based on selected inputs. The Android based bot is freely downloadable from the Google app store (https://play.google.com/store/apps/details?id=com.boenci.naboborshamongol). The bot asks for the mobile numbers and name of the first-time user and then uses the phone's location to provide weather information based on Accuweather© free data for the coming five days. After registration is completed, the bot asks the user to type "Hi" and then asks specific sets of questions based on the framework of gradation already prepared (Supplementary Material -Appendix 2) and embedded in the software logic of the bot. The bot asks for inputs from the users in the form of MCQ only, and one has to type the corresponding serial number of the right option or choice to progress to the next stage. After grading the user, the bot provides a crop advisory and risk assessment based on further inputs like *Kharif* (monsoon) or *Rabi* (winter) crops for the sowing or mid-cycle stage. After generating the first advisory, the bot will ask the user whether they want to continue or exit. If the exit button is chosen, then a comprehensive report is generated. Otherwise, the bot continues based on user input. A screenshot of the Android bot is shown in Figure 3.

3.5. Field testing of the Android based bot

The Android based bot was field tested in both locations, with 120 farmers trained to use the system in the most effective way. Farmers also provided detailed feedback. Eighty-eight percent of farmers found the bot very easy to use. Twenty-nine percent of farmers said internet connectivity was a problem for availing the bot service, but all of them indicated this could easily be solved as the bot uses a live location to provide a weather forecast but does not depend upon a live location to generate crop suggestions. Thus, the farmer can easily get his or her response from another farmer in a location with faster internet connectivity by sharing the required inputs. The suggestion generated can be communicated to the original beneficiary as a downloaded document or screenshot. Seventy percent of farmers complained that the bot allotted higher risk grading levels to the farming practices they followed as they are not following agroecological methods, but such methods are not easily available to them nor sufficiently trained to do such practices. Eighty-nine percent of farmers admitted that agroecological practices are more resilient and can reduce costs, but there is a shortage of indigenous seeds, proper training and suitable markets for the end products and resources for such practices. Ninety-

FIGURE 2. Ongoing Participatory Rural Appraisal (PRA) is going on as a part of Participatory Action Research (PAR) based crop calendar (CC) involving 4C (crop, climate, contrivances and contingency) at the field level.

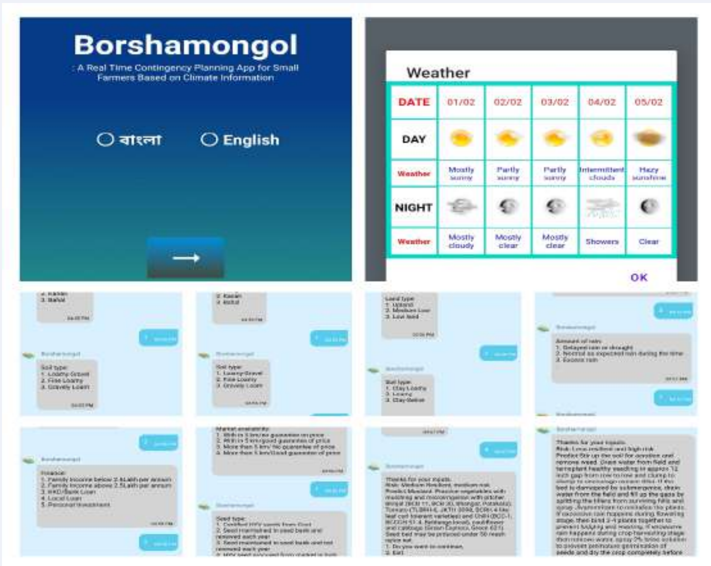

FIGURE 3. Screenshot of the Android based bot.

one percent of farmers appreciated the contingency plans pertaining to weather extremes based on their specificity and easier methods of explicability were suggested.

4. CONCLUSION

An Android based bot in the form of a real-time crop advisory tool based on a Climate Information Network has been developed for Purulia in India and Shyamnagar in Bangladesh. This tool has been developed not only as a means of sharing adaptive strategies but also as a process for preparing against climate change-induced weather extremes. The major aim of the intervention under discussion is to prepare the most vulnerable communities in the climate milieu with resilient crops and cropping practices. Analysis of historical weather data and future climate change prediction studies revealed that increments in summer and winter temperatures in both locations with an increase in weather extremes like drought, dry spells and flash floods in Purulia; and extreme rainfall, saltwater inundation and extreme cyclones in Shyamnagar.

Both stakeholder feedback and participatory rural appraisal have been done to develop a place-based crop calendar. The crop calendar also includes alternative indigenous crops, resilient cropping practices based on indigenous traditional knowledge and suggested contingency actions under extreme events. The Android based bot grades the farmer user in various categories based on his or her inputs and embedded grading matrix and provides crop and cropping advisory and risk assessment. This unique agriculture-related decision support system method uses all kinds of available information at ground level to reach a fully interactive place-based solution. The system has been satisfactorily tested at both locations among 120 farmers. Farmers have found the system easy to use in both locations, with only a few minor impediments. The two important lessons which can be derived from this activity are: (1) the CIN-based agriculture decision-making tool can provide successful adaptive management in the climate milieu if it can be coupled with ecologically informed practices and availability of heirloom seeds; and (2) such a tool can prevent untimely or incorrect distribution and procurement of seed, fertiliser, water and other input factors thus reducing costs and carbon emissions.

One crucial lesson from these endeavours is that such a system cannot function as a standalone solution, given the multifaceted nature of various driving factors, which also require simultaneous policy-level attention to achieve SDGs such as No Poverty (SDG 1), Zero Hunger (SDG 2), and Climate (SDG 13). Specifically:

1. The availability of resilient crops and indigenous seeds is too small;

2. Three generations of green revolution practices contributed to the loss of Indigenous and Traditional Knowledge (ITK);

3. Large-scale socio-political and psychological inertia remains in the community, which may resist further transformation;

4. Weather data, rental costs of cloud servers and mobile data have become too costly for marginal commons and need to be affordable;

5. Each *Panchayat* (village government in India) needs to have its own local weather and satellite station, making real-life contingency planning worthwhile; and

6. Market linkages and value chains of resilient and indigenous crops are still in their infancy and are dominated by unsustainable market demands

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6. APPENDICES

Appendices are available online at https://doi.org/10.30852/sb.2023.2188.

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Climate change risk perceptions, vulnerability, and adaptation in high altitude farming regions of Hindu Kush Himalaya

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ABSTRACT

Hindu Kush Himalaya (HKH) is highly vulnerable to climate change, but there is the least understanding of the impacts of climate change. This study explored local climate change risk perceptions, vulnerability, and adaptive responses in the three HKH countries, Pakistan, Nepal, and Bhutan. For this purpose, 379 farm households from low, medium, and high elevations in the study districts of Rasuwa in Nepal, Gilgit in Pakistan and the Central District in Bhutan were surveyed. A semi-structured digital survey was used for data collection. Further, the study used the IPCC climate vulnerability framework to explore the farm-level vulnerability to climate change in three HKH countries. The study revealed that farmers in the study areas strongly agreed that the climate was changing in the region with high summer temperatures and increasing frequency and intensity of weather-related extreme events. Increasing poverty and limited institutional services make farmers more vulnerable to climate risks. Farmers reported reduced agricultural productivity and decreased revenue caused by climate change. Crop yields at high altitudes were slightly higher, but only because of multiple cropping triggered by weather patterns. Lack of information, resources, and institutional support significantly hamper the farmers' adaptive capacity. A small fraction of the farmers adopted improved crop varieties and land management. The study recommends improving outreach and institutional services, especially climate-specific farm advisory services in HKH countries.

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KEYWORDS

Climate smart agriculture, mountains, farm advisory, livelihood, adaptive capacity

HIGHLIGHTS

- Farmers expressed that climate change is hampering agriculture in the study areas.
- Multi-cropping at high altitudes slightly increased agricultural productivity.
- A small number of farmers were adapting through improved agricultural practices.

1. INTRODUCTION

The world is witnessing severe changes in climate in the form of increasing temperatures, uncertain rains, and increased intensity of extreme weather and climate-related events. The impacts of these changes have been increasingly overwhelming, particularly for developing countries with the least adaptive capacity to cope with the adverse effects of climate change (Abid, Scheffran, Schneider, & Elahi, 2019). Future projections suggest a more variable climate with high vulnerabilities in lower-income countries. With no exception, the Hindu Kush Himalayan region is among the areas experiencing rapid global warming. A recent ICIMOD report shows that even if the world can limit global temperature rise to 1.5 °C, warming in the HKH region will likely be between 0.3 °C–0.7 °C having deleterious impacts on mountainous ecosystems (Rana, Kaur, & Sharma, 2021).

The ongoing and projected changes in climate could trigger a multitude of biophysical and socioeconomic impacts in the form of increased glacial melting, biodiversity loss, and changes in river runoff with adverse effects on agriculture, hydropower, and water quality in some regions (IPCC, 2022). The high mountains supporting agricultural livelihoods for centuries are now at high risk due to climate change (Hussain et al., 2021). For instance, agricultural communities depend on adequate soil moisture levels at planting time, often relying on irrigation water from upstream glaciers and snowmelt water, which are now exposed to risk due to cryosphere changes (Mukherji, Sinisalo, Nüsser, Garrard, & Eriksson, 2019). The relative poverty in high-altitude farming regions contributes to their vulnerability to the impacts of these ongoing and future climate changes (Gioli et al., 2019).

Agriculture production in the Hindu Kush Himalayan region is overwhelmingly represented by small-scale monoculture or bi-culture subsistence farms. With increasing recognition of potential climate changes in the Himalayas high-altitude areas, scholars and policymakers are increasingly concerned about how these changes impact the local agricultural systems and what coping mechanisms are being adopted (Mishra et al., 2019). However, limited research on high-altitude farming regions regarding potential climatic changes makes it difficult to understand the exact picture. Further, most of the studies from high-altitude regions (e.g., Krishnan et al., 2019; Usman, Pugh, Ahlström, & Baig, 2021; Wester, Mishra, Mukherji, & Shrestha, 2019; Zahoor et al., 2021) use top-down approaches incorporating scenario-based analysis and future projects and often fail to cover the local socioeconomic dynamics and factors which define a certain adaptation and coping behaviour. The literature on local vulnerability to climate change available from high-altitude regions (e.g., Gupta et al., 2019; Pandey et al., 2018; Venus, Bilgram, Sauer, & Khatri-Chettri, 2022) suggests that increased variability and uncertainty in weather and climate have led to increased uncertainty in the region's agricultural production. This uncertainty in agricultural output often also negatively impacts local livelihoods, mainly tied to the subsistence agricultural system. However, individual farm-level impacts of these changes may affect the magnitude and variability of the stressors, the ability of the farmers to cope with the stressors, and the availability of information, resources, or tools that farmers may use to understand the resilience of their systems. Further, non-climate stimuli also impact farm-level adaptation decisions and make the decision-making process more complex, which may be further characterized by several political, economic, institutional, and biophysical factors (Abid, Schilling, Scheffran, & Zulfiqar, 2016). In addition to external conditions, internal factors such as personal characteristics, social behaviour, attitudes, farming practices, and individual circumstances may also define a particular individual farmer's response and adaptive capacity (Bryan et al., 2013).

To support farmers in adapting to climate change in high-altitude farming regions through innovative policy measures, an in-depth understanding of climate vulnerability, along with an understanding of local perceptions of climate change, related risks and their impact on local production systems, is needed. Further knowledge of current adaptation patterns and vulnerability aspects may also help to devise need-based policies and capacity modules for farmers and relevant institutional capacity measures. Considering this critical knowledge gap, this study aims to explore the research gaps through field data collection and empirical research to better understand the vulnerability of farming communities in the HKH region, focusing on Pakistan, Nepal and Bhutan. For data collection and further analysis, the study took the climate vulnerability framework of IPCC (2014) as a reference. Further, it follows the studies by Abid, Schilling et al. (2016) and Schilling, Freier, Hertig, and Scheffran (2012) for the selection of indicators exploring the vulnerability of farming communities, starting with the assessment of farm-level risks and associated adaptation behaviour of farmers. In the next step, we measure farmers' sensitivity to various perceived risks, followed by exploring farmers' adaptive capacity and various constraints and bottlenecks in adapting to climate change.

In the first step, this paper briefly synthesizes vital aspects of farm-level vulnerability and adaptation in HKK study countries to climate-related risks (1) and provides an overview of the vulnerability concept (2). This is followed by a methodology section (3) that includes the study framework, sample design, sampling and data collection, and description of study areas. In the next step, the study's findings are further divided into sub-sections per the study's objectives (4), followed by the conclusion and recommendations section (5).

2. FARM-LEVEL VULNERABILITY TO CLIMATE CHANGE

The vulnerability concept has its root in various disciplines, such as natural hazards, climate change, food security, and political ecology. Different meanings and interpretations are used to explain the concepts (Brooks, 2003; Smithers & Smit, 1997). For instance, biophysical vulnerability often focuses on the likeliness, magnitude, frequency, and extent of natural hazards (Belliveau, Smit, & Bradshaw, 2006; Turner et al., 2003). On the other hand, social vulnerability focuses more on socioeconomic and political factors while explaining the capacity of humans against related risks (Belliveau et al., 2006; Cutter, Boruff, & Shirley, 2003). Some studies (Downing et al., 2001; Kelly & Adger, 2000) linked access to various institutional services, resources, poverty, and food insecurity to social vulnerability.

However, in the climate change field, the vulnerability concept is considered an intersection of natural and social vulnerability, which combines both factors and may be defined, according to IPCC (2014), as *"the propensity or predisposition to be adversely affected. Vulnerability encompasses a variety of concepts and elements including sensitivity or susceptibility to harm and lack of capacity to cope and adapt"*. Here the vulnerability of any system considers the system's sensitivity and capacity while considering exposure more as part of the risk. It implies that a system's vulnerability increases with the sensitivity of the system to climate risks and simultaneously reduces adaptive capacity (Fellmann, 2012). This study uses the same approach to explore farmers' vulnerability in three HKH countries. Here, we defined climate change as observed changes in the local environment over the past twenty years or more in terms of extreme environmental events such as droughts, floods, and extremely high or low temperatures (Bryan et al., 2013). The degree to which a system (in our case, an agricultural system with a farm as a basic unit) is vulnerable to an environmental or climate stimulus is related to the system's capacity to be negatively affected and ability to cope with its adverse impacts (Abid, Schneider, & Scheffran, 2016). Here sensitivity of a system refers to the "degree to which system is affected or responds to an environmental stimulus and is related to characteristics of the system and to broader non-climatic factors, e.g., livelihood, infrastructure, and government policy" (Adger, 2006; Turner et al., 2003).

In the context of the study, we consider various kinds of climate-related risks, i.e., flood, drought, extreme temperature events, and extremely low or high temperatures, which may influence the productivity of agricultural lands and local livelihood in direct and indirect ways. Vulnerability to the identified risk may be reduced if farmers imply specific coping mechanisms at their farm to adapt to observed changes. (Bryant et al., 2000; Smit & Skinner, 2002; Wheaton & Maciver, 1999). Such ability and potential of a system to respond to potential threats or risks are called adaptive capacity. Adaptive capacity is usually considered a positive attribute of a system in reducing vulnerability (Engle, 2011). The more adaptive capacity a system has, the greater the chances it can cope with it and thus is less vulnerable to climate change (Bryant et al., 2000; Bryan et al., 2013; Gorst, Groom, & Dehlavi, 2015). Further, how farm managers (farmers) understand and perceive climate risks is very important because it may influence their short to long-term decisions in adopting certain practices and ways of managing their farms (Lebel, Whangchai, Chitmanat, Promya, & Lebel, 2015). Technological, financial, and information resources; institutions; social setup, and strong local interactions are some other factors that may influence farm-level adaptation decision-making processes (Bryant et al., 2000; Bryan et al., 2013; Gorst et al., 2015).

3. METHODOLOGY

Based on the data from the three HKH countries, this paper intends to analyze the vulnerability of farmers to climate-related risks, including exposure to climatic risks, their sensitivity and their adaptive capacity to cope with the negative impacts of climate change. The study uses qualitative and quantitative data collected through field surveys to facilitate a more profound understanding of the context. The study implies a bottom-up approach to investigate farmers' experiences with climate change and their responses in line with observed changes; therefore – what, how, when, and where questions were used in the study (Berg, 2004). Farm households were asked to share their experience of climate change and associated risks. Further, we included questions to specify the broad definition of sensitivity, focusing on its resource dimension, which covers the availability of affected resources (before the climate stimuli) and the significance of resources for communities which may help them to cope with the negative impacts of climate change. To explain it further, we collected information from farmers on the availability of essential resources us as water, inputs, poverty, and access to institutional services. Further constraints to adaptation were also investigated through farmer surveys.

The key hypothesis for the study is that the vulnerability to climate change may vary across regions as well, depending on the altitude. Further, the study also assumed that the vulnerability to climate change might be linked to various internal and external factors described by exposure, sensitivity and coping mechanism.

Figure 1 shows the flowchart of various steps adopted to analyze the climate risk vulnerability.

3.1. Study areas

The study conducted a field survey across three study sites in Pakistan, Nepal, and Bhutan. In Pakistan, the Gilgit district was selected as the study site, whereas the Rasuwa district in Nepal and the central district were chosen as the representative area from Bhutan.

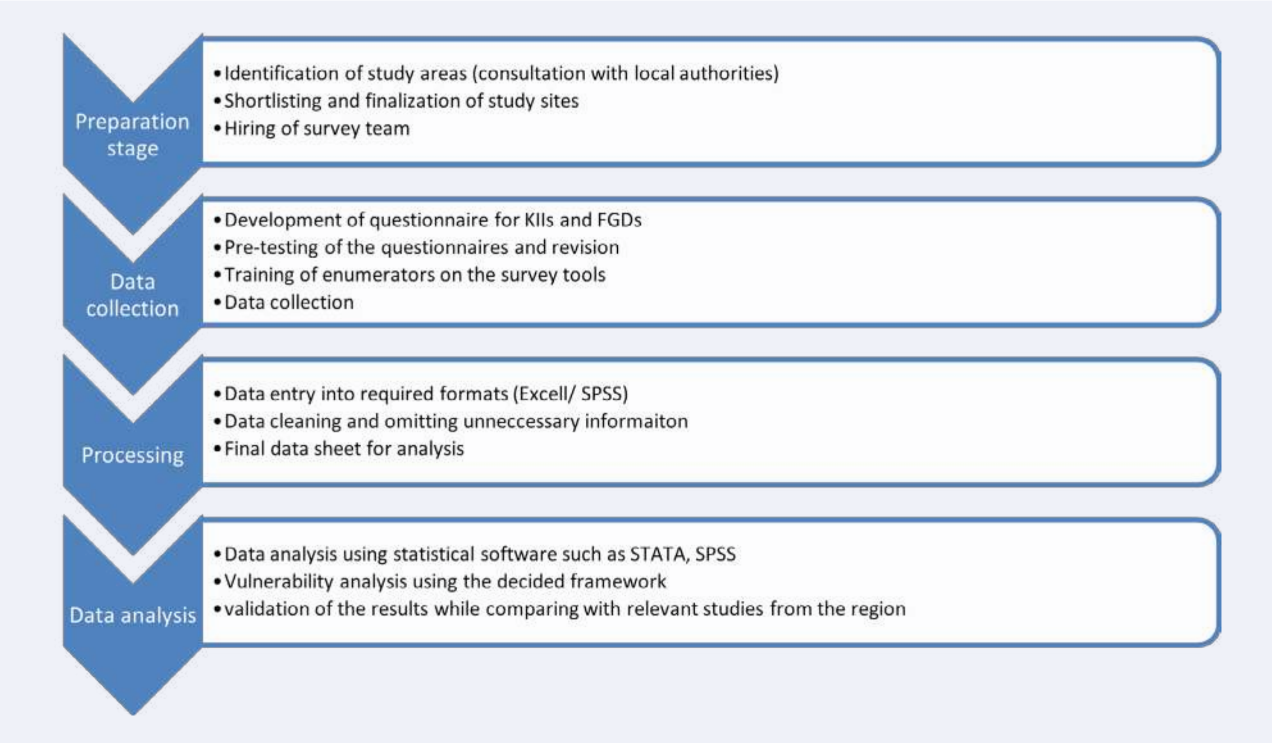

FIGURE 1. Methodology flowchart.

Gilgit is the part of Gilgit Baltistan (GB) province of Pakistan. Future projections show a 1.4 °C–3.7 °C increase in mean temperature in Pakistan by 2060 (higher than the expected global average), with the north, mainly GB, potentially experiencing higher temperatures than the country's south. Temperatures in Pakistan are also expected to rise more in winter than in summer. Precipitation change projections are less confident due to significant model uncertainties for the region. Changes in monsoons and rising temperatures will almost certainly pose substantial challenges to agriculture in the already climate change vulnerable north of the country. Climate variability and extreme events are estimated to cost US$ 270–360 million annually (in 2013), or 1.5 to 2% of the country's GDP.

Future climate projections for Nepal based on the averages of several Global Circulation Models (GCMs) indicate a continued increase in mean annual temperature, faster warming of the country's western regions (compared to the east), changes in precipitation during the monsoon season (with variations ranging from −14 to 40%), and an increased likelihood of heavy precipitation events. While there is considerable uncertainty in precipitation models, Nepal will most likely receive total rainfall in the future, particularly in the central and western regions. Changes in precipitation patterns are expected to impact rainfed agricultural activities, resulting in significant annual yield variability and increased production risks.

The monsoon influences Bhutan's climate, which is characterized by dry winters and high precipitation from June to September. Topography, elevation, and rainfall patterns all influence climate. Rain shadow effects caused by the country's mountainous terrain account for the significant variation in rainfall over a relatively short distance. Precipitation decreases significantly from south to north. Over the last few years, the country has seen rapid changes in average temperatures, precipitation patterns, and increased risks of climate hazards such as heavy rains, flash floods, windstorms, hailstorms, and droughts, resulting in massive losses and damage to farming households. Most farmers rely entirely on monsoons for irrigation. The delayed arrival of the monsoon can cause landslides and floods. Such weather events also put rural

	District			
	Pakistan (N = 126)	Nepal (N = 130)	Bhutan (N = 127)	Average (N = 363)
a. Adaptation practices adopted by farmers				
Change in cropping practices (e.g., alternative crops, new crop varieties, change in planting dates, Integrated pest management)	38	45	49	43
Change in management practices (change input mixes such as fertilizer, water)	30	25	30	36
Conservation practices (zero tillage, water saving, intercropping)	12	25	11	13
Livelihood options (crop diversification, migration to urban areas etc)	20	5	10	10
b. Number of adaptation measures implemented out of ten reported measures				
No adaptation	30	35	36	42
Adapted only one measure	37	59	40	42
Adapted any two measures	8	31	28	20
Adapted any three measures	18	9	12	15
Adapted any four measures	10	01	10	07
Adapted any five or above than five measures	37	00	10	17

TABLE 1. Adaptation practices adopted by farm households (%) across three study areas HKH countries.

communities at risk, as many are isolated due to inadequate or damaged infrastructure.

3.2. Data collection

The study uses a multi-stage sampling technique to select sample respondents. In the first stage, In Pakistan, the Gilgit district was chosen as the study site, whereas the Rasuwa district in Nepal and the central district were selected as the representative area from Bhutan, considering local climate, geography, demography, and cropping patterns. Since biophysical conditions vary with altitude, the second stage involves randomly selecting three villages from each study area's lower (valley), middle and upper elevations of the selected study sites. The third stage involves selecting 40 farmers from each village and 120 from each study area using a stratified random sampling method. This made the overall sample size 364.

Further, nine FGDs (three in each area) were conducted (see Table 1 for summary statistics). The key participants of the FGDs were the local farmers and heads of the farm households. It is important to mention that in Pakistan, women's participation in the data collection was limited due to local customs and their lack of decision-making power. However, in Nepal and, to some extent, in Bhutan as well, the situation was the opposite, where more women than men participated in the FGDs. Moreover, the study conducted 20 key-informant interviews with identified stakeholders, including community leaders and key government officials in each area dealing with the agriculture sector. For data collection, a standard protocol was followed where first we developed standardized questionnaires for each type of data collection, i.e., FGDs, KIIs and household surveys and then pre-tested those questionnaires in the field to avoid missing important information. To ensure uniformity in collecting field data, the project team also conducted a short training for field researchers in Nepal, Bhutan, and Pakistan. A list of key indicators and sub-indicators was developed for survey design and questionnaire construction. The farm household survey includes questions on household characteristics, farming, climate-related risks, effects, adaptation and constraints to adaptation to climate-related risks.

3.3. Data analysis

To analyze the data on farm-level vulnerability to climate change, we followed the IPCC vulnerability framework and used a conceptual comparative analysis as proposed by Schilling et al. (2012) and Abid, Schneider et al. (2016) to explore various elements of vulnerability (exposure, effects and adaptative capacity). Under this framework, we used simple statistical analysis to discuss the current state of various indicators of vulnerability and their relevance to the local context. Under the exposure section of the vulnerability, we explored how climate is evolving in three case study regions and how local agricultural communities perceive these changes. In the next steps, we explored how climate change is impacting local agricultural communities. Then, we explored the sensitivity and factors that affect agricultural households' sensitivity to climate change. At the end, we explored how farmers are adapting to climate change and what constraints they are facing while implementing adaptation at the local level.

4. RESULTS AND DISCUSSION

The study's findings start with analyzing farm-level perceptions of climate change and related risks to agricultural productivity and livelihood in three HKH countries (4.1). The analysis then proceeds to explore the different aspects of vulnerability, including farm-level sensitivity to climate-related risks and their impact at the farm level, adaptation practices, and the role of factors affecting the adaptive capacity of farmers' adaptive ability including constraints to adaptation and finally a synthesis of results (5).

4.1. Farm-level vulnerability in the HKH region

4.1.1. Exposure to climate change

This section focuses on the most important climate variables, temperature and precipitation and related factors in the agriculture sector in Hindu Kush Himalaya with a particular focus on Pakistan, Nepal and Bhutan.

To fully capture the situation, first, we collected information on local perceptions regarding over-time changes in the key climatic parameters in three study countries and tried to tally it with the climate data using a literature review.

Field research in three study areas reveals important information on how the region's climate is evolving and how much farmers are observing those changes. The distribution of farm-level perceptions regarding overtime change in climate-related parameters and related risks are summarized in Figure 2. Regarding changes in winter temperature, there is an agreement between farmers in Nepal and Bhutan that the winter temperature is increasing; on the contrary, a vast majority of the farmers in Pakistan (>50%) observed winter temperature decreasing. However, more than 60% of farmers in all three study sites believed there had been a significant increase in summer temperature over the past 20 to 30 years. In case of changes in precipitation patterns, farmers' perceptions were divided. For instance, more than half of the farmers in Nepal perceived winter precipitation as increasing. Still, on the other hand, around 40% of farmers from Nepal perceive winter rainfall as decreasing. The same is the case with Pakistan. However, in the case of Bhutan, more than 40% of the farmers did not observe any significant changes in winter rainfall patterns. Concerning changes in summer rainfall, most farmers in all three study sites observed a substantial increase in summer rainfall, except in Pakistan, where most farmers perceive a decline in summer rainfall. As demonstrated by other scientific studies (e.g., Abid et al., 2019; Budhathoki & Zander, 2020), a significant variation in farm-level responses in perceiving rainfall patterns may be explained by uncertainty in the overall precipitation patterns in the Hindu Kush Himalaya region.

While responding to additional questions on growing season length, most farmers in the three study countries agreed that growing season length has increased over time. The same is the case with

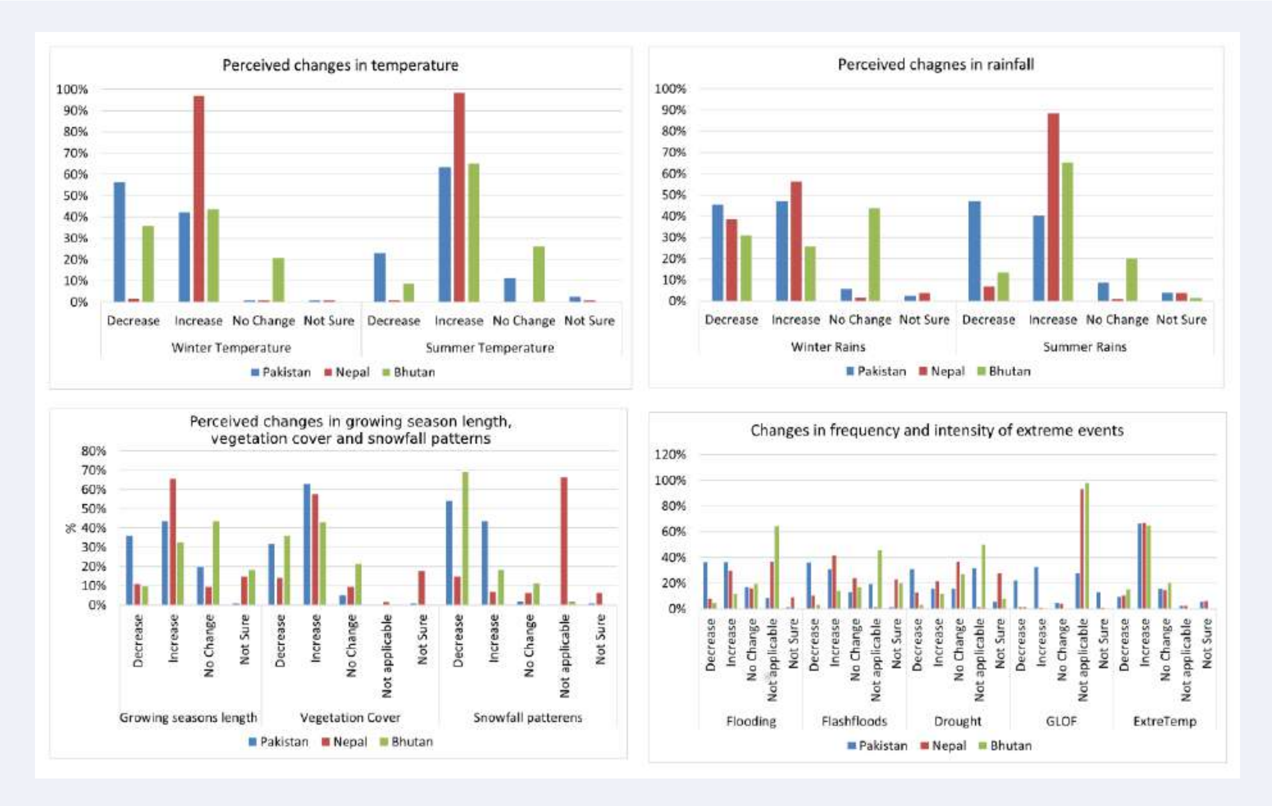

FIGURE 2. Climate risk perceptions in the HKH countries.

vegetation cover, where most farmers see it as a positive impact of changes in climate conditions that led to more vegetation and allow farmers to shift their farming from monoculture farming to a bi-culture farming system in many cases. In the next step, we explored farmers' perceptions of changes in extreme events. The key extreme events perceived by farmers include flooding, flash flooding, extreme temperatures and drought. These findings extend nuanced findings from previous work in the HKH region (Baylis & Githeko, 2006; Hussain, 2015; Younas, Ishaq, & Ali, 2012), which identified an increase in the extent and occurrence of climate-related events.

Effect of climate-related risks

This section summarizes the effects of climate-related risks at the farm level explored through field research conducted in three study areas. Overall, farmers in HKH countries are facing three types of impacts from changes in climate, namely, direct effects, indirect effects, and adaptation costs. Direct effects include impacts on crop production, livestock production, and risk of natural hazards. On the other hand, indirect effects include socioeconomic consequences from climate change at the farm level. Further, the adaptation cost incurred to minimize the negative impacts of climate change is an additional expense that farmers have to bear in addition to regular production activities. In Figure 3, we explored farmer responses to the potential impacts of climate change at the local level in three countries. As shown in Figure 3, most farmers were concerned about increased climate-induced diseases for humans and livestock, followed by damages to physical assets due to the increased severity of extreme events.

Further, we received mixed responses on the impacts of climatic changes and related risks on crop and livestock productivity. For instance, farmers in high-altitude regions benefit from increased summer and winter temperatures as they can grow more crops and hence see an increase in their productivity of crops and livestock production due to more grazing available for their livestock. On the other hand, farmers located at the tail of the

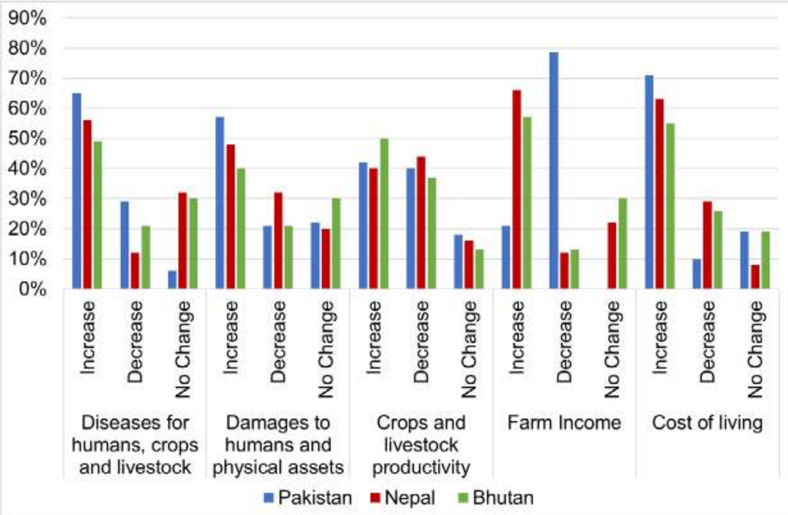

FIGURE 3. Farmer responses to potential impacts of climate change at the local level in three countries.

mountains observed climate changes negatively impacting the productivity of their crops and livestock. The same is the case with changes in farm income, where farmers in high-altitude regions of Nepal and Bhutan see an overall increase in their income. However, most farmers in Pakistan perceive a decrease in their farm income due to the rise in production costs because of climate change. The study results follow the findings of other studies in the region. For instance, Baig and Amjad (2014), and Tingju et al. (2014) have indicated a considerable decline and inconsistency in the yields of major crops such as wheat, maize, rice, sugarcane, and cotton in Pakistan due to climate-related extreme events.

4.1.2. Sensitivity

Sensitivity to climate change and climate-related risks explains how a system is affected by climate stimuli. Here, we focus on the resource dimension of sensitivity as suggested by Barnett and Adger (2007) and therefore explore the status of resources at the local level in HKH countries, first by discussing the effect of observed climate-related risks at the farm level to show how farm households are being affected by climate change. It is followed by exploring several factors, i.e., such as availability of water, the status of poverty, and the role of locals in describing the farm-level sensitivity to climate change.

Factors affecting sensitivity at the farm-level

Water is one of the essential resources for agriculture at the farm level, whose non-availability may increase the impact of climate-related shocks. For instance, despite being close to the river, farmers in Gilgit (a study area in Pakistan) often rely on water from streams and use it through community-led water channels. Similarly, farmers in Bhutan and Nepal face water availability fluctuations due to climate changes. Uncertainty in water availability puts agriculture and the livelihood of rural agricultural households in HKH countries at risk.

Poverty is widespread across the HKH region due to limited access to economic resources and heavy reliance on natural resources and hence may define the sensitivity of farming communities to potential climate-related risks or threats. According to an estimate, about one-third of HKH countries' population lives under the poverty line. Lack of resources and limited income may restrict farmers from adapting their agriculture to the negative impacts of climate change.

Livelihoods in the HKH region are mainly dependent on natural resources and subsistence agriculture, characterized by low yields due to limited

Study country	FGDs	Total Participants	Gender		Average age
			Male	Female	
Pakistan	FGD1	25	20	5	34.40
	FGD2	29	21	8	40.33
	FGD3	35	30	5	41.11
Nepal	FGD1	24	7	17	36.51
	FGD2	21	5	16	38.67
	FGD3	26	8	18	37.10
Bhutan	FGD1	28	16	12	39.09
	FGD2	23	13	10	37.04
	FGD3	22	14	8	35.69

TABLE 2. Summary statistics for participants of the Focus Group Discussions (FGDs).

access to productive resources and finance. Due to a high level of rural poverty and associated limited access to farm resources, crop yields in our study regions were far below potential. Further, poor households usually do not have access to improved seeds, advanced technologies, and other inputs that can reduce the vulnerability of crops to climate-related risks. Poor and small farmers thus have little capacity to absorb climate-induced crop or livestock income shocks and recover. A slight income loss may be devastating and set off a ratchet effect that leads to further poverty and future vulnerability due to a lack of limited assets and the absence of economic and social safety nets.

4.1.3. Adaptation to climate change

While farm households are exposed to various climate-related risks, the degree of their vulnerability depends on their ability to adapt to those risks. Farm households who adapt timely to risks may be less vulnerable or more profitable than farm households who adapt lately or do not adapt. Distinguishing between adaptation to climate-related risks and adaptation to other risks is challenging. However, when farm households were asked about risks, the households were able to distinguish between measures to manage climate-related risks and other risks.

Adaptation measures

Table 2 shows the adaptation measures taken in response to various observed climate-related risks by farm households. We here divided the adaptation options into four main categories; (1) Change in cropping practices (e.g., alternative crops, new crop varieties, change in planting dates, Integrated pest management); (2) Change in management practices (change input mixes such as fertilizer, water; (3) Conservation practices (zero tillage, water saving, intercropping) and Livelihood options (crop diversification, migration to urban areas, etc.).

Changing cropping practices, which were implemented by farm households at the farm level, may be short-term or long-term, depending on the nature of the risk. Specifically, changing crop variety was employed by farmers in response to more crop pest attacks on old varieties or to an extreme maximum temperature which were negatively affecting the growth of old varieties. Similarly, farmers in Bhutan reported more use of heat-tolerant wheat varieties in response to an increase in the frequency of extreme maximum temperature events. Changing crop types were adopted by farmers against incidents of heavy pest and insect attacks, soil problems, and extreme temperature events. For instance, in Nepal, many farmers reported replacing maize with rice due to its exposure to heavy pest attacks due to changing weather conditions. The measure of changing planting dates was adopted by farm households in response to variability in daily weather conditions.

Changing farm management practices include changing fertilizer and pesticide, irrigation, and changing farming techniques implemented at the farm level by farm households. For instance, in case of drought or extreme maximum temperature, farmers reported using more irrigation for their crops, especially at the sowing stage. In case of more crop pests due to heavy rainfall in the monsoon season, farm households reported increased use of pesticides to protect their crops from pests. Similarly, farmers who reported soil problems as well used micronutrients or changing combinations of different fertilizers to maintain soil fertility. The increased irrigation adaptation measure was mainly used by farmers in Gilgit, who reported a decrease in overall rainfall over time. Farmers also complained about increased hot and dry days and their negative impacts on crop growth. Changing farming techniques were implemented by farmers to prevent their crops from different weeds and soil issues such as salinity.

Advanced land management measures were also adopted at the farm level to cope with livelihoods against different climate-related risks. Farmers who reported an increase in the frequency of extreme temperatures often found conserving their land through soil and water conservation measures and involved in intercropping and diversifying their cropping patterns. For instance, farmers in Gilgit reported more use of organic matter (farmyard manure) as a soil conservation technique to preserve soil quality. Some farmers also used intercropping as an adaptation measure in Nepal and Bhutan to protect crops from increased temperature and reduce the damage to crop growth from increasing temperature.

Changing livelihood options was another adaptation mechanism adopted by farmers across study areas to minimize the risks from climate-related risks. For instance, farm households in Nepal reported increased migration to urban areas or abroad due to losses in agricultural production due to changing climatic conditions and reduction in farm margins. Similarly, few farm households diversified their farms by increasing the number of animals, having more crops under cultivation instead of one or few crops due to the loss of a single crop by extreme climatic events such as sudden rainfalls or floods and drought. Primarily farm diversification was implemented by farm households in Pakistan.

The results also showed that most households in all three study countries preferred changing cropping practices as key adaptation options followed by changing farm management practices etc., at their farms, keeping in view the nature of the problem and their capacity. A small number of farm households adopted advanced land use management options such as soil conservation and plantation of trees. Results also demonstrate that a minimal number of farmers in the study districts adopted different livelihood options as an adaptation measure to climate variability and related risks. Table 2b shows the frequency of adaptation practices applied in three study areas in the HKH region. Results revealed that most of the farmers in the study areas were restricted to only one or a few adaptation options. The study findings stand at par with other studies conducted in the region.

Constraints to adaptation

The study identified the following key constraints that restrict farmers from effectively implementing adaptation practices at the farm level: (1) lack of farm resources, (2) limited financial capacity, (3) information and knowledge gaps, and (4) poor advisory services (Figure 4).

The first constraint is related to the limited availability of the resources required to implement farm-level adaptation practices. One of the main reasons behind limited access to resources for farming is the geography and topography of the Himalayan agricultural system, making farming a challenging job in the HKH region. Farmers had to struggle to manage water and other inputs for their agriculture. In the last few years, climate changes have badly impacted the water supply to

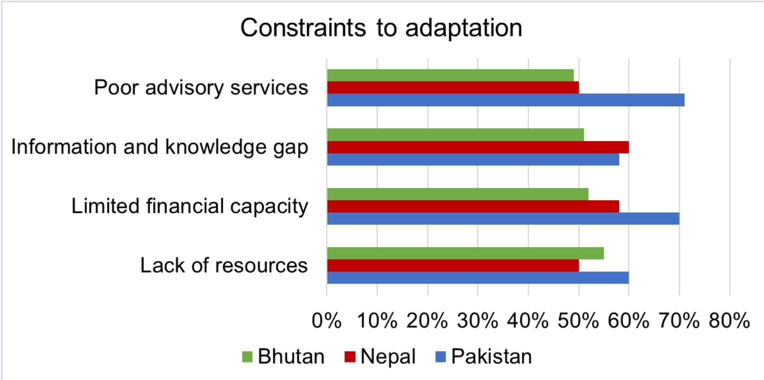

FIGURE 4. Key constraints that restrict farmers from effectively implementing adaptation practices at farm level.

high-altitude farming regions due to considerable fluctuations in water availability, followed by damages to water channels caused by flash flooding and heavy rains in parts of HKH.

The second major constraint that limits farmers' adaptive capacity is their limited financial capacity which is again linked to their subsistence agriculture and heavy reliance on natural resources. Being in high altitudes, farmers often complain about limited access to formal financial systems. Even if services are available, farmers often do not have the collateral required to take credit for agricultural purposes. In some cases, misuse of agricultural credit is also reported when farmers do not have access to non-agricultural credit.

The third constraint to adaptation is the information and knowledge gap, which restrict farmers from accessing relevant information on best management practices and climate change. Here farmers also reported a lack of a proper early warning system, which is very important to protect livelihoods from potential natural disasters such as flooding or heavy rains. Another critical constraint restricting farmers from adapting to climate change is the poor advisory service network. In many cases, farmers report little to no contact with the agricultural extension department and often rely on their informal contacts to get advice on issues related to agricultural production. According to the results presented in Figure 5, only one-third of the farmers have access to proper advisory services in Pakistan. In Nepal, the extension system is well developed, and more than half of the survey farmers have access to advisory services available through public and private sources. In Bhutan, about 40% of the farmers have access to extension services.

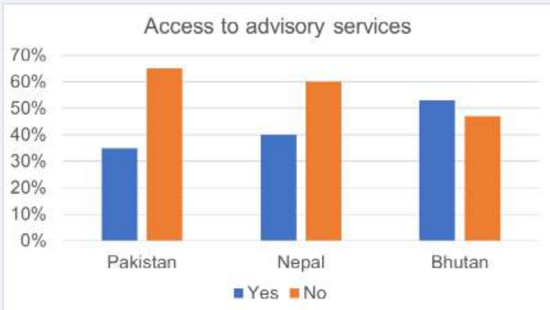

FIGURE 5. Access to advisory services.

5. CONCLUSION AND RECOMMENDATIONS

This study provides an overview of climate-related risks faced by farmers in three HKH countries, followed by exploring the sensitivity and adaptive responses to identified risks. Further, we also discuss constraints limiting farmers' adaptive capacity to cope with the negative impacts of climate change in high-altitude farming regions. The perception of changes in climate and the occurrence of extreme events vary across three study regions, which are in line with the past and projected changes in the climate as per scientific findings. For instance, farm-level observations on the overall increase in summer and winter temperature agreed with the latest IPCC 6th Assessment Report. The same is the case with overtime changes in the precipitation trends, where mixed responses were reported. Regional climate modelling studies also explain the same uncertainty.

While exploring the sensitivity aspect of climate vulnerability, we investigated how farmers link climate changes and the occurrence of various extreme events with changes in their livelihood or agricultural productivity. Most farmers in the three study regions agreed that climate changes directly or indirectly impact their livelihood through fluctuations and decrease in crop and livestock yields, changing cropping calendars, reducing farm margins due to reduced productivity, and increase in input cost on account of climate impacts. The study also found variations across three study areas regarding the impact of climate-related risks. For example, farmers in Pakistan reported more uncertainty and reduction in crop and livestock yields and change in farm income compared to the other two regions. This study also found that challenges of decreasing or uncertain water availability, poverty, and lack of access to institutional services in adaptation make farm households more sensitive to climate-related risks.

Key adaptive measures reported by farmers include changes in crop type, crop varieties, and sowing dates, followed by implementing land management practices. On the other hand, farmers also identified a lack of resources, limited financial resources, and a lack of institutional services as crucial constraints to adaptation in KHK countries. Further, limited marketing services and access to weather forecasting and information were other factors in adapting farming to climate change. Based on the study findings, we recommend improving the outreach and extending institutional services related to climate adaptation so that farmers may have better access to information on climate risks and coping measures.

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Review

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Formation mechanism and source apportionment of nitrate in atmospheric aerosols

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ABSTRACT

Atmospheric particulate nitrate is relevant to various atmospheric processes and shows profound impacts on regional air quality and global climate change. Exploring the formation mechanism and sources of nitrate in atmospheric particulate matter is essential for the successful mitigation of nitrate. This review summarises the different formation mechanisms, sources, and source apportionment methods of nitrate. In particular, the current progress of the nitrogen/oxygen (N/O) isotope technique coupled with the Bayesian isotopic mixing model (MixSIAR) is fully depicted. The limitations of the current source apportionment methods are also presented and the promising direction for the source apportionment of nitrate is proposed. As such, this review provides a thorough understanding of nitrate formation mechanisms and sources, which is particularly helpful for mitigating nitrate pollution in polluted cities such as those in East Asia.

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KEYWORDS

Source apportionment, formation mechanism, isotope, MixSIAR, PMF

HIGHLIGHTS

- Detailed formation mechanisms of atmospheric nitrate are presented.
- The application of the N/O isotope technique in source apportionment is reviewed.
- The isotope method is compared with the PMF method to reach a promising direction.

1. INTRODUCTION

Nitrate (NO_3^-) in atmospheric aerosols is closely related to atmospheric environmental problems. Particulate NO_3^- can scatter sunlight radiation and pose direct radiative forcing on the radiation system of the earth's surface. Being an important hygroscopic component of fine particulate matter, NO_3^- can also act as cloud condensation nuclei and indirectly affect the radiation budget of the earth-atmosphere system. Increasing the mass percentage of particulate NO_3^- in $PM_{2.5}$ can increase the hygroscopicity of $PM_{2.5}$, which consequently increases the light extinction coefficients of $PM_{2.5}$ and reduces atmospheric visibility. Given the same mass concentration of $PM_{2.5}$, the atmospheric visibility is decreased with the increase of the mass percentage of NO_3^- in $PM_{2.5}$ when $PM_{2.5} > 20$ μg m^{-3} (Hu et al., 2021). Moreover, the condensation of nitric acid and ammonium can produce ammonium nitrate nanoparticles, which is an important process during the new particle formation event in urban areas, particularly in winter (Wang et al., 2020). The same process also plays an important role in the new particle formation in the free troposphere, where the presence of water vapour facilitates the fast-growing of ammonium nitrate nanoparticles.

HNO_3 was perceived as the permanent sink of NO_x (NO and NO_2). However, the reverse oxidation cycle of HNO_3 has been proven to be able to produce NO_x (Wang, Zhang, Nenes, & Fountoukis, 2012; Kumar et al., 2014). According to the laboratory results of Ye et al. (2016), the photolysis rate of particulate NO_3^- into NO_x was two orders of magnitude higher than the photolysis rate of gaseous NO_3^-. Under typical marine atmospheric boundary layer conditions, the reverse oxidation cycle of HNO_3 maintains the observed levels of HONO and NO_x during noon time. As over 70% of the earth is covered by the sea, the photolysis of particulate NO_3^- could be an important source of NO_x in the troposphere. The photolysis of NO_3^- can not only affect the oxidation capacity of the atmospheric boundary layer in the polar, marine, and terrestrial areas (Domine & Shepson, 2002; Ye et al., 2016), but also impact the NO_x and •OH budgets in the remote atmosphere (Shi et al., 2021) and promote the formation of SO_4^{2-} (Xue et al., 2019; Zheng et al., 2020). In addition, the photolysis of NO_3^- in the water film of atmospheric particulate matter or atmospheric hydrometeors can produce reactive oxygen species and reactive nitrogen species, which contributes to the photooxidation of atmospheric organic compounds and subsequently the formation of brown carbon (BrC) (Yang, Au, Law, Lam, & Nah, 2021). For example, in the presence of inorganic nitrate, guaiacol and 5-nitroguaiacol, which are two typical phenolic compounds, can quickly react under irradiation to form BrC, and the reaction rate and yield of BrC are dependent on the initial concentration of inorganic nitrate (Yang et al., 2021).

Regarding the significant role of nitrate in the atmospheric environment and the related environmental impact, as shown in Figure 1, it is, therefore, important to understand the formation mechanism and sources of atmospheric nitrate. This review summarises the different formation mechanisms, sources, and source apportionment methods of nitrate. In particular, the current progress of the

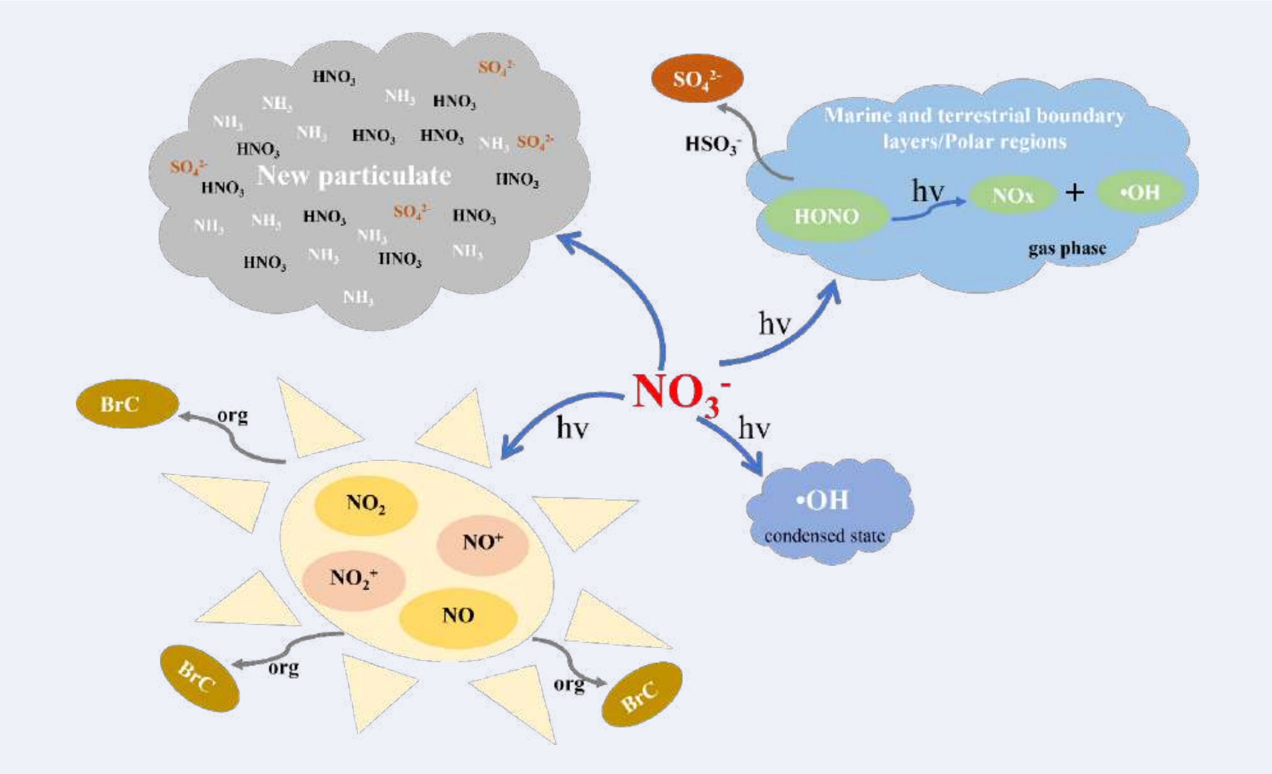

FIGURE 1. Environmental processes and impacts of atmospheric nitrate.

nitrogen/oxygen (N/O) isotope technique coupled with the Bayesian isotopic mixing model (MixSIAR) is fully depicted. As such, this review would be helpful for mitigating nitrate pollution in polluted cities such as those in East Asia.

2. FORMATION MECHANISM OF NITRATE

NO_x is the major precursor of atmospheric nitrate. Once emitted into the atmosphere, NO can be quickly oxidised into NO_2 by atmospheric oxidants such as O_3, HO_2•, RO_2•, and halogen oxides (XO, X representing Br, Cl, and I), as demonstrated by the Chemical Equation (R1). Meanwhile, NO_2 can also photolyze at $\lambda < 398$ nm to form NO + O during the day. The conversion rate of NO_x between NO and NO_2 during the day is several orders of magnitude higher than the oxidation rate of NO_x to form NO_3^- (Michalski, Scott, Kabiling, & Thiemens, 2003).

As shown in the chemical equations, the major oxidation pathways from NO_x to NO_3^- include the oxidation by •OH (R2) during the day and hydrolysis of N_2O_5 (R3–R4) at night (Alexander et al., 2009). According to the reactive halogen chemistry simulated using tropospheric chemical models, inorganic nitrate produced through the hydrolysis of halogen nitrate (XNO_3, X representing Br, Cl, and I) (R5) is also an important sink of NO_x, which can further affect the formation of tropospheric O_3, •OH, reactive halogen, and aerosols (von Glasow & Crutzen, 2004; Yang et al., 2005; Parrella et al., 2012; Saiz-Lopez et al., 2012; Long et al., 2014; Schmidt et al., 2016; Sherwen et al., 2016). Other formation pathways of inorganic nitrate include the heterogeneous uptake of NO_2 and NO_3 (R6), reaction between NO_3 radical and hydrocarbons (HC) or dimethyl sulfide (DMS) (R7), hydrolysis of organic nitrate (R8–R9), direct oxidation of NO by HO_2• (R10) and heterogeneous reaction between N_2O_5 and particulate Cl^- (R11) (Atkinson, 2000). The two major oxidation pathways from NO_x to NO_3^-, i.e., oxidation by •OH and hydrolysis of N_2O_5, contribute equally to the formation of NO_3^- globally in the lower atmosphere with altitude <1 km, while the total contribution of other formation pathways of NO_3^- is generally less than 6% globally (Alexander et al., 2020). However, exceptions could occur in particular regions during a particular time. For example, Luo et al. (2020) found that the formation pathways of NO_3^- via N_2O_5 + H_2O/Cl^-, NO_3 + VOCs, and $ClNO_3$ + H_2O contributed around 53%–89% to NO_3^- formation during the severely polluted period in Beijing, but •OH + NO_2 was the dominant formation pathway of NO_3^- during the non-polluted period with the contribution of 37%–69% to NO_3^- formation.

The partition between gaseous HNO_3 and particulate NO_3^- depends on the abundance of aerosols, aerosol water content and chemical composition, and temperature. The inorganic nitrate returns to the earth's surface through dry and wet deposition, and the life cycle for deposition is around 3–4 days (Park, Jacob, Field, Yantosca & Chin, 2004).

$$NO + O_3/HO_2/RO_2/XO \rightarrow NO_2 \quad (R1)^*$$

$$NO_2 + {\bullet}OH \rightarrow HNO_3 \quad (R2)$$

$$NO_2 + O_3 \rightarrow NO_3 \quad (R3)$$

$$NO_3 + NO_2 \rightarrow N_2O_5 \xrightarrow{\text{hydrolyse}} HNO_3 \quad (R4)$$

$$NO_2 + XO \rightarrow XNO_3 \xrightarrow{\text{hydrolyse}} HNO_3 \quad (R5)^*$$

$$NO_2 + H_2O \rightarrow HNO_3 \quad (R6)$$

$$NO_3 + HC/DMS \rightarrow HNO_3 \quad (R7)$$

$$NO_3 + BVOCs \rightarrow RONO_2 \xrightarrow{\text{hydrolyse}} HNO_3 \quad (R8)$$

$$NO + RO_2 \rightarrow RONO_2 \xrightarrow{\text{hydrolyse}} HNO_3 \quad (R9)$$

$$NO + HO_2 \rightarrow HNO_3 \quad (R10)$$

$$N_2O_5 + Cl^- \xrightarrow{\text{aerosol}} HNO_3 \quad (R11)$$

* In Reactions 1 and 5, XO represents halogen oxides, with X representing Br, Cl, and I.

3. SOURCE APPORTIONMENT OF NITRATE

3.1. Sources of nitrate

Nitrate is dominantly formed by the gaseous precursor NO_x through secondary reactions in the atmosphere. Therefore, the sources of nitrate are virtually the sources of NO_x, except that some emission sources, such as the ammonium nitrate fertiliser plants, can also release nitrate into the atmosphere directly.

Anthropogenic emission sources such as fossil fuel combustion, biofuel combustion and agricultural fertilisation are the major sources of NO_x in the atmosphere (Jaegle, Steuberger, Martin, & Chance, 2005). The anthropogenic emissions of NO_x varied with time historically. At the end of the 20th century, fossil fuel combustion took 95% of the total NO_x emission globally (Anenberg et al., 2017), with 90% in Europe (Sutton et al., 2011), 88% in East Asia (Ohara et al., 2007), and 96% in North America (Air Pollutants Emissions Inventory, 2023), respectively. However, the contribution of non-fossil fuel sources to NO_x emission has greatly increased in recent years. According to the work of Song et al. (2021), non-fossil fuel sources took over 50% of the total NO_x emission globally; the annual emission of NO_x from non-fossil fuel sources was 21.6 ± 16.6 Mt in East Asia, 7.4 ± 5.5 Mt in Europe, and 21.8 ± 18.5 Mt in North America, respectively. The anthropogenic emissions of NO_x also show great spatial variability globally. Vehicular emission used to be the major source of NO_x in developed countries in North America and Europe. However, with the implementation of control measures targeting stationary and mobile emission sources, non-fossil fuel sources have shown an increased contribution to NO_x. The soil-related sources, such as agricultural land, forest, and animal manure emissions, now contribute highly to NO_x in developed countries (Almaraz et al., 2018; Guo et al., 2020; Skiba et al., 2021). In comparison, in many developing countries, fossil fuel combustion remains the major source of NO_x due to the growing urbanisation and industrialisation processes. For example, the energy and industry sectors were India's dominant source of NO_x, followed by vehicular emission (Garg, Bhattacharya, Shukla, & Dadhwal, 2001). Similarly, the mobile source took 46.1% of total NO_x emission in Tehran, Iran (Shahbazi, Hassani, & Hosseini, 2019), and the roadside NO_x emission flux could reach as high as (36.46 ± 12.86) × 10^{24} molec./s in Beijing, China (Huang et al., 2020).

Because atmospheric nitrate is dominantly formed through the reactions of NO_x, the sources of nitrate show similar spatial and temporal variability to NO_x. However, the formation mechanism of nitrate is complicated, and some primary sources also contribute to nitrate in the atmosphere.

Therefore, it may not be completely effective to control atmospheric nitrate pollution by merely understanding the sources of NO_x. A recent study conducted in the North China Plain showed that with a considerable reduction of NO_x by 31.8% in 2010–2017, the atmospheric surface concentration of NO_3^- only decreased by 0.2% (Fu et al., 2020). A thorough understanding of the sources and formation mechanisms of nitrate is essential for the successful mitigation of nitrate.

3.2. Source apportionment of nitrate based on isotope analysis

Since nitrate is dominantly formed in the atmosphere, it is difficult to apply the common source apportionment methods of atmospheric aerosols, such as emission inventories, receptor models, and source diffusion models, to identify nitrate sources and formation mechanisms in the atmosphere. Particularly, the nitrogen/oxygen (N/O) isotope technique coupled with the Bayesian isotopic mixing model (MixSIAR) is a powerful tool to trace nitrate aerosols' sources and formation pathways. The isotope technique was first developed in the 1950s and used to apportion the sources of nitrate in rainwater (Eriksson, 1959; Freyer, 1978; Freyer, 1991). Later, with the aggravation of air pollution worldwide, the isotope technique was applied to apportion the sources of nitrate in TSP, PM_{10}, and $PM_{2.5}$ (Widory, 2007; Zong et al., 2017; Lin et al., 2021). With the establishment of the N/O isotopic composition data pool of different sources and the development of source apportionment models, the nitrogen/oxygen (N/O) isotope technique has now been widely used to trace the sources of NO_3^-/NO_x in the atmosphere (Song et al., 2019; Zong et al., 2020a; Lin et al., 2021).

The nitrogen stable-isotope composition of nitrate ($\delta^{15}N-NO_3^-$) is influenced by the sources of NO_x and shows spatial and temporal variability due to the impact of different human activities (Felix et al., 2012; Felix & Elliott, 2014; Walters, Goodwin, & Michalski, 2015; Fibiger & Hastings, 2016; Zong et al., 2020b). The $\delta^{15}N-NO_3^-$ technique has been well extended with the continuous investigation of the nitrogen isotopic compositions of NO_x. Felix et al. measured $\delta^{15}N-NO_x$ of coal-fired power plant (Felix, Elliott, & Shaw, 2012) and that of NO_x emitted from soil and animal manure (Felix & Elliott, 2014), finding that the $\delta^{15}N-NO_x$ value of coal-fired power plant was higher than that of NO_x from other emission sources. Walters and Michalski (2015) measured $\delta^{15}N-NO_x$ of gasoline and diesel vehicles and found negative correlations between $\delta^{15}N-NO_x$ and the NO_x concentration as well as the vehicle running time. Miller et al. (2018) revealed a significant difference of $\delta^{15}N-NO_x$ in the agricultural land applied with different fertilisers, which was affected by nitrification and NO consumption. In general, the $\delta^{15}N-NO_x$ value of NO_x from coal combustion is higher than that from vehicular or soil emissions.

The nitrogen isotope fractionation is related to the oxygen isotope fractionation during the reaction of NO_x to form NO_3^-. Therefore, the measurement of oxygen isotope can be used to evaluate the nitrogen isotope fractionation effect (Walters & Michalski, 2015, 2016). Generally, the oxygen stable-isotope composition of nitrate ($\delta^{18}O-NO_3^-$) is dependent on the contributions of different reaction pathways to NO_3^- formation. Thus the stable oxygen isotope is a powerful tool to efficiently evaluate the contributions of different formation mechanisms of nitrate. According to the current research findings, the formation of NO_3^- is highly affected by the gaseous oxidation of NO_x by •OH during the day and hydrolysis of N_2O_5 at night (Alexander et al., 2009). Besides, the reaction of NO_3 + HC/DMS may also contribute highly to NO_3^- formation under heavy pollution conditions. According to the work of Hastings, Sigman, and Lipschultz (2003), for NO_3^- formed during the reaction of •OH + NO_2, 2/3 of $\delta^{18}O-NO_3^-$ comes from NO_x and 1/3 of $\delta^{18}O-NO_3^-$ comes from •OH; meanwhile, for NO_3^- formed during the hydrolysis of N_2O_5, 5/6 of $\delta^{18}O-NO_3^-$ comes from O_3 and 1/6 of $\delta^{18}O-NO_3^-$ comes from H_2O. Generally, higher $\delta^{18}O-NO_3^-$ is associated with O_3 (+90‰–+122‰ $\delta^{18}O$) oxidation, while lower $\delta^{18}O-NO_3^-$ is associated with •OH (-25‰–0‰ $\delta^{18}O$) oxidation (He et al., 2018; Wu et al., 2021; Zhang et al., 2021). Zong et al. (2020b) measured $\delta^{18}O-NO_3^-$

in five megacities in China in 2013–2014 and observed significant seasonal variation of $\delta^{18}O-NO_3^-$. The $\bullet OH + NO_2$ reaction contributed highly to NO_3^- in summer, with the contribution reaching 58.0 ± 9.82%, but the contribution of $\bullet OH + NO_2$ was relatively low in winter, with a contribution of 11.1 ± 3.99%. Zhang et al. (2021) estimated the contributions of different mechanisms to NO_3^- formation in Beijing during the winter of 2017–2018, and the contributions of $\bullet OH + NO_2$, $N_2O_5 + H_2O$, and NO_3 + HC to NO_3^- formation were 45.3%, 46.5%, and 8.2%, respectively.

3.3. Limitations of the source apportionment methods of nitrate

By tracing the direct emission sources of NO_X, the nitrogen/oxygen (N/O) isotope technique coupled with the Bayesian isotopic mixing model can be effectively used to apportion the sources of NO_3^-. However, the sources resolved by this method are limited by the availability of N/O isotopic composition of each source. The MixSIAR model can only quantify the contributions of sources with known isotopic composition. Previous studies mostly included vehicular emission, coal combustion, biomass burning, and soil biogenic emission as the sources of NO_3^- (Liu et al., 2017; Song et al., 2019; Zong et al., 2020a, 2020b; Lin et al., 2021; Rai et al., 2021). However, other emission sources, such as industrial emissions and mineral dust, can also contribute to NO_3^- in the atmosphere. Besides, when the number of sources > the number of isotopic tracers + 1, the MixSIAR model results would not be sole, and the sources resolved by the model could show a significant negative correlation. The significant negative correlation between the resolved sources indicates overlap and overestimation of such sources (Stock et al., 2018; Lin et al., 2021). For example, in previous studies, there were occasions when vehicular emission and biomass burning (Zhang et al., 2021) or coal combustion and biomass burning (Lin et al., 2021) could not be differentiated using the MixSIAR model.

In addition to the MixSIAR model based on the isotopic technique, the positive matrix factorization (PMF) model based on chemical tracers is also a powerful tool for apportioning the sources of atmospheric aerosols (Zong et al., 2018). Based on a large quantity of samples and careful selection of source tracers, PMF can provide a full view of the sources of atmospheric aerosols. Therefore, the PMF source apportionment result may compensate for the limited sources resolved by the isotope technique. However, while the PMF model can differentiate primary sources and secondary formation, it is difficult to link the species that are largely formed in the atmosphere to the direct emission sources, which happens to be the strength of the isotope technique (Zhu et al., 2018). Therefore, combining the two methods, isotope/MixSIAR and PMF, appears to be a promising direction for apportioning the sources of NO_3^-, which will not only provide complete information on the contributing sources but also quantify the primary and secondary contributions of different sources.

4. IMPLICATIONS FOR AIR POLLUTION CONTROL

Major cities in East Asia, such as Beijing and Ulaanbaatar, are still facing severe air pollution problems. In recent years, strict measures on air pollutant mitigation have been implemented in China, leading to a rapid transition of energy demand from solid fuels to cleaner energy, such as natural gas. For example, Beijing has 100% completed the Clean Heating Plan for Northern China in Winter and used natural gas instead of coal for central heating in winter (Ai et al., 2023). In Beijing, owing to the efforts on air pollution mitigation, the particulate SO_4^{2-} has decreased by 63% (from 24.0 μg m^{-3} to 7.4 μg m^{-3}) and the particulate NH_4^+ has decreased by 51% (from 15.5 μg m^{-3} to 7.6 μg m^{-3}) in 2013–2020. Compared to SO_4^{2-} and NH_4^+, NO_3^- showed a smaller reduction of 44% (from 24.9 μg m^{-3} to 14.0 μg m^{-3}) and has become the dominant inorganic species in $PM_{2.5}$ (Lei et al., 2021). During the haze episodes, the mass percentage of NO_3^- in $PM_{2.5}$ can reach as high as 50% (Sun et al., 2015), indicating that NO_3^- could be one of the key factors driving the occurrence of heavy pollution. In Ulaanbaatar, SO_4^{2-}

is still the dominant inorganic species in $PM_{2.5}$ due to the high dependence on coal combustion. However, the government has implemented several mitigation measures to reduce air pollutants, mainly targeting stationary sources with coal combustion. It is predictable that NO_3^- will also become the major pollutant in $PM_{2.5}$ in Ulaanbaatar as a result of the control measures, similar to the evolution of air pollution in Beijing. Therefore, understanding the pollution characteristics and sources of NO_3^- in the atmosphere would help to formulate effective measures to mitigate local air pollution.

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Capacity development of farmer group in using affordable micro-irrigation for small-scale farming in marginal land

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ABSTRACT

Timely water availability and the use of traditional, less efficient irrigation methods are among the main constraints affecting the productivity of small-scale farming in many developing countries. Climate change, population growth, lack of skills and resources and less community resilience to respond are negatively affecting food security in many lower-income countries. Therefore, the use of small-scale efficient irrigation methods can be instrumental in improving local productivity and community resilience to climate change. Addressing these issues, this study is focused on developing a low-cost micro-irrigation technology and improving the skills of small landholder farming communities on the effective use of this system in the marginal lands of Indonesia. A series of capacity development activities were conducted during the project period, including focused group discussion (FGD), soil and water sampling, and design and construction of low-cost micro-irrigation systems. Moreover, following the principle of seeing is believing and learning by doing, a demonstration plot on the use of high-efficiency micro-irrigation was also established for on-hand training and troubleshooting. The result revealed a tremendous improvement in local awareness and adoption of the micro-irrigation system by the local community. Hence the capacity building strategy adopted emerged successful in achieving improved local awareness and adoption and thus can be recommended for future programs in other areas of developing countries.

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KEYWORDS

Micro irrigation system, capacity development, demonstration farm, smallholder farmers, irrigation water productivity, low-cost drip irrigation

HIGHLIGHTS

- Technology demonstration is more effective in expediting local awareness and adaptation.
- Low-cost micro-irrigation technology is affordable for small-scale farming in the marginal lands of Indonesia.
- Training and capacity building of smallholder farmers is more effective in improving agricultural production and income.

1. INTRODUCTION

1.1. Background

Increasing agricultural productivity is crucial to reducing poverty and promoting food security in Indonesia. Some dry regions in Indonesia face water scarcity during periods of droughts, which will constrain agricultural production and affect farmers' income and livelihood opportunities, especially in rural areas. In an arid climate where rainfall is very limited, some rain-fed fields are not planted due to water shortages and lack of access to irrigation. Most of the farmers rely mainly on rainfall as their source of irrigation. In addition, most of the farmers in Indonesia practice surface or basin irrigation to irrigate agricultural land. Farmers cultivate common crops such as paddy, maize and some cereals once or twice a year which needs huge water consumption. Crops are planted in closely spaced furrows or basins, and the whole field is flooded. This system has low water use efficiency as well as considerable labour (Apriyana, Sarvina, Dewi, & Pramudia, 2017; Setiawan, Liyantono, Fatikhunnada, Permatasari, & Aulia, 2016). It indicates a need to utilise more efficient irrigation systems to reduce water consumption in dry regions.

The drought-prone areas of Indonesia are negatively impacted by financial constraints and a lack of resources (Khanal & Regmi, 2018). Therefore, farmers are challenged to use effective and efficient low-cost irrigation techniques for sustainable crop production in many water-scarce places. Recent years have seen a rapid development of micro-irrigation, which has been embraced for growing a variety of high-value crops in water-scarce areas as a strategy to boost water use productivity. A system of valves, pipes, emitters, and tubing is used in micro-irrigation to slowly apply water to plant roots. Water is either deposited on the soil's surface or straight into the root zone. By lowering soil evaporation and drainage losses, micro-irrigation techniques such as surface and subsurface drip irrigation (trickle irrigation), pitcher irrigation, and subsurface irrigation utilising a clay pipe can be utilisd to increase irrigation efficiency on vegetable crops (Batchelor, Lovel, & Murata, 1996). Even when well-designed and properly used, a drip irrigation system can achieve higher irrigation efficiency (70–90%) than surface irrigation or flood irrigation (40–50%) because of its capacity to localize water application (Postel, 2000). Due to its capacity to reduce water loss brought about by leakage during water transport, surface evaporation, and deep percolation, subsurface irrigation has better water-saving effectiveness when compared to other irrigation techniques (Babiker et al., 2021). Another reason for employing subsurface irrigation is to lessen the significant effort required for seasonal installation and collection of surface drip system laterals and components (Lazarovitch, Shani, Thompson, & Warrick, 2006).

Although micro-irrigation techniques have been traditionally used for field crops and horticultural crops for many years and have a long list of benefits, their application is still very limited. Due to the high initial capital expense of installing the system, the high cost of maintenance, and the moderate level of managerial sophistication, many farmers are hesitant to adopt these approaches. Furthermore, when used in rural parts of underdeveloped nations where farming is typically performed on a much smaller scale, several of the sophisticated and expensive modern irrigation technology tend to fail. In order to promote irrigation technology in such locations, it is essential to employ local knowledge and resources. With the creation of a variety of low-cost/affordable micro irrigation systems suited to various farmer income levels and farm sizes, the prospects for the growth of this technology have improved (Keller, 2002; Kulkarni, 2005). Pressurised irrigation systems are becoming increasingly popular among small-scale farmers in developing nations due to their low cost and ease of use. In addition to assisting in increasing crop output, these systems also help many smallholder farmers by increasing employment opportunities and ensuring their access to food. Lowder, Skoet, and Singh (2014) reported 78% of Indonesian farmers own less than 1 ha of land, making the country's farms relatively small. To address the critical constraint of expansion and adoption of micro-irrigation technologies for smallholder farmers, the project collaborators proposed a one-year capacity-building project aimed at providing low-cost micro-irrigation technologies in drought-prone locations that will allow small-scale and impoverished farmers to efficiently use scarce water resources while cultivating home gardens and another land for the production of food needed for the family and some trade.

1.2. Objectives

In general, the project primarily aimed to enhance the capacity of smallholder farmers through the development of low-cost affordable micro-irrigation technologies. Specifically, this project was to develop the knowledge and skills of farmers in designing, constructing and maintaining the appropriate micro-irrigation systems based on their local conditions.

2. METHODOLOGY

2.1. Project site

The project study was implemented in Salohe Village of Sinjai Regency (Figure 1). Astronomically, Sinjai Regency is located between 502′56″–5021′16″ South Latitude and between 119056′30″–120025′33″ East Longitude, which has an area of 819.96 km^2 with a distance of 223 km^2 from the capital of South Sulawesi Province. According to BPS-Statistics of Sinjai Regency (2022), the poverty line of Sinjai Regency in 2021 was IDR 352,490/per capita/month, with a total population of 21,686 poor and the percentage of poor people 8.9% who live in rural areas. Salohe village is located in east Sinjai. The land use in and around Salohe is agricultural land. The farmers mainly produce rice and maize in the rainy season. The area is in the tropics and has two seasons; the dry season occurs from September to March, and the rainy season occurs from April to July. The annual temperature ranges between 27.2–34.6 °C, while the relative humidity ranges between 69–87%, with annual rainfall varying between 78–860 mm. The study area was categorised as an arid climatic condition with less rainfall and high temperature.

In arid climatic conditions, most of the agricultural fields in Sinjai Regency are rainfed; in other words, most farmers rely on rainfall as a source of irrigation water. Farmers cultivate paddy in the rainy season once or twice a year to get income from their paddy production. In addition, agricultural productivity remains low due to the massive application of chemical fertilisers and pesticides, which causes less fertility of soils. Thus, it become a serious environmental and socio-economical problem in Sinjai. Additionally, the farming practices in the project area are nearly exclusively of the traditional variety, and the non-traditional variety is very few.

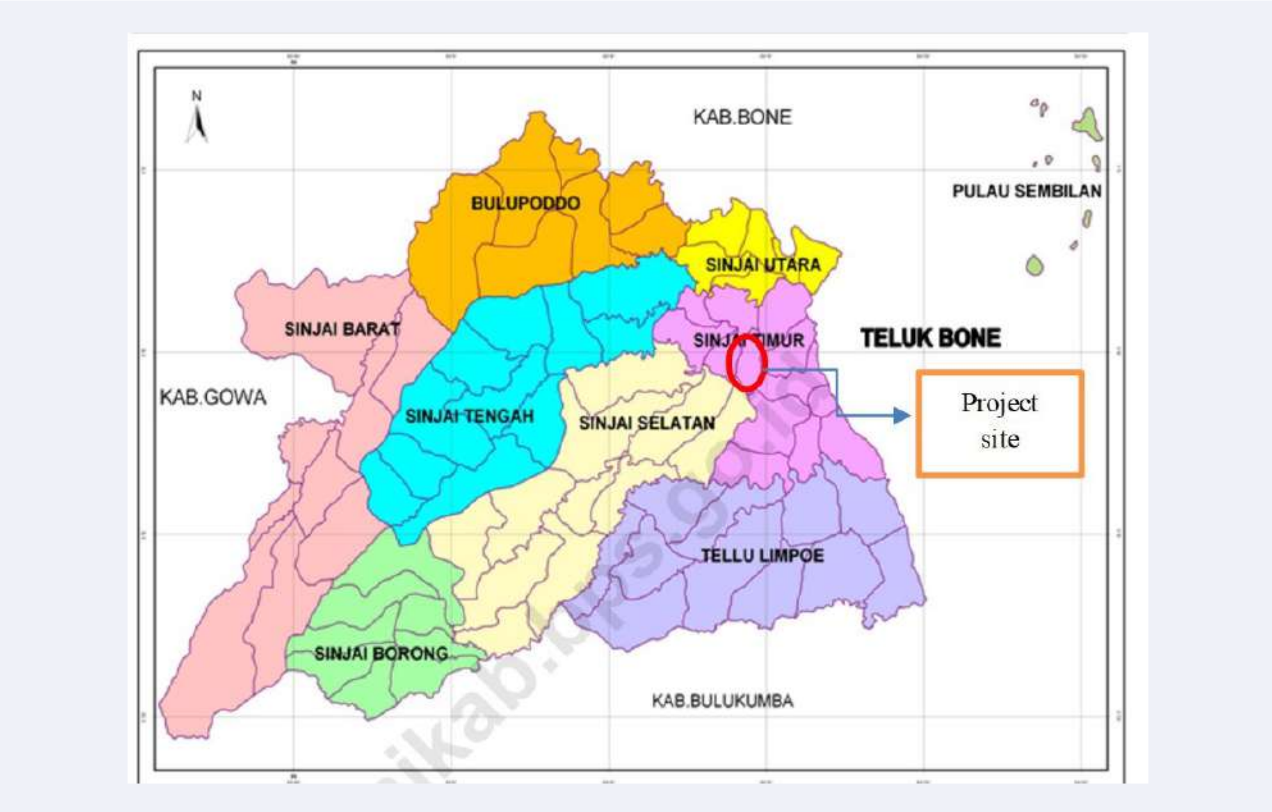

FIGURE 1. Project site (source of Map: http://www.sinjaikab.bps.go.id).

2.2. Program socialisation and focus group discussion (FGD)

In the early stages, a focus group discussion (FGD) was conducted in preparation for implementing the field school as part of the capacity building. The purpose of the FGD was to introduce and socialise the program to local stakeholders and conduct a needs assessment for participants. The socialisation took place in the first session for two hours, in the form of presentations and discussions. In the second session, FGD involving capacity-building participants was conducted to introduce several low-cost micro-irrigation technologies to the participants. Then, we carried out a needs assessment to obtain information that was used to design the format of the field school. The information to be gained was; (1) an overview of the problems currently faced by participants, especially regarding irrigation and water use in their village, (2) an overview of their knowledge and experience about micro-irrigation systems, (3) an overview of the attributes of innovation of micro irrigation systems, and (4) the description of the design of the field school (schedule, frequency of meetings, and the location of field school).

2.3. Selection of farm field for demonstration plots

Farmers and project collaborators visited the farmer's field to select a demonstration plot of development micro-irrigation technologies. Farmers and project collaborators had a chance to discuss the demonstration plot's criteria (Figure 2). It was important to select a location for the demonstration plot, which has some criteria as follows:

1. Accessibility of the farm where micro-irrigation technologies would be established
   In this criterion, we considered a demonstration plot that was easy to access by farmers and others who want to develop and adopt the new irrigation technologies. Furthermore, when the demonstration plot is accessible, the technicians and farmers would be easy to move and carry the micro-irrigation components to the field.
2. Topography of land

FIGURE 2. Discuss with farmers to decide on the field of the demonstration plot.

The demonstration plot should have flat or minor slopes. It should be considered to design micro-irrigation systems easily. When the field of the demonstration plot has a minor slope, it will increase the uniformity of water distribution through pipeline connections and emitters. Thus, increasing the performance of irrigation techniques.

3. Water resource for irrigation
   The important factor that needs to be considered is the irrigation water source. The demonstration plot should be near the water source, either from a small pond or a shallow well. Water from a small pond will be delivered to the field through a pump and pipes network.

2.4. Capacity development activities

Capacity development activities were initiated in early September 2021 after discussing with farmers, field facilitators and engineers to decide the actual schedule of FFS training. The training included as follows:

2.4.1. Soil and water sampling

Soils and water irrigation samples were collected in the selected field of the demonstration plot. Farmers were given orientation on how to collect soil and water samples in order to increase their knowledge of farmers on the actual soil structure condition in the field. Determining the physical-chemical properties of soils would give more information for planning and managing farm practices on the project site. Soil samples were collected using an auger at different depths from 0 cm to 50 cm. Aluminium ring samples with a diameter of 10 cm and a height of 5 cm were inserted at six different depths. A total of 18 soil samples were subjected to various physical and chemical analyses in the soil laboratory of Hasanuddin University.

2.4.2. Construction and installation of low-cost micro-irrigation systems

The establishment of micro-irrigation systems was conducted in early October 2021. Project collaborators contracted the expertise involved in the construction and installation of micro irrigation systems. Two engineers from the Department of

FIGURE 3. Trainee-farmers work together for land preparations.

Agriculture provided their technical assistance in the appropriate design of micro irrigation systems to the trainee farmers. The materials, all components of micro irrigation and tools were provided by the project. Before the construction of micro irrigation components, farmers worked together in the field for land preparation activities (Figure 3). Land preparation activities include clearing the field, ploughing and tilling. All the stages were arranged in FFS activities training by the field facilitator. The field facilitator described the importance of land preparation stages in order to support crop growth performance.

These activities allow the trainee farmers to interact with each other and build their capacity and motivation, which would develop their sense of ownership of the project. In addition, the participation of farmers in all stages of the project activities would strengthen the farmers to recall the strategies and methods much better when they have seen them in the field.

Farmers with engineers constructed the three micro irrigation systems in the field of the demonstration plot, which were low-cost sprinkler irrigation, small gravity drip irrigation and subsurface irrigation with the ring-shaped emitter. Each micro-irrigation system was constructed in the field (Figure 4). Six rise beds were prepared for each irrigation system. Farmers were trained to install the components of micro irrigation systems and operate and maintain these systems. Each micro irrigation has characteristics and advantages/disadvantages, which allow farmers to choose the best irrigation system that suits their field and conditions.

2.4.3. *Package of sustainable farm practices under melon construction*

The package of sustainable farm practices was also delivered to smallholder farmers through a farmer field training program. This session's subjects included agricultural practices, including horticultural crop production, managing soil fertility and using fertilisers effectively to help farmers increase yields, as well as managing pest control.

3. RESULTS

3.1. Program socialisation and focus group discussion (FGD)

The socialisation involved the capacity-building participants (trainees), local agricultural extension workers, the local government represented by the Department of Agriculture, and the village government. We invited all relevant stakeholders to increase the participation of local participants and stakeholders to create a space of collaboration

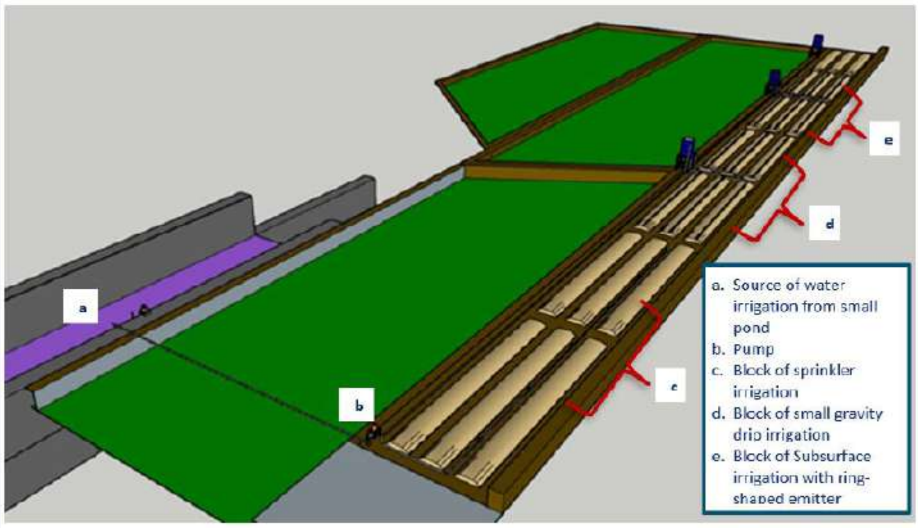

FIGURE 4. The block design of three kinds of micro-irrigation systems shows six beds for sprinkler irrigation, six beds for small gravity drip irrigation and six blocks for subsurface irrigation with the ring-shaped emitter.

throughout the activity. A total of 30 audiences joined the program socialisation and FGD (Figure 5).

As a result of the FGD, we obtained information about the forms of micro irrigation suitable for the local situation. The micro irrigation systems were sprinkler irrigation and drip irrigation. In addition, the participants agreed on the location of the field school, including training and demonstration plots, in accordance with the conditions and the needs of the trainees. In addition to that, the participants settled the time schedule adjusted to the flexibility of the participants' time, combined with the stages in melon cultivation. Through the FGD, we also learned that participants' knowledge about micro irrigation is still very minimal. In fact, the majority of participants have never seen or heard of any type of micro-irrigation technology before, justifying the vital need of this training.

From the FGD meeting (Figure 6), 23 smallholder farmers, including women farmers, were selected to have a commitment with project collaborators in capacity development activities. Twenty-three selected farmers would actively join on-farm demonstrations through field school. Farmers would work together with project collaborators and technicians to develop and construct micro-irrigation systems on a farm demonstration plot. Three micro irrigation systems would be introduced and established in the farm field, namely low-cost sprinkler, drip irrigation, and subsurface irrigation with the ring-shaped emitter. It allowed farmers to select the best system which suited their local conditions and needs. This sparked a sense of "ownership" among the community, which sped up the adoption of technologies that would turn out to be useful and pertinent.

3.2. Demonstration plots for micro-irrigation technologies

Based on the criteria (Section 2.3), project collaborators and farmers decided one farmer's field was selected as the demonstration plot. The field is represented in Figure 7.

3.3. Capacity development activities

3.3.1. Soil and water sampling

Physical-chemical properties of the experimental soil samples were summarized in Table 1.

From the soil analysis, the soil was categorised as heavy soil texture with high clay content. It showed that due to the densely compacted soil profile particles, water is absorbed very slowly and runoff can emerge if water is supplied immediately. As a result, lateral movement will be greater than

FIGURE 5. Program socialisation.

FIGURE 6. FGD with the potential farmers.

Depth (cm)	Soil Particles (%)			Soil Texture	Bulk Density (g/cm^2)	Particle Density (g/cm^2)	Porosity (%)	EC (mS/cm)	Organic Matter		
	Sand	Silt	Clay						C (%)	N (%)	C/N
5	36	30	34	Clay loam	1	2.7	63	0.65	2.25	0.13	18
10	30	47	23	Silt loam	0.98	2.53	61	0.49	1.96	0.15	13
20	39	27	34	Sandy Clay	0.91	2.72	66	1.02	1.84	0.14	13
30	26	22	51	Clay	0.78	2.5	69	1.07	1.46	0.09	17
40	34	23	43	Clay	0.72	2.42	70	0.46	0.97	0.09	10
50	34	19	48	Clay	0.65	2.5	74	0.66	0.77	0.13	6

TABLE 1. Physical-chemical properties of soil at the initial stage of the experiment.

vertical movement. The kind of soil is always considered when designing a drip irrigation system. This aids in the choice of emitters and drippers as well as their discharge (Khan & Farooq, 2017). In dense soil, the water dispersion will be more spherical in shape, wider, and shallower. It suggested that a drip emitter with 2 Lph (litre per hour) discharge would be used for heavy soils.

In a drip irrigation system, the water emerges from emitters with very small pores that are susceptible to clogging because of salts and soil particles that are constantly present in water. Hence,

FIGURE 7. Selected demonstration plot in farmer's field: (a) demonstration plot, and (b) small pond for an irrigation water source to the field.

while developing an effective drip irrigation system for the area, water quality is a crucial concern (Khan & Farooq, 2017). The source of water supply to irrigate in the field of the demonstration plot came from a small pond that was located 50 m from the demonstration plot. The water quality was suitable for watering crops with an EC value of 0.7–1.12 dS/m with neutral pH of 6.2.

3.3.2. *Construction and installation of low-cost micro-irrigation systems*

In order to irrigate fields using sprinklers, water was sprayed over them at a specific pressure that was often supplied by a pumping system. Water was pumped under pressure and forced through micro-orifices or nozzles to create the spray. It should be noted that careful consideration must be given to the selection of nozzle diameters, operating pressure, sprinkler spacing, and the quantity of irrigation water necessary to refill the crop root zone in order to achieve efficient sprinkler irrigation.

Figure 8 depicts the primary elements of sprinkler irrigation systems, including a. Pumping system; b. Mainline; c. Lateral lines; d. Sprinkler riser; and e. Nozzles.

Water was applied by emitters or drippers positioned along a lateral line for the small farm gravity drip irrigation system at low pressure. The "emitter," which is either built into the lateral line or projected onto it, is the component that emits water into the soil. Water emitted from emission points permeates the soil and moves further due to capillary action and gravity. The device is powered by gravity from a tank that is between 1 and 1.5 m high. It is a solid seasonal installation, a closed piped gravity system, and a localized approach. It can run normally without the need for any external electricity. As a result, it is perfect for small-scale agricultural production in rural locations where there is a lack of water and a limited supply.

The small farm gravity drip irrigation system was built and installed using the following materials: a plastic water reservoir, mainline pipes,

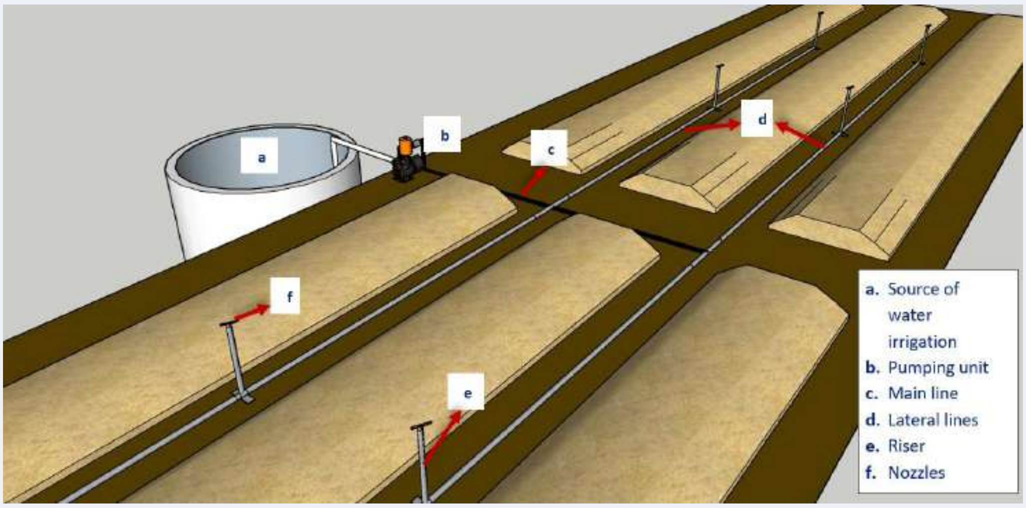

FIGURE 8. Component of a typical sprinkler irrigation system.

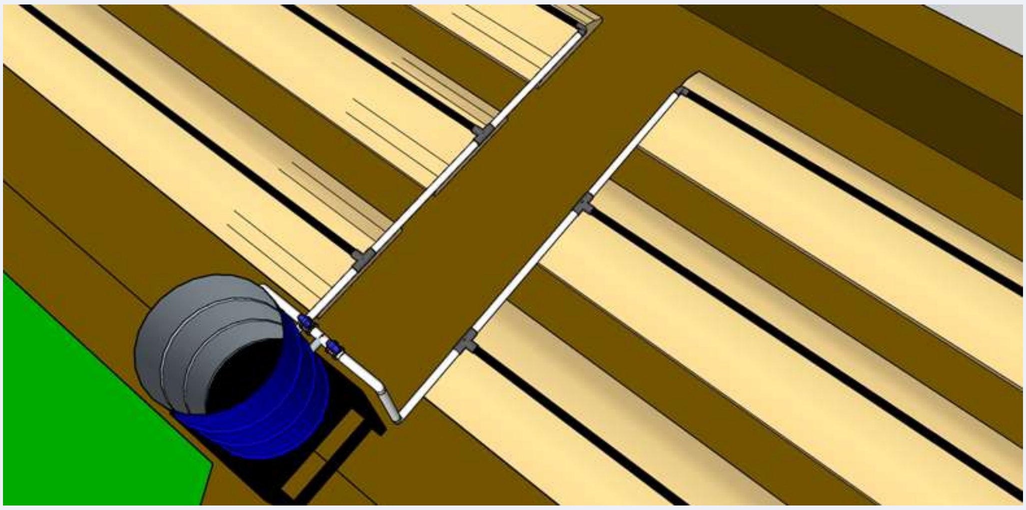

FIGURE 9. The layout of the small farm gravity drip irrigation system.

sub-mainline pipes, lateral pipes, water filters, valves/regulators, and improvised micro emitters (Figure 9). The entire irrigation system functioned by gravity from a 300-l plastic tank that was elevated 1 m above the ground to provide the system with sufficient head for water pressure. All of the pipes were made of PVC. The crop rows were lined with the lateral lines that connected to the sub-main lines, and 50 cm-spaced micro emitters were placed. The water tank has a drain tap at the bottom for routine cleaning and flushing out of suspended solid particles.

The small farm gravity drip system installation was carried out in three stages, which included the following: a. Building the water tank stand and installing the tanks; b. Pipe and fitting laying; and c. Fitting testing and measuring emitter flow rate.

To meet the minimum pressure requirements, a wooden water tank stands at a height of 1 m above ground level was built. A water jet pump delivers water into the water tank (the source of water). To prevent emitter clogging, a simple filter was screwed into a union and connected to the mainline pipe after the system was linked to the water supply. The later-

FIGURE 10. Connecting water source.

FIGURE 11. Connecting lateral pipes.

als were joined to the sub-mainline that ran parallel to the plant rows and sloped downward. Construction of the stands, laying and fixing of fittings into the pipes are shown in Figures 10–12.

The operation system of a ring-shaped emitter for subsurface irrigation (Saefuddin, Saito, & Šimůnek, 2019; Saefuddin, Setiawan, Saptomo, & Mustaningsih, 2014) was similar to small gravity

FIGURE 12. Plastic water tank and stand.

FIGURE 13. Farmers were trained to install, operate and maintain low-cost micro irrigation systems.

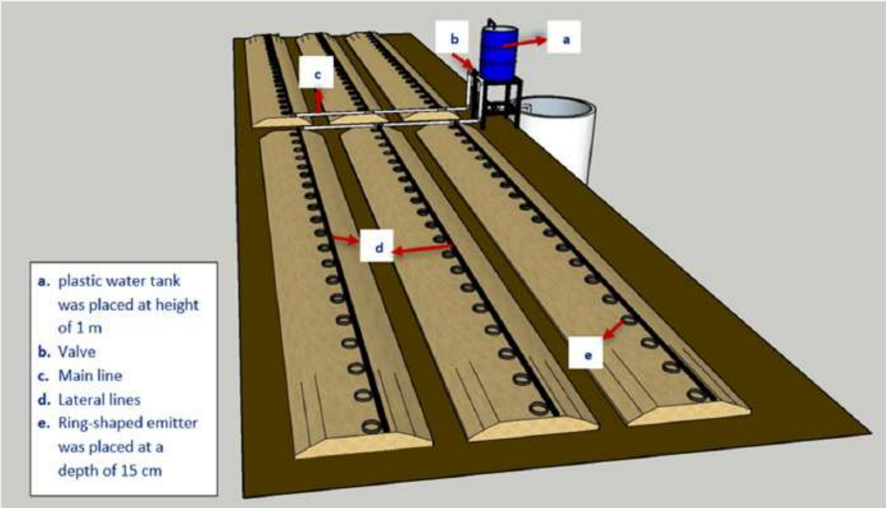

FIGURE 14. Layout of subsurface irrigation with ring-shaped emitter in the field of demonstration plot.

drip irrigation; the difference only was in the emitter. Ring-shaped emitter can be made by farmers. For small-scale farmers, in particular, the rubber hose emitter is economically feasible. Five 5-mm holes are drilled at set intervals after a rubber hose is curved into a ring form with a diameter of approximately 20 cm. The ring-shaped hose is wrapped entirely to allow irrigation water to be distributed through the material in all directions surrounding the emitter. A supply tube that connects a water tank and the ring-shaped emitter supplies water to both. In this irrigation system, a ring-shaped emitter was positioned immediately in the root zone at a depth of 15 cm for melon cultivation. The main components of the subsurface with a ring-shaped emitter are shown in Figure 14.

3.3.3. *Package of sustainable farm practices under melon construction*

A total of 14 farmer training meetings were arranged by considering the flexibility time of farmers. Farmers who took part learned techniques (Figures 15–17) for promoting ecologically friendly farming methods and enhancing the production of safe, high-quality food. Each meeting's agenda was created by project collaborators and field facilitators and connected to the crop's current stage of development as well as the relevant farm management and water control measures. The exercises involved a close evaluation of the elements influencing farm performance and group consideration of potential solutions. Farmers were able to pinpoint the fundamental reasons for their management issues throughout the training and explore potential solutions that suited their unique physical and socioeconomic circumstances. Farmers were able to modify input suggestions or technical packages to suit local conditions by using the skills they learned in local analysis. In addition, project collaborators and field facilitators also prepared the economical visibility analysis of the three micro irrigation systems. It was important to train smallholder farmers in the economic analysis of farm practices under using these technologies in order to know the cost affordability and investment of financial. The materials of farmer training were designed simply, and were easy to understand by smallholder farmers.

4. DISCUSSION

The project facilitated training activities for smallholder farmers in Salohe Village, which enhanced farmers' capacities and skills in developing low-cost micro-irrigation technologies and intensifying agricultural production in a sustainable manner as well as improving water and food security in such drought-prone areas. In this project, smallholder farmers were not seen as merely recipients of

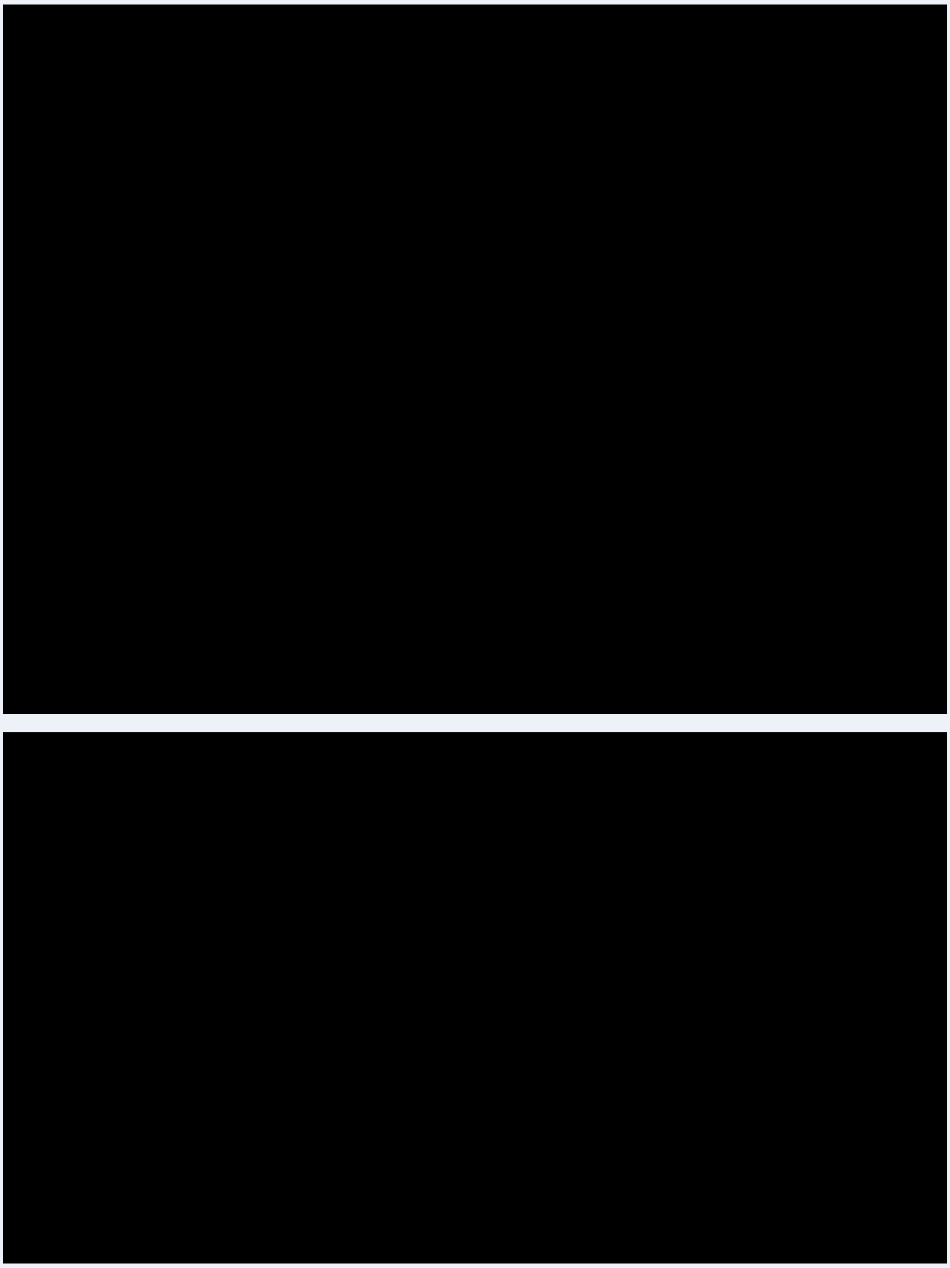

FIGURE 15. (a) Farmers were trained to calculate the economic analysis of farm practices using micro-irrigation technologies, and (b) farmers were trained to use appropriate fertilisers and water management.

the project but, more importantly, as active partners in all phases of the project implementation, as well as the key players in the innovation process. Enhancing farmers' managerial abilities, capacity for problem-solving, and ability to create, adapt, and disseminate new technologies and practices among themselves from farmer to farmer led to the development of the participatory extension.

Building harmonisation among smallholder farmers, project collaborators, and field facilitators, as well as the willingness to work together, played an important role in the completion of micro irrigation technologies projects in the targeted area. The idea and suggestions from farmers during capacity development activities were well recognized by the project collaborators and field facilitator, which created no gap among them. Project collaborators and field facilitators also learned the actual condition of farmers and the existing farm practices, strength-

FIGURE 16. (a) Farmers were trained to appropriate land preparation, and (b) Project collaborators and field facilitator demonstrated how to make biopesticide from local materials to control pest.

ening the project collaborators' capacity and building proper learning materials and guidance.

The demonstration plot of micro irrigation technologies was an effective method for enhancing the adoption of new irrigation technologies. A similar benefit of demonstration plots was suggested by Sseguya et al. (2021) study; demonstration plots and demonstration plots with small packs are an effective model for enhancing improved technology adoption. Farmers were able to learn directly and observe the improved technologies of micro irrigation in the farm practices before they decided to adopt the appropriate technology that suited their farm conditions. The summative

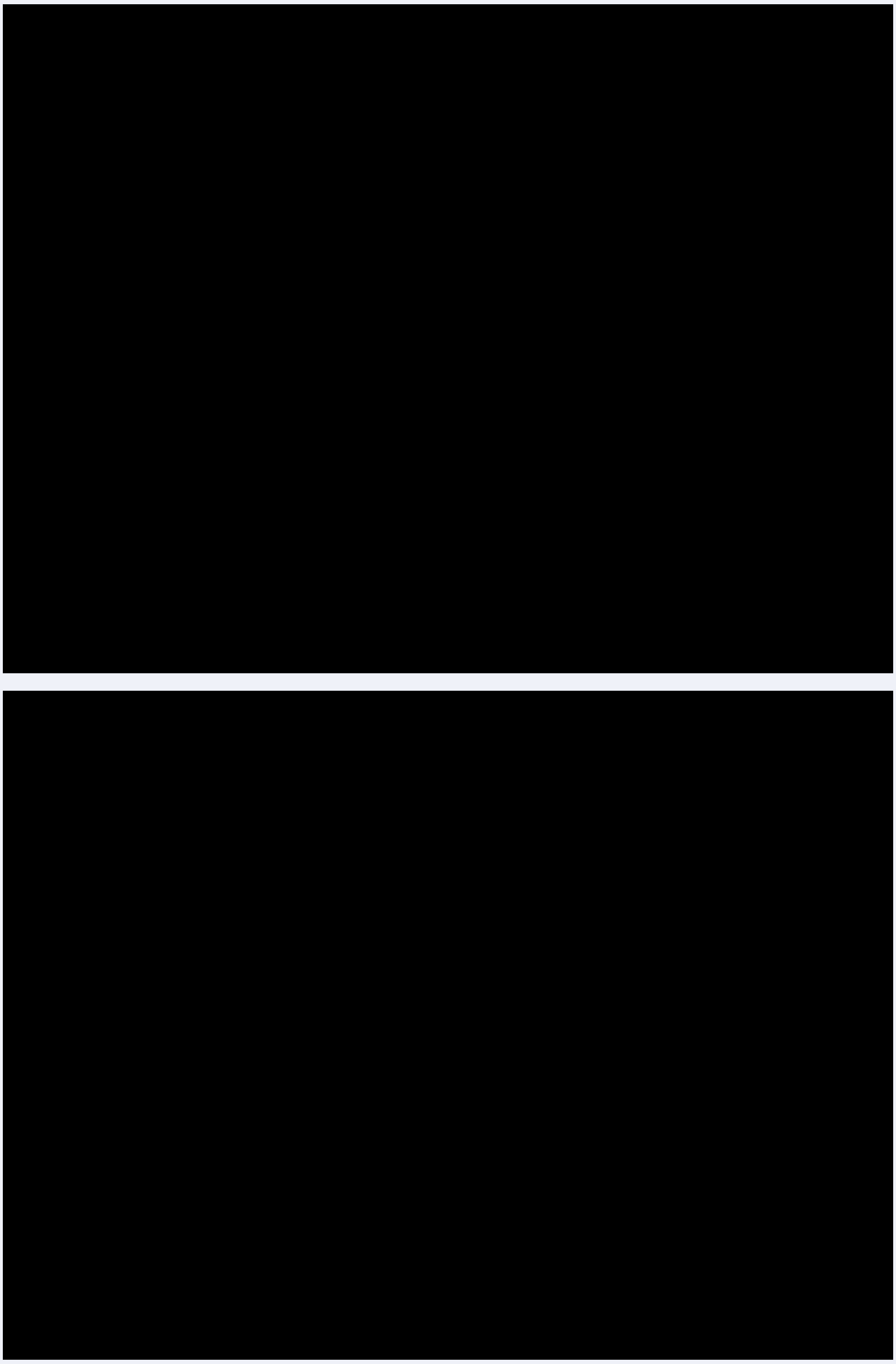

FIGURE 17. (a) Farmers were trained to control pest management, and (b) Farmers were trained to make liquid organic fertiliser from agricultural waste.

evaluation conducted in this study revealed that farmers were motivated to adopt micro-irrigation systems demonstrated in this study. The evaluation through interviews with 21 farmers indicated that 71% of the respondents were interested in adopting and using the micro-irrigation systems for farming, while four of the respondents were already adopted the micro-irrigation systems.

One of the best methods to transfer new technology for smallholder farmers by showing the benefit of technologies because farmers would change their perception after seeing the performance of the technology in the demonstration plot. Through demonstration plots, farmers found it much easier to apply and modify new micro-irrigation technologies on their own farms. In addition, it allowed farmers to share their experiences with other farmers, which created space for the dissemination of micro irrigation techniques. Landicho, Cabahug, and De Luna (2009) also assumed that the farmers learn from other farmers as they share similar symbols and experiences.

Furthermore, the demonstration plot incorporates the form of a farmer field school (FFS) that was provided in this project to facilitate a series of training to support smallholder farmers and escalate their capacity to develop sustainable agricultural practices in regions where water availability is limited. Through the incorporation of fundamental behaviours into their farming operations, such as appropriate land preparation, proper spacing, use of fertiliser and improved seeds, water and soil management, pest and disease control, and pre-harvest/harvest/post-harvest practices, it was intended to facilitate positive changes in farmer practices. Such hands-on instruction in the demonstration plots is the first step in providing farmers with the knowledge and abilities they need to implement better methods, which will raise marginal sales and yields.

Since it has been shown that farmers can become experts in analysing specific issues related to their farming activities and make educated decisions about essential treatments, the FFS approach concept has achieved exceptional success. FFS, with participatory approaches in the design of activities, continuous advisory, and the use of demonstrations, were an effective way of demonstrating the implementation of low-cost irrigation systems through process and result demonstrations, leading to farmers' intention to use low-cost irrigation and disseminating affordable innovation. Luther, Maryono, Purnagunawan, Satriatna, and Siyaranamual (2018) stated farmers also could adapt and adopt the knowledge gained from FFS as they underwent a process of learning by doing.

Although the project ended in July 2022, continuous communication among project collaborators, the farmers' community and the village extension officer are still being developed. According to the leader of the farmers' community in Salohe Village, farmers are going to replicate and scale up the project activities by getting financial support from the government of Salohe Village. Farmers work together to cultivate 3000 Melon crops in the field and use small gravity drip irrigation for cultivation. By supporting from the local government, the dissemination of the adoption of new irrigation technologies is more robust. This indicated that the implementation of project activities brought successful adoption.

5. CONCLUSION

This project improved farmers' knowledge in designing, constructing, and maintaining the appropriate micro-irrigation systems that suit their local conditions, showed by the high interest of farmers to adopt the irrigation systems. In order to improve agricultural productivity and land productivity in the areas where water is limited, the adoption and implementation of micro irrigation technologies must be triggered. Even though these technologies have many advantages compared to conventional irrigation techniques, they should be designed properly to increase the performance in water use efficiency. Technical guidance of appropriate design of all major components has been provided in a strong on-farm demonstration and farmer education program (FFS training), which resulted in increasing the adoption of micro irrigation technologies.

The project has facilitated the farmers through FFS training to learn and enhance their knowledge on using the micro-irrigation systems to increase the utilisation of water consumption and agricultural production, which enables them to generate their income from their farm activities. Project collaborators conducted a short-term evaluation of the impact of the FFS training program on the adoption of the new technologies of micro-irrigation at the end of the project. As a result, 23 farmers were well-trained in constructing the micro-irrigation systems. Moreover, 21% of trained farmers have adopted this technology in their farming.

When considered as a whole, this project shows that demonstration plots and FFS training are useful tools to promote the dissemination of knowledge about new agricultural technologies since they can lead to novel interactions and dialogues between farmers who might not be part of the same social network. This contrasts with more conventional diffusion models, which rely on farmers' underlying or pre-existing social network. Because they offer an alternative to conventional strategies, policy-makers should take into account methods such as demonstration plots to disseminate knowledge to farmers.

6. ACKNOWLEDGEMENT

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Original article

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Air quality management status and needs of countries in South Asia and Southeast Asia

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ABSTRACT

Countries in South Asia and Southeast Asia are experiencing severe air pollution problems. Most countries lack technical capabilities and adequate air quality management (AQM) infrastructure. A capacity building workshop on AQM was organised from 19–23 September 2022 for countries in South Asia and Southeast Asia. A total of 17 countries (eight in South Asia and nine in Southeast Asia) participated in the workshop. Each country was invited to present on available AQM infrastructure, including challenges and needs. This article synthesises information on available AQM facilities, challenges and needs of the countries. The information reveals that, except for a few low-population countries and Thailand, most countries lack enough ambient air quality monitoring stations (AAQMS) based on the population-weighted criteria. It is also found that only a few countries have started compiling emissions inventories (EI) and performing air quality modelling, including air pollution impact assessments. It is noted that all countries have enacted air pollution mitigation regulations, including the development of clean policies and action plans. However, policies and action plans lack scientific evidence based on local data. The findings of this article, including challenges and gaps, provide immense opportunities for countries to invest in strengthening various components of AQM, including mobilising financial resources from international funding agencies.

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KEYWORDS

Air quality management, air quality monitoring, air pollution policies, population-weight criteria, capacity building

HIGHLIGHTS

- Most countries in South Asia and Southeast Asia lack adequate numbers of air quality monitoring stations.
- A few countries have started developing emissions inventories and air quality modelling.
- Countries face many challenges in AQM, including lacking technical capacities and financial resources.
- There are vast opportunities to invest in AQM, including mobilising financial resources from international agencies.

1. INTRODUCTION

With rapid urbanisation and industrialisation, countries of South Asia and Southeast Asia are experiencing severe air pollution problems. The air quality in these countries is deteriorating at an alarming rate due to increasing emissions of air pollutants from various sources, including industrial operations, construction, road traffic, residential cooking, open burning of agricultural residual and municipal waste, and other activities (Jabbar et al., 2022; Soejachmoen, 2019). In April 2022, the World Health Organization (WHO) published air quality data from 117 countries for 2020. The data revealed that almost 99% of the global population is respiring air that exceeds WHO air quality guideline values of 5 µg/m³ for $PM_{2.5}$ (particulate matter (PM) $\leq$ 2.5 µm), 15 µg/m³ for PM_{10} (PM $\leq$ 10 µm), and 10 µg/m³ for nitrogen dioxide (NO_2)) (WHO, 2021, 2022). As a result of exposure to a high level of air pollution, about nine million premature deaths were estimated yearly in 2019, mostly in developing countries, including Asian countries (Fuller et al., 2022). Many Asian cities are among the list of most polluted cities in the world. In fact, South Asia alone hosts nine most polluted cities out of 10 world's most polluted cities, with an ambient concentration of $PM_{2.5}$ exceeding WHO air quality guidelines of 5 µg/m³ (World Bank, 2022). Most countries in South Asia and Southeast Asia are lagging behind the timeframe for achieving the Sustainable Development Goals (SDGs) linked to improving air quality, including reducing the concentration levels of $PM_{2.5}$ to a level of 35 µg/m³, PM_{10} to a level of 70 µg/m³ and NO_2 to a level of 40 µg/m³ – an Interim Target (IT-1) set by WHO (HEI, 2020). The increasing air pollution is not only affecting human health and the environment but also causing a significant economic burden on the national health budget of countries and a significant loss in agricultural productivity (Pandey et al., 2021; Taghizadeh-Hesary & Taghizadeh-Hesary, 2020).

Air quality management (AQM) refers to all activities undertaken by regulatory authorities to avoid the harmful effects of air pollution on human health and the environment. Figure 1 shows the components of AQM, which include air quality monitoring, emission inventory development, air quality modelling, impact assessment, and mitigation policies and action plans. Air quality monitoring is done by establishing air quality monitoring stations in an area. The data is also used for legislation and compliance checks, impact assessments, developing air pollution control strategies and action plans, forecasting, and scientific research. At the same time, emission inventory development is a process of compiling emissions of air pollutants from var-

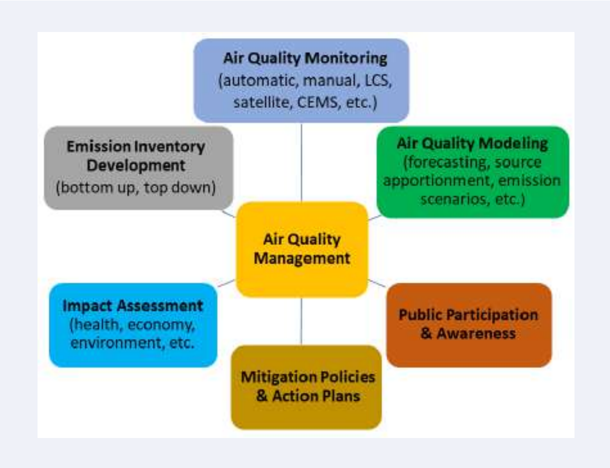

FIGURE 1. Components of air quality management.

ious emission sources. It is generally done through two approaches – bottom-up and top-down. The bottom-up approach is multiplying the activity data (amount of fuel consumption by source) with source-specific emission factors. The top-down approach derives emissions of air pollutants by inputting source characterisation and ambient air pollutant concentration into a suitable receptor model. Both approaches are necessary to validate emissions inventory data. Air quality modelling is a mathematical simulation of how air pollutants disperse and react in the atmosphere to affect ambient air quality. Air quality models are divided into three categories, namely, dispersion models (e.g., ADMS (Atmospheric Dispersion Modelling System), AERMOD (American Meteorological Society/Environmental Protection Agency Regulatory Model), CALPUFF (California Puff Model), CMAO (Community Multiscale Air Quality Modeling System), etc.), photochemical models (e.g., CMAQ, CAMx (Comprehensive Air Quality Model with Extensions), REMSAD (Regional Modeling System for Aerosols and Deposition), UAM-V (Variable-Grid Urban Airshed Model), etc.), and receptor models (e.g., PMF (Positive Matrix Factorization), PCA (Principal Component Analysis), CMB (Chemical Mass Balance), MLR (Multiple Linear Regression)). Air quality models are used to estimate the concentration of air pollutants downwind from a source; photochemical models are used to simulate secondary pollutants (e.g., PM, ozone (O_3), etc.), whereas receptor models are used for identification and source apportionment of air pollutants. All three types of models are needed in AQM.

Air quality impact assessment is a technique to determine how much the existing concentrations of pollutants or potential emission sources affect the receptor sites. It is a part of environmental impact assessment (EIA) and can be used for strategic environmental planning. The selection of models and monitoring depends on the objective of the assessment. This involves several steps in the assessment process, such as source identification, prediction, evaluation of critical variables and potential changes in air quality. Whereas air pollution mitigation regulations, policies and action plans mainly aim to regulate the prevention, control and abatement of emissions of air pollutants from various sources. The regulations, policies and action plans vary depending on the target pollutant sources, cities and countries. Public participation involves the public in AQM activities and raising awareness about the harmful effects of air pollution.

Many countries in South Asia and Southeast Asia lack the technical capabilities to manage their air quality, including adequate infrastructure required for monitoring key air quality parameters, such as PM (PM_{10} and $PM_{2.5}$) and trace gases (carbon monoxide (CO), nitrogen oxides (NO_x), O_3, sulphur dioxide (SO_2), etc.). Most countries do not have air pollutant emission inventories, although few have compiled emission inventories for some point sources and cities. Countries lack the technical capabilities to use AQM tools for air pollution impact assessments and emissions scenario development. Most countries also lack effective air pollution mitigation policies and action plans supported by scientific evidence.

The capacity development programme aimed to enhance AQM capabilities in countries in South Asia and Southeast Asia in order to foster effective policy formulation and decision-making. The Asia-Pacific Network for Global Change Research (APN) provided financial support to organise two capacity building workshops on AQM in 2021 and 2022. The first five-day capacity building workshop was organised online from 13–17 September 2021, in which about

Country	Participants' Organisation	Website
Bangladesh	Ministry of Environment, Forest and Climate Change	http://www.moef.gov.bd/
Bhutan	National Environment Commission	http://www.nec.gov.bt/
Brunei	Department of Environment, Ministry of Development	http://www.env.gov.bn/
Cambodia	Ministry of Environment	https://www.moe.gov.kh/en
India	Ministry of Environment, Forest, and Climate Change	https://moef.gov.in/en/
Indonesia	Ministry of Environment and Forestry	https://www.menlhk.go.id/
Iran	Department of Environment	https://en.doe.ir/
Lao PDR	Ministry of Natural Resource and Environment	http://www.monre.gov.la/
Malaysia	Ministry of Environment and Water	https://www.doe.gov.my/en/utama-english/
Maldives	Ministry of Environment, Climate Change, and Technology	http://www.environment.gov.mv/v2/en/
Myanmar	Ministry of Transport and Communications	https://www.motc.gov.mm/
Nepal	Ministry of Forests and Environment	https://www.mofe.gov.np/
Pakistan	Ministry of Climate Change and Environmental Coordination	https://www.mocc.gov.pk/
Philippines	Environmental Management Bureau	https://emb.gov.ph/
Singapore	Ministry of Sustainability and the Environment	https://www.mse.gov.sg/
Sri Lanka	Ministry of Environment	http://www.env.gov.lk/web/index.php/en/
Thailand	Environmental Research and Training Center and Pollution Control Department	https://www.pcd.go.th/

TABLE 1. Country-wise participants' organisation.

200 participants from 29 countries participated. A detailed report on the workshop proceedings has been published on the APN website (Verma et al., 2022). The second five-day capacity-building workshop on AQM was organised from 19–23 September 2022 (onsite) for countries in South Asia and Southeast Asia. A detailed report on the workshop proceedings has been published on the APN website (Verma et al., 2023). The major objective of the workshops was to build the capacities of participating countries on AQM. The five-day workshops covered all aspects of AQM, including air quality monitoring, emissions inventory development, air quality modelling, air pollution impact assessment on health and the environment, and air pollution mitigation policies and action plans. AQM components are shown in Figure 1.

Participants from member countries of the ASEAN (Association of Southeast Asian Nations) Agreement on Transboundary Haze Pollution (ASEAN Haze Agreement) and the Malé Declaration on Control and Prevention of Air Pollution and its Likely Transboundary Effects for South Asia (Malé Declaration) were invited to the workshop. A total of 17 countries' participants, including nine Southeast Asian (member countries of the ASEAN Haze Agreement: *Brunei, Cambodia, Indonesia, Laos, Malaysia, Myanmar, the Philippines, Singapore, and Thailand*) and eight South Asian (member countries of the Malé Declaration: *Bangladesh, Bhutan, India, Iran, Maldives, Nepal, Pakistan, and Sri Lanka*) participated in the workshop. Participants were mainly government officials (policymakers, technical and scientific staff) working with the ministries of environment and pollution control agencies. Table 1 provides country-wise participants' organisations with their websites where readers may explore detailed country-specific information about the AQM status, such as air quality monitoring infrastructure, air quality modelling and impact assessment studies, rules and regulations, and policies and action plans. Furthermore, details of participants, including their name, designation, and affiliated organisation, are given in Annex 1 in the workshop report (Verma et al., 2023).

Although we did not have participants from Vietnam, we added AQM-related information from Vietnam in the article to provide complete coverage of Southeast Asia, collected through personal communication with the Northern Center of Environmental Monitoring (NCEM) and the Vietnam Environment Administration (VEA).

During the workshop, each participating country was invited to present the status of AQM in their country, including challenges and needs for effective air quality management. This article extracted information on the status of AQM in 17 countries of South Asia and Southeast Asia (plus Vietnam through desktop review and personal communication), including challenges and their needs for effective air quality management in their country. The information provided in this article will be useful to UN organisations, international organisations, and funding agencies in assisting the countries of South Asia and Southeast Asia in building their capacities on various components of AQM.

2. METHODOLOGY

During the workshop, each participating country was invited to make a presentation on the status of AQM in their country, including air quality monitoring facilities (monitoring stations: automatic, manual, low-cost sensors, infrastructure, country map with air quality monitoring stations, instruments, laboratories, manpower, etc.) and monitoring data; emission inventory developments (pollutants, sectors, data); studies on air quality modelling and impact assessments; air pollution mitigation plans, actions, and policies; success stories, lessons learned, and challenges; and any other information/data which countries would like to share during the workshop. From the countries' presentations, information about air quality monitoring facilities, emission inventory development, AQM and impact assessment studies, air pollution mitigation policies and action plans, challenges, and needs of the countries (required for effective management of air quality) were extracted and presented in this article.

3. RESULTS AND DISCUSSION – STATUS OF AQM

3.1. Ambient air quality monitoring stations

The objective of establishing ambient air quality monitoring stations (AAQMS) in an area is to measure concentrations of key air pollutants to define the air quality (good, moderate, unhealthy, very unhealthy, and hazardous) based on air quality index values derived from the monitoring data. There are several criteria suggested for establishing the number of AAQMS in an area, such as source attribution (industries, road traffic, power plants, etc.), location (urban, rural, remote), topography and meteorology, inhabitant populations, population density, target air pollutants, cost-effectiveness, and several other factors (Choudhary, Kaur, Saharan, & Kumar, 2022 and references therein). However, to get accurate information on population exposure to air pollution, population-weighted criteria are commonly recommended for establishing the number of AAQMS in an area. Table 2 provided recommendations on population-weighted criteria for establishing the number of AAQMS in an area (BIS, 2000).

Although, within the population-weighted criteria, there are some sub-criteria for establishing the number of AAQMS. However, in general, at least four monitors need to be installed per 100,000 to 1 million population to measure each air quality parameter: PM, nitrogen dioxide (NO_2), sulphur dioxide (SO_2), and carbon monoxide (CO) (BIS, 2000; Steinar, Rob, & Helmis, 1999).

Countries in South Asia and Southeast Asia are operating or have installed a number of AAQMS for monitoring key air quality parameters, including PM (PM_{10}, $PM_{2.5}$), SO_2, NO_2, CO, Ozone (O_3), meteorology, and other parameters. While not all monitoring stations in the countries are equipped with monitors for all key air quality parameters, at least PM monitors are installed at the majority

Pollutant	Population of evaluation area	Minimum no. of AAQMS
SPM (or PM)	< 100,000	4
	100,000–1,000,000	4 + 0.6 per 100,000 population
	1,000,000–5,000,000	7.5 + 0.25 per 100,000 population
	> 5,000,000	12 + 0.16 per 100,000 population
SO_2	< 100,000	3
	100,000–1,000,000	2.5 + 0.5 per 100,000 population
	1,000,000–10,000,000	6 + 0.15 per 100,000 population
	> 10,000,000	20
NO_2	< 100,000	4
	100,000–1,000,000	4 + 0.6 per 100,000 population
	> 1,000,000	10
CO	< 100,000	1
	100,000–5,000,000	1 + 0.15 per 100,000 population
	> 1,000,000	6 + 0.05 per 100,000 population
Oxidants	- do -	- do -

TABLE 2. Recommended population-weighted criteria for establishing the number of AAQMS in an area (BIS, 2000).

of monitoring stations. In this section, air quality monitoring facilities, primarily the number of AAQMS operated or installed, are evaluated with population-weighted criteria. For simplicity, we used the criteria of four monitors for monitoring the key air quality parameters per million of population.

Table 3 and Figure 2 show an evaluation of the number of AAQMS operated or installed in countries in South Asia and Southeast Asia using the population-weighted criteria (number of AAQMS per million population).

As mentioned, countries need to operate at least four monitors for each key air quality parameter per million population to get better information on population exposure to air pollution. In South Asia, India is the largest country, with a population of over 1408 million (as of 2021). Considering its large population, India needs to operate 5,632 AAQMS nationwide. However, currently, India is operating 1,254 AAQMS in the country, and it needs 4,378 more AAQMS to fulfil the population-weighted criteria. Pakistan, with a population of over 231 million (as of 2021), operates only two air AAQMS in the country. However, at least 926 more AAQMS are needed to fulfil the population-weighted criteria. Similarly, Bangladesh, with a population of over 169 million (as of 2021), is operating 31 AAQMS in the country and needs at least 678 AAQMS to fulfil the criteria, and it needs to install 647 more AAQMS in the country. Iran, with a population of 88 million (as of 2021), is operating 200 AAQMS in its air quality monitoring network and needs at least 352 AAQMS to fulfil the population-weighted criteria and is required to install 152 more AAQMS. The population of Nepal is about 30 million (as of 2021), and as per the population-weighted criteria, it needs at least 120 AAQMS. Currently, Nepal is operating or has installed 27 AAQMS in the country, and it needs 93 more AAQMS in the country to fulfil the criteria. Sri Lanka, with a population of 22 million (as of 2021), operates only three AAQMS. However, it needs at least 88 AAQMS in the country to fulfil the criteria and is required to install 85 more AAQMS. Maldives and Bhutan are relatively smaller countries in South Asia, with a population of less than a million. Both countries have installed a sufficient number of AAQMS in the country to fulfil the population-weighted criteria for the number of AAQMS required.

In Southeast Asia, Indonesia is the largest country in terms of population, with 273.8 million (as of 2021). Indonesia is operating 56 AAQMS across the

Name of country	Population (in millions as of 2021)	Air quality monitoring stations				No. of AAQMS currently in operation or installed (f = b + c + d + e)	No. of AAQMS required as per population-weighted criteria (g = a × 4)	No. of AQMS required more (h = g – f)	CEMS
	(a)	Automatic[#] (b)	Manual[$] (c)	Mobile[€] (d)	LCS[£] (e)				
South Asia									
Bangladesh	169.4	31	NA	NA	NA	31	678	647	NA
Bhutan	0.777	2	1	NA	3	6	4	0	NA
India	1408	372	882	NA	NA	1254	5632	4378	Yes
Iran	87.92	200	NA	NA	NA	200	352	152	NA
Maldives	0.521	1	NA	NA	8	9	4	0	NA
Nepal	30.03	27	NA	NA	NA	27	120	93	NA
Pakistan	231.4	1	NA	1	NA	2	926	924	NA
Sri Lanka	22.16	2	1	NA	NA	3	88	85	NA
Southeast Asia									
Brunei Darussalam	0.45	7	NA	NA	NA	7	4	0	Yes
Cambodia	16.59	10	NA	1	53	64	66	2	NA
Indonesia	273.8	56	NA	NA	NA	56	1095	1039	Yes
Lao PDR	7.43	10	NA	1	NA	11	30	19	NA

Continued on next page

TABLE 3. Status of air quality monitoring in countries in South Asia and Southeast Asia, including the number of AAQMS currently in operation or installed, the number of AAQMS required to fulfil the population-weighted criteria, the number of AAQMS required more, and the continuous emission monitoring systems (CEMS) installed.

TABLE 3. *Continued.*

Name of country	Population (in millions as of 2021)	Air quality monitoring stations				No. of AAQMS currently in operation or installed (f = b + c + d + e)	No. of AAQMS required as per population-weighted criteria (g = a × 4)	No. of AQMS required more (h = g – f)	CEMS
	(a)	Automatic# (b)	Manual$ (c)	Mobile€ (d)	LCS£ (e)				
Malaysia	33.57	68	14	3	NA	85	134	49	Yes
Myanmar	53.8	25	NA	NA	NA	25	215	190	NA
Philippines	113.9	54	55	NA	NA	109	456	347	Yes
Singapore	5.45	23	NA	NA	NA	23	22	0	Yes
Thailand	76.6	100	10	7	1680	1797	306	0	Yes
Vietnam*	98.5	104	NA	NA	150	254	394	140	Yes

NA – information not available.

* Personal communication with the Northern Center of Environmental Monitoring (NCEM), Vietnam Environment Administration (VEA), Vietnam.

Continuous ambient air quality monitoring stations (CAAMS) – data acquired automatically to the data centre.

$ Monitoring station operated manually, such as changing PM filter paper and analysis of samples manually in the laboratory.

€ A vehicle with installed necessary monitoring instruments and equipment which can be taken to the desired location for air quality monitoring.

£ Low-cost sensors (LCS) are portable air quality monitoring sensors that can be installed and operated at desired locations with minimum operating cost. LCS sends data to the server through the wireless network. LCS used a light scattering technique for determining the concentration of particles (e.g., PM) and non-dispersive infrared radiation absorption (NDIR) for gaseous pollutants. Common techniques used in the LCS are summarised by Bucek, Maršolek, and Bılek (2021).

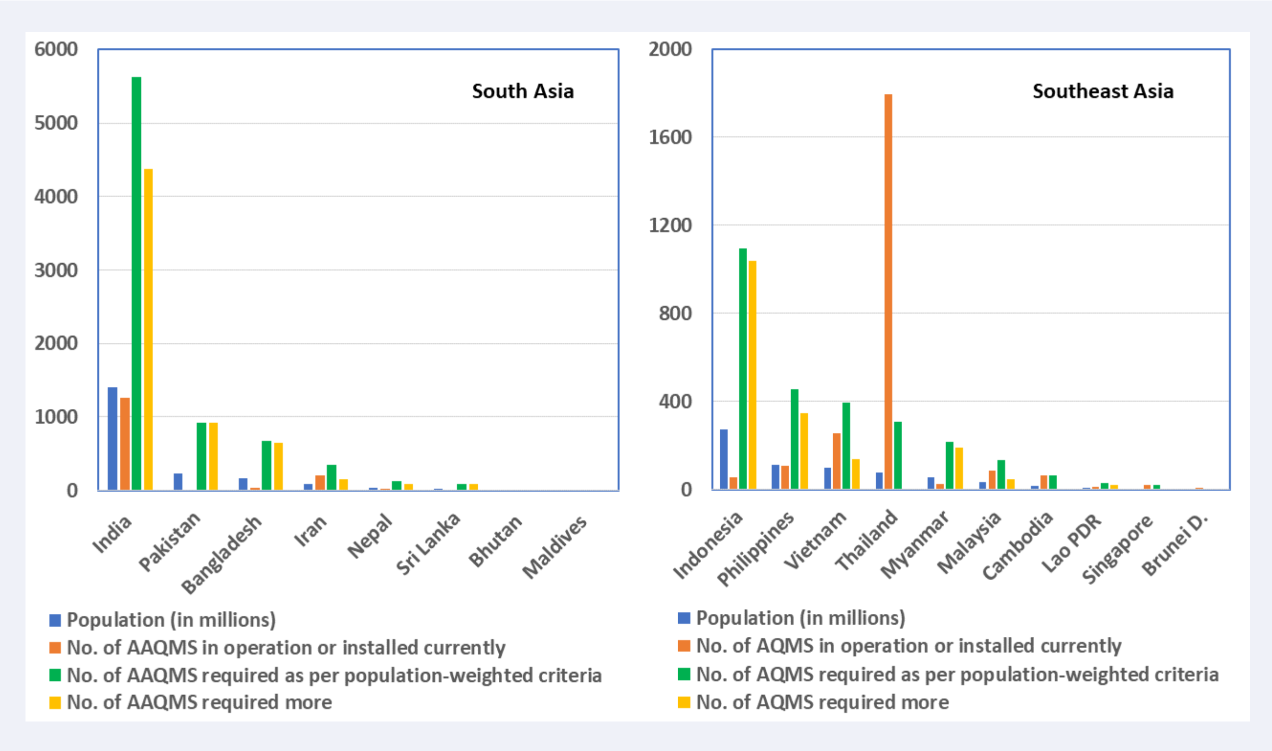

FIGURE 2. Number of AAQMS in countries in South Asia and Southeast Asia, including the number of AAQMS in operation or installed currently (including LCS), the number of AAQMS required as per population-weighted criteria, and the number of AAQMS required more.

country. However, considering its large population size, it needs to operate at least 1,095 AAQMS to fulfil the population-weighted criteria and is required to install 1,039 more AAQMS to fulfil the criteria. Similarly, the Philippines, with pollution of 114 million (as of 2021), is operating or has installed 109 AAQMS in the country. Considering its population size, the Philippines needs to operate 456 AAQMS in the country to fulfil the population-weighted criteria and is required to install 347 more AAQMS. With more than 98.5 million of the population (as of 2021), Vietnam is operating 254 AAQMS and requires 394 AAQMS to fulfil the criteria and needs 140 AAQMS more. Thailand, with a population of 77 million (as of 2021), is operating 1,797 AAQMS in the country, including 100 automatic, ten manual, seven mobile, and 1680 LCS, which are more than enough AAQMS required to fulfil the population-weighted criteria for the number of AAQMS in the country. Malaysia, with a population size of 33.6 million (as of 2021), is operating 85 AAQMS across the country; however, it needs 134 AAQMS to fulfil the criteria and required 49 more AAQMS in the country. Myanmar, with a population of 54 million (as of 2021), is operating 25 AAQMS in the country; it needs 215 AAQMS to fulfil the population-weighted criteria and needs 190 AAQMS more. Cambodia, with a population of 16.59 million, is operating 64 AAQMS across the country, and it needs 66 AAQMS to fulfil the population-weighted criteria and needs just two more AAQMS for that. Lao PDR, with a population of 7.43 million (as of 2021), is operating 11 AAQMS in the country. Considering population size, Lao PDR needs 30 AAQMS to fulfil the criteria and 19 more AAQMS. In the case of Singapore and Brunei Darussalam, both countries are operating enough numbers of AAQMS in the country and fulfil the population-weighted criteria for the number of AAQMS.

It could be noted that the population-weighted criteria for establishing the number of AAQMS have some limitations. The criteria are mostly applicable in the urban region where a considerable size of the population lives. In island countries, such as Indonesia, the Philippines, and the Maldives, where the population is scattered and live on many islands, these countries may choose to establish the number of AAQMS based on the population size living on a specific island rather than based on the whole country's population.

Continuous Emission Monitoring System (CEMS) is a real-time point source emission monitoring of air pollutants (e.g., PM, CO, carbon dioxide (CO_2), SO_2, NO_x, hydrochloric acid (HCl), ammonia (NH_3), volatile organic compounds (VOC_s), mercury (Hg), etc.) from large industries, such as refineries, cement plants, power plants, chemical industries and other manufacturing industries in which smoke is emitted from the stacks. CEMS provides a real-time concentration of air pollutants which could be used for regulatory purposes, including compliance checks. In South Asia, only India has started operating and installing the CEMS in several industries. At the same time, no information is available about the installations of CEMS in the industries of the rest of the South Asian countries, namely Bangladesh, Bhutan, Nepal, Pakistan, Sri Lanka, and Maldives. In Southeast Asia, Brunei Darussalam, Indonesia, Malaysia, the Philippines, Singapore, Thailand, and Vietnam have installed or started installing the CEMS in their heavy industries and power plants. At the same time, no information is available about the installation of CEMS in Cambodia, Lao PDR and Myanmar.

The information given in Table 3 and Figure 2 on the numbers of AAQMS operated or installed in the countries of South Asia and Southeast Asia revealed that, except Bhutan, Maldives, Brunei Darussalam, Singapore, and Thailand, most countries are not operating or have installed enough numbers of AAQMS in the countries which could fulfil the population-weighted criteria for the adequate numbers of AAQMS. This implies that population exposure to air pollution information, which uses for air pollution health impact assessment, is unreliable in South Asia and Southeast Asia. On the other hand, the information in Table 3 provides immense opportunities for countries to invest more in strengthening their air monitoring network, including the mobilisation of financial resources from international funding agencies to countries for establishing more air quality monitoring stations.

It could also be noted that, except for Thailand, most countries in South Asia and Southeast Asia are operating traditional instruments for air quality monitoring, which requires significant financial resources to operate the AAQMS. This provides an opportunity to explore the use of LCS for air quality monitoring since operating the LCS requires comparatively lesser financial resources. Also, only 8 out of 18 countries have installed or are in the process of installing the CEMS in their heavy industries. This provides significant business opportunities to invest financial resources to install the CEMS in the industries of these countries.

3.2. Emissions inventory development

Emissions inventory (EI) data (in addition to air quality monitoring data) is a primary requirement for formulating effective air pollution mitigation policies and action plans. Figure 3 provides qualitative information on the status of emissions inventory development in countries in South Asia and Southeast Asia, while detailed information is given in Table 4. In South Asia, only three out of eight countries (Iran, the Maldives and Nepal) have developed or started developing their EI. For example, Iran has developed EI for CO, nitrogen oxides (NO_x), sulphur oxides (SO_X), VOC and PM from various sources in ten major cities; Maldives has developed EI of organic carbon (OC), black carbon (BC), PM, NH_3, SO_2, NO_x, VOCs, methane (CH_4), CO and CO_2 including future emissions scenarios. Nepal has started developing EI from the brick and cement industries. No information is available on the status of EI development in the remaining South Asia countries in (India, Bangladesh, Pakistan, Bhutan and Sri Lanka).

In Southeast Asia, six out of ten countries (Cambodia, Indonesia, Malaysia, Myanmar, the Philippines and Thailand) have developed or started developing EI. For example, Cambodia has developed EI for OC, BC, PM, NH_3, SO_2, NO_x, VOCs, CH_4, CO, and CO_2 from various sources; Indonesia completed the

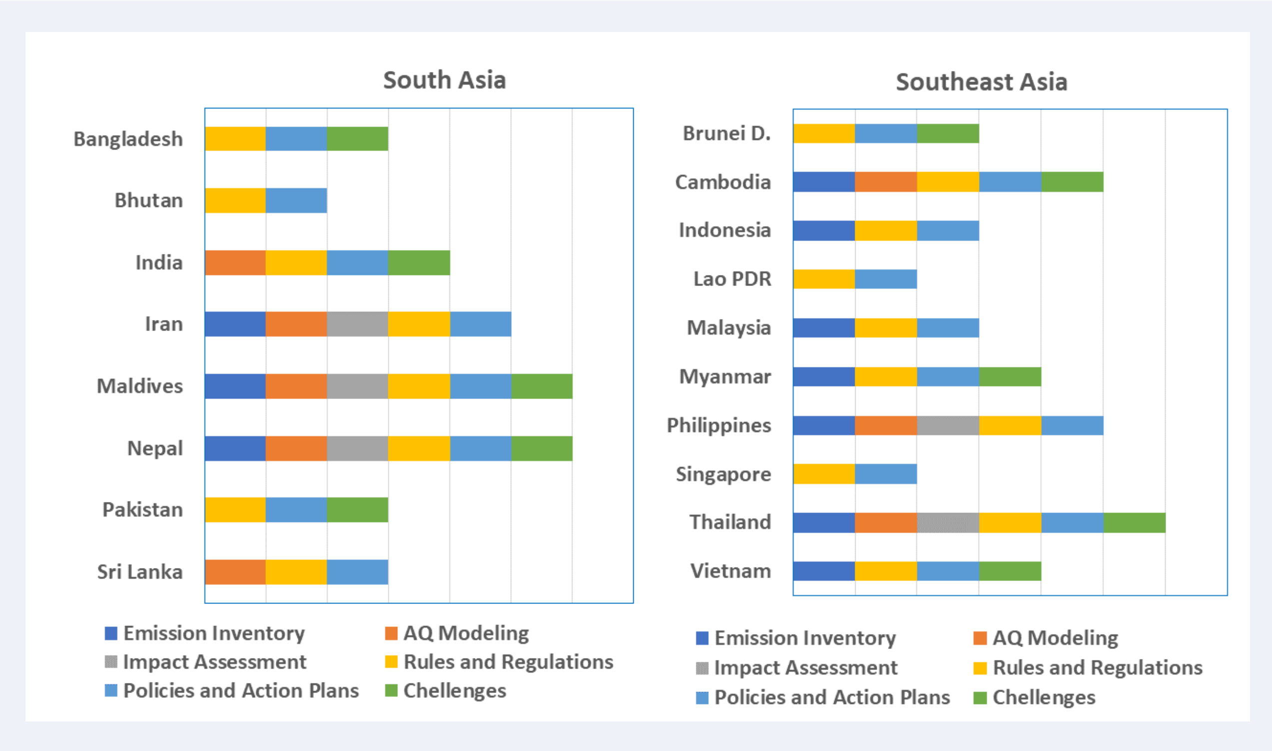

FIGURE 3. Qualitative information on the status of emission inventory development, air quality modelling, impact assessment, rules and regulations, policies and action plans, and challenges of countries in South Asia and Southeast Asia in AQM. Detailed information is given in Table 4.

EI in 30 cities; Malaysia has developed the EI of SO_2, NO, PM, and CO from industrial sources; Myanmar has developed EI for PM, NO_x, CO, CO_2, CH_4, and VOCs from road transport and agriculture sector; the Philippines has developed EI from stationary and mobile sources and developed an online EI databank; and Thailand has developed the EI of $PM_{2.5}$, NO_x, non-methane volatile organic compounds ($NMVOC_s$), SO_2 for the Bangkok Metropolitan Region (BMR) and 77 provinces. Vietnam has started to develop a guideline for EI development for the country. No information is available on the status of EI development in the rest of the countries of Southeast Asia (Brunei Darussalam, Lao PDR, and Singapore).

3.3. Air quality modelling

Air quality modelling is a crucial aspect of AQM. It involves estimating the concentration of air pollutants downwind from sources like industry and road transportation. These models also simulate secondary pollutants like PM and O_3, aid in identifying and apportioning pollution sources, provide air pollution forecasts, understand weather patterns and transport mechanisms through meteorological data input, conduct impact assessments, and support regulatory decision-making.

The status of air quality modelling in countries in South Asia and Southeast Asia is given in Figure 3 and Table 4. In South Asia, India has started air quality forecasting using the WRF-Chem and SILAM in Delhi and National Capital Region (NCR) and other major cities in India. Iran has conducted point source modelling (e.g., power plants) and air quality forecasting in Tehran. The Maldives has developed emissions scenarios for air pollutants, while some researchers have undertaken dispersion modelling in Nepal. Sri Lanka has recently acquired the AERMOD model. No information is available about the status of air quality modelling in Bangladesh, Bhutan and Pakistan.

In Southeast Asia, Cambodia has developed emission scenarios for air pollutants. The Philippines is conducting dispersion and source apportionment modelling, while Thailand is conduct-

Name of country	Emission inventory	Air quality modelling	Impact assessment	Air pollution control and abatement regulations	Air pollution mitigation policies and action plans	Challenges
South Asia						
Bangladesh	NA	NA	NA	- Environment Conservation Act 1995 - Environment Conservation Rule 1997 - Air Pollution Guideline 2021 - Air Pollution Control Rules 2022 - Gazette Notification for Construction dust management	- National Environment Policy 2018 - Phasing out leaded fuels - Ban on two-stroke vehicles - Promoting CNG vehicles - Banning old vehicles - Implement vehicle emissions standards - Policies on emission reduction from Brick Kilns - Ban on high sulphur-containing coal	- Euro 4 vehicles - Transboundary air pollution - Modern technology for Industrial pollution - Brickfield management - Open Burning - Coverage of open space area - Online monitoring system - Capacity building - Lack of funds and research
Bhutan	NA	NA	NA	- Environmental Assessment Act 2000 - National Environment Protection Act 2007 - Euro VI Emission standards	- Electric vehicle initiative - Sustainable Low-Emission Urban Transport System - Guidelines on Industries	NA

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TABLE 4. Status of development of emission inventory, air quality modelling, impact assessment, air pollution mitigation policies and action plans, and challenges.

TABLE 4. *Continued.*

Name of country	Emission inventory	Air quality modelling	Impact assessment	Air pollution control and abatement regulations	Air pollution mitigation policies and action plans	Challenges
India	NA	Air quality forecasting using WRF-Chem and SILAM in Delhi-NCR and major Indian cities	NA	- Air Prevention and Control of Pollution Act 1981 - Environment Protection Act 1986 - National Ambient Air Quality Standards 2009	- National Ambient Air Monitoring Programme - National Clean Air Programme - Fuels of BS VI standards - Phasing out old - EV Policy launched - Intelligent Traffic Management System - Cleaner fuels (CNG, CBG, and ethanol blending) - Stringent norms for power plants and industries - Real-time tracking of industrial emissions - Ujjawala scheme for cleaner cooking fuel - Waste management – Swatch Bharat, EPR	- Many non-attainment cities - Dust contributing to PM_{10} & $PM_{2.5}$ in most urban areas - Lack of scientific evidence for policies - Complexity in developing action plans - Implementation of actions plans and target setting - Lack of stakeholders participation - Limited public involvement - Lack of coordination among relevant agencies - Limited monitoring and evaluation of the implementation of action plans - Financial constraints

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TABLE 4. *Continued.*

Name of country	Emission inventory	Air quality modelling	Impact assessment	Air pollution control and abatement regulations	Air pollution mitigation policies and action plans	Challenges
Iran	Developed emission inventories for CO, NO_x, SO_X, VOC & PM from various sources in 10 major cities	Conducted air quality modelling from point source emissions (e.g., power plants) and forecasting of air quality in Tehran	Conducted air pollution health impact assessment in Tehran	- Environmental Protection Act 1974 - National Clean Air Regulations 1975 - Clean Air Law 2017	- Review of air pollutant permissible limits for industries. - Development of air pollution reduction action plans for 18 cities - Clean Air Law implementation review - Development of air pollution emission inventories for cities. - Upgrading fuel standard and vehicle emission standards	NA
Maldives	Developed emission inventories of OC, BC, PM, NH_3, SO_2, NO_x, VOCs, CH_4, CO, and CO_2 from various sources	Developed air pollution emission scenarios	NA	Policy framework and planning to guide the overall development direction of the Maldives from 2019-2023	- Revision of vehicle and vessel emission standards and - Development of fuel quality standards - Development of emission inventories - Implementation of Integrated Transport Master Plan - Expansion of Air Quality Monitoring network.	- Lack of financial resources - Lack of technical capacity and human resources - Lack of public interest - Limited air quality data, including emission sources. - Lack of technology
Nepal	Developed emission inventories from the brick and cement industry	Conducted some dispersion modelling by researchers	Study on air pollution health impacts conducted in Kathmandu Valley in 2021	- Environmental Protection Act 2019 - Environment Protection Regulation 2020 - National Environment Policy 2021	- Kathmandu Valley Air Quality Management Action Plan 2019 - Various standards: NAAQS 2012, Vehicular Emission Standard, Incinerators, Brick Industry, and Cement	- Continuous operation of AQMS - Shifting from EURO III to EURO IV - Continuous industrial monitoring - Emission inventory and air quality modelling - Open burning and forest fires

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TABLE 4. *Continued.*

Name of country	Emission inventory	Air quality modelling	Impact assessment	Air pollution control and abatement regulations	Air pollution mitigation policies and action plans	Challenges
Pakistan	NA	NA	NA	- Pakistan Environmental Protection Act 1997 - NEQS for Industries 2000 - NEQS for vehicles 2009 - NAAQS 2010	- Installation of pollution control technologies in steel industries - Smog action plan implementation - Implementation of EV Policy and EURO-V Standard Fuel	- Vehicular emission and crop burning - Inconsistent in data collection - 18th Constitutional Amendment - Lack of capacity
Sri Lanka	NA	Started air quality modelling using the AEROMOD software	NA	- National Environmental Act - Management environment policies - Air quality management unit - National air quality management policy	- Permissible Ambient Air Quality Standards 2008 - Stationary Source Emission Control 2019 - Vehicle Emission Testing Programme 2013 - Introduced low sulphur diesel 2014 - Banded burning of plastic in 2017 - Introduced EURO4 standard in 2018	NA
Southeast Asia						
Brunei Darussalam	NA	NA	NA	- Environmental Protection and Management 2016 for air pollution control and opening burning - A comprehensive review of air quality preventive and mitigation measures	- Target is set to achieve 100% good days in a year of PM10 less than 50 μg/m³ by 2035 - Enforcement of continuous environmental monitoring systems in industries	- Unregulated open burning activities. - The lack of participation of public and industries stakeholders in complying to air guidelines - Unprecedented weather changes (e.g., prolonged dry conditions)

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TABLE 4. *Continued.*

Name of country	Emission inventory	Air quality modelling	Impact assessment	Air pollution control and abatement regulations	Air pollution mitigation policies and action plans	Challenges
Cambodia	Developed emission inventories of OC, BC, PM, NH_3, SO_2, NO_x, VOCs, CH_4, CO, and CO_2 from various sources	Developed air pollution emission scenarios	NA	- Environmental Protection and Natural Resource Management Law 1996 - Air Pollution Control and Noise Disturbance sub decree 1999 - Circular on Measures to Prevent and Reduce Ambient Air Pollution 2020	- Ambient Air Quality Standard - Emission Standard for Mobile Sources - Emission Standard for Stationary Sources - Technical Guideline to Control Air Pollution from Industries	- Limited resources and equipment for air pollution control, monitoring, and inspection - Limited technical expertise in air quality management - Limited source analysers and modern technologies - Limited cooperation in information and data sharing by industries - Lack of technical and financial support
Indonesia	Emission inventory in 30 cities has been completed.	NA	NA	- Decree on Air Pollutant Standard 2020 - Regulation on Implementation, Protection and Management of Environment 2021 - Decree on Environmental Quality Index 2021 - Decree on Continuous Industrial Monitoring Information System 2021	- Law enforcement for the prevention of forest fires - Encouraging public participation in air pollution control activities - Enforcement of fuel standards - Strengthening of air quality standard - Installation of emission control systems in industries - Development of emission inventories	NA

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TABLE 4. *Continued.*

Name of country	Emission inventory	Air quality modelling	Impact assessment	Air pollution control and abatement regulations	Air pollution mitigation policies and action plans	Challenges
Lao PDR	NA	NA	NA	- Environmental Protection Law 2013 - Decree on National Environmental Standard 2017 - Decision of Pollution Control 2021	- Upgrading existing AQM stations by installing additional instruments. - Expanding the AQM network nationwide by installing new AQM stations - Improving air quality data management and information system	NA
Malaysia	Developed emission inventories of SO_2, NO, PM, and CO from various sources	NA	NA	- Control of emission from diesel engines regulations 2000 - Control of petrol and diesel properties regulations 2007 - Clean air regulations 2014	- Every premise shall install an air pollution control system - Technical guideline on performance evaluation of air pollution control system - Industries are encouraged to implement seven environment mainstreaming tools - Implementation of Euro 5 fuel quality	NA
Myanmar	Developed emission inventory of PM, NO_x, CO, CO_2, CH_4, and VOCs from road transport and agriculture sector	NA	NA	- National environment policy 2019 - Environment Conservation Law 2012 and Rule 2014	National environmental quality guidelines 2015	- Insufficient monitoring stations - Lack of resources, technologies, awareness, and cooperation

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TABLE 4. *Continued.*

Name of country	Emission inventory	Air quality modelling	Impact assessment	Air pollution control and abatement regulations	Air pollution mitigation policies and action plans	Challenges
Philippines	Developed emission inventories from stationary and mobile sources and developed online emission inventory databank	Conducted dispersion and source apportionment modelling	NA	- Clean air act 1999 - Implementing Rules and Regulation 2000 - National ambient air quality guideline values for criteria pollutants 2000 - National emission standards for source-specific air pollutants 2000	- Guidelines for designation of attainment and non-attainment areas 2005 - Emission charge system - Emission averaging of existing sources - Updating of Best Available Control Technologies - Airshed management - Online emissions inventory system	NA
Singapore	NA	NA	NA	- Environmental Protection and Management Act - Air impurities regulations - Off-road diesel engine emissions regulations - Prohibition on the use of open fires - Vehicular emissions regulations - Transboundary haze pollution act	- Comprehensive policies for air pollution control from stationary sources - Development control and environmental assessments - Licensing and pollution control - Encourage the adoption of vehicles with low emissions - Periodic inspection of vehicles	NA

Continued on next page

TABLE 4. *Continued.*

Name of country	Emission inventory	Air quality modelling	Impact assessment	Air pollution control and abatement regulations	Air pollution mitigation policies and action plans	Challenges
Thailand	Conducted emission inventories of $PM_{2.5}$, NO_X, $NMVOC_s$, SO_2 in BMR region and 77 Provinces	Conducted air quality modelling using the models (WRF-Chem, Chemax, GAINS, CALINE4, AERMOD, CMB, and PMF)	Evaluated health impacts and social impacts using the models (BenMAP Abacas, LEAP-IBC)	- Automotive emission standards for new and in-used motor vehicle 1994 - Environment Act 2004 - Energy Conservation Promotion Act 2009 - Volatile Organic Compounds in Ambient Air 2007 - National ambient air quality standards 2022	- Development of vehicle pollution control strategy - PM2.5 National Action Plan Agenda and Plan 2020 - Periodic inspection licensing of vehicles for pollution control - Develop NDC to manage air pollution and Climate Change with a target of carbon neutrality in 2050 and zero emission in 2065	- PM and O_3 still exceed the standards. - Increasing number of vehicles - Extreme traffic congestion - Low dispersion of pollutants - Lack of technical and financial support - Lack of scientific evidence for policies - Complexity in developing action plans, implementation and target setting
Vietnam	Guideline for EI development for the country is under preparation.	NA	NA	- Law on environmental protection - National technical regulation on ambient air quality - Circular on technical procedures for air emissions monitoring - Decree on environmental protection planning, strategic environmental assessment, environmental impact assessment and environmental protection plans	- Directive on increasing control of air pollution - Circular on environmental protection in industrial clusters, business zones, services centres, and craft villages - National action plan on air quality management by 2020, vision to 2025 - Implementation of solutions to control crop residue open burning in some provinces - Lower sulphur diesel - National technical regulation on controlling emissions from heavy industries	- Limited resources (technical, human resources, financial support) and infrastructure for air quality management - Limited cooperation in data and information compilation and data sharing by industries and organisations - Lack of coordination among relevant agencies - Limited public involvement - Limited scientific evidence at local levels

NA – information not available.

ing air quality modelling using the WRF-Chem (Weather Research and Forecasting Model coupled with Chemistry), GAINS (Greenhouse Gas and Air Pollution Interactions and Synergies), CALINE (California Line Source), AERMOD, CMB, and PMF (Figure 3 and Table 4). No information is available about the status of air quality modelling in Brunei Darussalam, Indonesia, Lao PDR, Malaysia, Myanmar and Singapore. Some studies on the application of air quality modelling have been conducted by various individual research groups/organisations in the region, but the national governments were not part of those studies.

3.4. Impact assessment

Air quality impact assessment is an important part of EIA and is used for strategic environmental planning. In South Asia, Iran in Tehran, and Nepal in Kathmandu (through a research organisation) conducted air pollution impacts on health. (Figure 3 and Table 4). No information on air pollution impact assessment on health and the environment in Bangladesh, Bhutan, India, Maldives, Pakistan, and Sri Lanka is available. In Southeast Asia, Thailand is assessing the health and social impacts of air pollution by using impact assessment models, including BenMAP (Environmental Benefits Mapping and Analysis Programme), ABaCAS (Air Benefit and Cost and Attainment Assessment System), and LEAP-IBC (Low Emissions Analysis Platform – Integrated Benefits Calculator). Whereas no information is available about air pollution impact assessment in the rest of the Southeast Asian countries.

3.5. Mitigation policies and action plans

Air pollution mitigation regulations, policies, and action plans mainly aim to prevent, control, and abate emissions of air pollutants from various sources to avoid adverse impacts on health and the environment. The regulations, policies, and action plans are varied with target pollutants sources, cities, and countries. It is noted that all countries of South Asia and Southeast Asia have formulated air pollution mitigation regulations, policies, and action plans depending on their needs and resources. Countries-wise air pollution mitigation regulations, policies, and action plans are briefly summarised in Table 4 and presented in Figure 3. The majority of air pollution control and abatement regulations include the Environment Conservations Act, Environment Assessment Rule, Air Pollution Control and Prevention Act, Environment Protection Act, Environmental Protection Law, National Clean Air Regulations, Clean Air Law, Air Pollution Guideline, National Ambient Air Quality Standards, stationary and mobile source-specific emission standards, and other related rules and regulations.

Whereas in the case of air pollution mitigation policies and action plans, countries of South Asia and Southeast Asia, depend on their needs and resources, have established National Environment Policy, National Air Monitoring Programme, National Clean Air Programme, implementation of clean fuel standards (e.g., low sulphur), setting up clean air targets, phasing out old vehicles and leaded fuels, introducing electric vehicles, improvement in traffic management, introduction of clean fuels (e.g., compressed natural gas (CNG), compressed bio gas (CBG) and ethanol blending), development and enforcement of emission standards for stationary and mobile sources, development of emission inventories for various emission sources, installation of emission control technologies in industries and power plants, development and enforcement of emission reduction action plans in cities, enforcement of stringent emission standards for industries and power plants, real-time monitoring of industrial emissions, introduction of clean cooking fuel (e.g., liquefied petroleum gas (LPG)), banning on open burning of municipal waste and agriculture residues, prevention and control of forest fires, setting up and management of airsheds, and several other relevant policies and action plans.

3.6. Challenges

Challenges in AQM are obstacles in the progress of achieving clean air goals. Table 4 summarises common challenges faced by the countries of South Asia and Southeast Asia. It revealed that South Asia and Southeast countries are facing enormous challenges in effectively managing air quality in their countries. One of the major challenges is the lack of scientific evidence at the local level to formulate effective air pollution mitigation policies and action plans and set up clean air targets. Regulations and policies are generally formulated referring to the UN guidelines and widespread local perceptions rather than authentic scientific evidence. In most countries in South Asia and Southeast Asia, local or regional level meteorology (e.g., prevailing stagnant weather conditions) play a crucial role in building up episodic higher pollution levels.

Countries in South Asia and Southeast Asia face common challenges, such as high pollution levels in major cities (e.g., India, Indonesia and the Philippines), the need for continuous air quality monitoring networks, emissions inventories, and air quality modelling. They also struggle with addressing dust contributions to PM levels in urban areas, creating effective action plans, implementing actions, setting targets, and adopting improved emissions standards (e.g., Euro 4, 5, 6). Other challenges include handling open waste burning, lacking modern emission reduction technologies for mobile and stationary sources, limited stakeholder participation, coordination issues among agencies, insufficient monitoring data and policy evaluation, transboundary impacts, and limitations in technical and financial resources.

3.7. Opportunities

Challenges always come with solutions and offer abundant opportunities for exploration. Countries in South Asia and Southeast Asia are currently grappling with various challenges in AQM and the pursuit of clean air goals (refer to Section 3.6). Despite these challenges, there are numerous avenues for exploration and utilisation.

For instance, Table 3 reveals that many countries in these regions do not operate enough AAQMS to meet population-weight criteria for obtaining reliable data on air pollution exposure. Traditional air quality monitoring instruments are predominantly used, demanding substantial financial resources for operation. This situation prompts an opportunity to consider LCS for air quality monitoring, which require comparatively fewer financial resources. Additionally, several countries have begun installing or are in the process of setting up CEMS, creating substantial business prospects for investments in these countries.

Furthermore, only a few countries have started developing EIs and establishing facilities for air quality modelling. Health impact assessments due to air pollution remain rare, and many countries lack scientifically-backed air pollution regulations and policies. These challenges underscore significant opportunities for governments to enhance air quality monitoring networks, establish emission inventories, assess impacts on health, ecosystems, economies, and the environment, and support the formulation of evidence-based air pollution policies and action plans.

International funding agencies have a role to play in leveraging technical and financial resources to help countries expand their air quality monitoring networks, introduce CEMS, establish EI development facilities, and foster science-driven policies. These initiatives collectively contribute to the effective management of air quality.

4. CONCLUSION

This article compiles data from 17 South Asian (Bangladesh, Bhutan, India, Iran, Maldives, Nepal, Pakistan, Sri Lanka) and Southeast Asian (Brunei, Cambodia, Indonesia, Laos, Malaysia, Myanmar, Philippines, Singapore, Thailand) countries, gathered during an AQM workshop in September 2022, and supplemented by personal communication for Vietnam. Assessing against population-weighted criteria (four monitors per million people), it is evident that, barring Thailand and lower-population nations, both South Asian and Southeast Asian countries lack sufficient AAQMS, compromising reliable air pollution exposure data. Only eight of 18 nations are implementing or planning to implement CEMS. South Asia sees three out of eight countries (Iran, Maldives, Nepal) developing EI, and Southeast Asia has six out of ten countries (Cambodia, Indonesia, Malaysia, Myanmar, Philippines, Thailand) doing the same. Air quality modelling is undertaken by a few (India, Iran, the Philippines and Thailand), and impact assessment studies are rare except for Iran, Nepal and Thailand. While all countries have air pollution regulations and action plans, scientific evidence to support them is lacking. The article underscores substantial opportunities for countries to enhance air quality monitoring, install CEMS, consider LCS, establish EI development facilities, and undertake air quality modelling and impact assessments. This presents an ideal moment for the UN, international organisations, and funding agencies to financially and technically assist countries in bolstering AQM components, achieving clean air targets, and enhancing air quality.

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Technical Report

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Developing capacity for post-typhoon disaster waste management in Lautoka, Fiji and Makati, Philippines

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ABSTRACT

In recent years, Asia and the Pacific have been ravaged by strong typhoons that caused widespread destruction. The powerful winds from these typhoons ripped off roofs, windows, doors and walls from houses, and destroyed trees and other vegetation, leaving a vast amount of wooden, metallic, plastic, and glass debris and waste scattered across a wide area. Proper management of disaster waste is a critical task during the initial phase of disaster recovery. It is essential for coastal cities that are frequently affected by typhoons to have adequate capacity for post-disaster waste management. This capacity development project aimed to contribute to this end by providing appropriate knowledge and training to government and non-government stakeholders. The project was implemented in Lautoka City, Fiji and Makati City, Philippines, with the support of four prominent universities. In total, six training sessions were conducted under the project. The primary outputs of this project are the disaster waste management contingency plans of the two participating cities. The project team disseminated information about the capacity development project through the project website and through presentations in academic conferences, webinars, workshops, training, non-academic conferences, and radio guest appearances.

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KEYWORDS

Circular economy, debris management, disaster waste management, resource recovery, contingency planning, Global South

HIGHLIGHTS

- Participating cities developed their disaster waste management contingency plans.
- The Philippine Association for Disaster Waste Management was established.
- More than 20 local and international presentations were conducted to promote disaster waste management.
- Experience and outputs are shared through a website: https://disaster-waste.org/.

1. INTRODUCTION

In recent years, Asia and the Pacific have been hit by strong typhoons[1] that caused widespread destruction. One of the most devastating was Typhoon Haiyan in 2013, which affected the Philippines, Vietnam, Mainland China, and Taiwan. Cyclone Winston in 2016 caused significant damage to Fiji and other South Pacific nations, while Typhoon Mangkhut in 2018 impacted the Philippines, Taiwan, Hong Kong, Macau, and Mainland China. The strong winds from these typhoons tore off roofs, windows, doors, and walls from houses and destroyed trees and other vegetation, leaving behind large amounts of wooden, metallic, plastic, and glass debris and waste scattered across a wide area. For example, Typhoon Haiyan generated 19 million tons of disaster waste in the Philippines, while Cyclone Winston produced 24,000 tons of disaster waste in Fiji (Ministry of the Environment, Japan [MOE Japan] & Japanese Society of Material Cycles and Waste Management [JSMCWM], 2018). In some cases, hazardous materials such as hospital and industrial waste were among the debris, which required careful collection and proper treatment.

Proper management of disaster waste is critical during the initial phase of disaster recovery (Asari et al., 2013; Brown, Milke, & Seville, 2011; Zhang, Cao, Li, Liu, & Huisingh, 2019). In catastrophic events such as Typhoon Haiyan, the sheer volume of waste generated can easily overwhelm local waste management capacity, impeding rescue operations and the delivery of humanitarian aid (ibid.). For instance, following Typhoon Nari in Taipei City in September 2001, it took over a month to dispose of 190,000 tons of waste, possibly due to inadequate estimation of the waste generated by typhoons and subsequent flooding (Chen, Tsai, Hsu, & Shen, 2007). Therefore, it is crucial to prepare in advance for scenarios where significant amounts of waste are generated by such disasters. This includes addressing policy gaps in disaster waste management (DWM) and addressing deficiencies in financial, technical, and institutional capacities (ibid.).

Disaster waste management consumes a significant portion of the disaster recovery cost (Crowley, 2017). Pre-disaster planning and capacity-building could significantly reduce costs (ibid.). To ensure efficient DWM, funding mechanisms, institutional arrangements, and assignment of roles to different stakeholders should be put in place before disaster strikes. This can lead to sound disaster waste management, resulting in both cost and time savings (ibid.). Statistical evidence provided by Crowley (2017) indicates that communities that have pre-disaster waste management arrangements tend to have more effective waste management processes than those without such arrangements.

Proper management of disaster waste can help to recover valuable materials, reduce pressure on the

[1] In this article, for brevity, the term "typhoon" is used as encompassing all tropical storm events in Asia and the Pacific. In the case of Fiji, the correct term is tropical cyclone.

environment for virgin raw materials, and minimize greenhouse gas emissions. Effective DWM can thus support the promotion of a circular economy and climate change mitigation initiatives. However, most existing DWM guidelines are prepared by developed countries, such as the United States and Japan, without taking into account the context and available resources in Global South countries. It is crucial to develop and promote guidelines that consider the specific circumstances and available resources in such countries. This technical report highlights the experience and outputs of a capacity-development project for disaster waste management in two Global South countries, namely Fiji and the Philippines. The project received financial support from the Asia-Pacific Network for Global Change Research (APN), with additional funding from the Institute for Disaster Management and Reconstruction (IDMR) at Sichuan University.

The overall aim of the project was to develop the capacity of Lautoka City, Fiji and Makati City, Philippines, for effective post-typhoon DWM. The following were the specific objectives of the project:

1. To raise awareness in and develop the capacity of the two participating cities to promote resource conservation and resource efficiency through waste prevention and by recovering valuable materials from typhoon-related disaster waste;
2. To determine the training needs of the participating cities related to capacity-building for effective post-typhoon disaster waste management;
3. To produce training materials and to deliver training on post-typhoon disaster waste management that can address the training needs of the participating cities;
4. To assist participating cities in developing a typhoon-specific disaster waste management contingency plan using the participatory learning and action (PLA) approach;
5. To promote international cooperation among the four participating universities, two cities, and United Nations Environment Program – International Environmental Technology Centre (UNEP-IETC) to facilitate knowledge sharing on post-typhoon disaster waste management based on the experiences and lessons learned from the project; and
6. To share lessons learned from the post-typhoon disaster waste management project to a wider audience by utilising different avenues, such as a dedicated project website and publication of journal articles, policy briefs, and project reports.

Pradhan and Xu (2018) discuss various methods for managing disaster waste, including waste generated by typhoons. In another study, Brown and Milke (2016) examined the feasibility and effectiveness of recycling disaster waste in the aftermath of five disaster events, including Hurricane Katrina. To learn from prior studies, particularly those focused on storm-related disasters, the project team gathered lessons from previous investigations and sought to apply those lessons to the current project. The project team also followed established disaster waste management guidelines, such as those developed by the Joint United Nations Environment Program - Office for the Coordination of Humanitarian Affairs (UNEP/OCHA) Environment Unit (Joint UNEP/OCHA Environment Unit [JEU], 2013), the Ministry of the Environment, Japan, and the Japanese Society of Material Cycles and Waste Management (MOE Japan & JSMCWM, 2018).

2. METHODOLOGY

2.1. Raising awareness of the project

Separate launching programmes for the project were held in Makati City and Lautoka City in October 2019, with 50 participants in Makati and approximately 30 attendees in Lautoka (see Figure 1). Both events were held at the respective city halls, and the welcome address was given by the representative of the Mayor of Makati and the Chief Executive Officer (CEO) of Lautoka. The project team provided an overview of the project and introduced the partner organizations, while officials from the participating cities gave presentations on the state of municipal solid waste management in their areas, as well as their past experiences in managing disaster waste.

FIGURE 1. Project launching in Makati City (left) and Lautoka City (right) in October 2019.

FIGURE 2. Focus group discussions in Lautoka City (left) and Makati City (right) for the training needs assessment.

The events concluded with a discussion among the attendees on ways to achieve the project objectives.

2.2. Training needs assessment

To identify gaps in current knowledge, skills and competency related to post-typhoon disaster waste management of city employees and other stakeholders, a detailed training needs assessment (TNA) was conducted in each participating city (Figure 2). In Lautoka, the TNA was carried out in September 2019 before the project launch, while the TNA in Makati was performed a few days after the launching. Data was gathered through questionnaire surveys, interviews and multistakeholder focus group discussions. The TNA instruments were based on materials produced by UNEP-IETC or its partner organisations, such as the Disaster Waste Management Guideline for Asia and the Pacific (MOE Japan & JSMCWM, 2018), the 2018 Caribbean Disaster Waste Management Training Programme (supported by UNEP-IETC), and several case studies from recent typhoon-related major disasters, including Typhoon Haiyan.

2.3. Production of training modules and delivery of training

The training needs assessment identified gaps in knowledge and skills related to post-typhoon disaster waste management among city employees and stakeholders. The project team developed training modules to address these gaps based on the findings. The modules covered topics such as (a) forecasting the types and amounts of disaster wastes, (b) disaster waste recycling and disposal options, and (c) preparing a temporary storage site (TSS). To provide expertise on TSS preparation, the

FIGURE 3. Training of Trainers in Ateneo de Manila University (left) and training in Makati City (right).

project team sought the help of an external expert from JSMCWM. The main objective of the training was to equip participants with the knowledge and skills to create a typhoon-specific disaster waste management contingency plan. In total, six training activities were conducted under the project. The trainees were chosen by the two cities.

- Training of Trainers on DWM in Ateneo de Manila University from 15–16 January 2020 (20 participants) (Figure 3)
- Face-to-Face Training for Makati City stakeholders on 17 January 2020 (50 participants)
- Online Training for new Makati City staff on 24 March 2021 (45 participants)
- Mentoring Seminar for Makati City staff on 18 June 2021 (15 participants)
- DWM Contingency Planning Training Workshop and Stakeholder Consultation in Lautoka on 23 March 2022 (50 participants)
- Mentoring Seminar for Makati City staff on 6 May 2022 (15 participants)

Before attending the training sessions, participants were asked to complete the online course "Disaster Waste Management: Best Practices and Tools" offered by the Environmental Emergencies Centre. By completing this course, participants were introduced to disaster waste management basics and better equipped to participate in the more comprehensive training modules. The online course, which takes approximately three hours to complete, was successfully finished by more than 30 participants.

2.4. Preparation of the DWM contingency plan

The major outputs of this project are the disaster waste management contingency plans of the two participating cities. Following the training sessions, the project team provided a suggested outline to the cities, including items such as the objectives of the contingency plan, relevant national laws and policies, and city ordinances. Other plans related to the disaster waste management contingency plan, such as the municipal solid waste management plan and the disaster risk management plan, were also included in the outline. Additionally, the suggested outline covered the forecast of the expected quantity of disaster wastes per type of material, disaster waste collection and removal strategies, identification of temporary storage sites, waste recycling and reuse options, final disposal sites, organisational chart, including assignment of roles and responsibilities, operations flowchart, and information to include in the appendices. The participating cities organised several meetings and workshops among their stakeholders and consulted with the project team for guidance and mentoring when needed.

2.5. Promoting international cooperation

The project team was composed of members from three sub-regions in the Asia-Pacific: East Asia (China and Japan), Southeast Asia (Philippines), and

FIGURE 4. Poster for the international webinar organised by the project team.

Oceania (Fiji). The team consisted of researchers from four reputable universities, namely Sichuan University, Kyoto University, Tongji University, and Ateneo de Manila University, who contributed their technical expertise in the capacity development project. Sichuan University runs the Institute for Disaster Management and Reconstruction (IDMR), with disaster waste management as one of its major areas of interest. The university also boasts a competitive Public Health programme, which provided valuable insights into the management of medical and healthcare waste. Tongji University and UNEP-IETC co-manage the UNEP-Tongji Institute of Environment for Sustainable Development (IESD), a think tank that conducts research on various topics, including climate change, disasters and conflicts, environmental governance, harmful substances, resource efficiency, environmental assessments, and technology transfer facilitation to developing countries. UNEP-IETC serves as the global centre of excellence for environmentally sound technologies, with a specific focus on waste management. Ateneo de Manila University's Department of Environmental Science aims to prepare the next generation of environmental scientists to apply classroom concepts to real-world issues, making it a valuable partner in the capacity building project. The university's Master in Disaster Risk and Resilience (MDRR) programme was designed to promote interdisciplinary and transdisciplinary approaches to risk management and resilience building, aligning with the interdisciplinary and transdisciplinary nature of this project. The four universities worked together to support the science-based decision-making of government and non-government stakeholders in the two participating cities.

2.6. Sharing lessons with a wider audience

Throughout the project, the activities were documented and shared on the dedicated project website (https://disaster-waste.org/). Knowledge products such as reports, policy briefs, scientific papers, photographs, and videos were made available on the website for researchers, policymakers, civil society organisations, and the general public to for easy accessibility. When available, the final version of the training materials will also be uploaded to the website, thus enabling widespread dissemination and adoption by the international community. The project team disseminated information about the capacity development project through presentations in academic conferences, webinars (as shown in Figure 4), workshops, training activities and non-academic conferences.

Objective	Outputs	Outcomes	Impacts
A	Project launching in participating cities; closing workshop	Promoted awareness among stakeholders of the project	Getting city officials to include DWM in their disaster risk management programmes
B	Training needs assessments	Gained awareness of the DWM capacity gaps in each city	Recognising the most critical training needs and producing training modules to address these needs
C	Training modules; trainings; mentoring sessions	Addressed the training needs of participating cities	Having staff members with DWM knowledge and skills
D	DWM contingency plans (one per city)	Gained familiarisation of the participatory DWM contingency planning process	Obtaining the ability to prepare DWM contingency plans for other hazards
E	Face-to-face and virtual meetings; email updates; establishment of a new non-government organisation (NGO); Sendai Framework Voluntary Commitment; networking with and membership in DWM-related organisations	Enhanced cooperation among existing partners; developed cooperation with new partners	Strengthening of mutually beneficial relationships among partners that can be easily tapped and mobilised in the future
F	Project website; session at the Sustainability Research and Innovation (SRI) Congress 2022; DWM webinar (Figure 4); publications; media reports, videos and digital content; awards and recognition	Shared experiences in and lessons learned from the project; developed advocacy-related skills	Promotion of post-typhoon DWM to a wider audience

TABLE 1. Outputs, outcomes and impacts of the project.

3. RESULTS AND DISCUSSION

3.1. Outputs, outcomes and impacts

The disaster waste management contingency plans of the two cities are the key outputs of this capacity development project. From 2020 to 2021, the project team organised and participated in various international and local conferences, webinars and training events to disseminate information about the project. As a result, the project helped generate significant interest in disaster waste management within the disaster risk reduction, environmental management, solid waste management and climate change stakeholder communities not only in Fiji and the Philippines, but also in other parts of the world.

Table 1 presents the outputs, outcomes and impacts of the project. This list is not exhaustive, as some of the anticipated outputs, including journal articles, are still in progress and undergoing peer review at the time of writing.

3.2. Challenges during project implementation

In January 2020, the project team planned to conduct the DWM training of trainers at Ateneo de Manila University and the face-to-face DWM training in Makati. However, the sudden eruption of Taal Volcano led to delayed or cancelled flights, preventing our team member from Lautoka City from attending the training and meeting with their counterparts in Makati. Moreover, flights for our team members from Kyoto University from Manila back to Japan were also delayed. As a result of the volcanic eruption, several trainees from Makati were deployed to the disaster-affected areas to provide assistance and were unable to attend the training. These unforeseen events led to a lower number of participants than initially anticipated.

Up until January 2020, the project team was able to stay on schedule with the implementation of project activities. However, the outbreak of the COVID-19 pandemic had a significant impact on the project timeline. In response to the pandemic, the project team made the decision to suspend the remaining project activities, as the local partners in Lautoka and Makati were among the frontline responders to the pandemic as the team member in Lautoka is a public health official, while the team member in Makati works in the city's Disaster Risk Reduction and Management Office. The project team felt it was important not to divert the attention of these local partners from their critical duties during the pandemic.

Until the end of August 2022, we were unable to return to Sichuan University in Chengdu, China, due to travel restrictions imposed by the COVID-19 pandemic. Two other team members from Sichuan University were also stranded in Tokyo and Montreal for some time.

One of the most significant activities in our project was the participatory preparation of a typhoon-specific disaster waste management contingency plan by our two participating cities. However, the DWM contingency planning was delayed as not all stakeholders in Lautoka and Makati had reliable Internet connections, and face-to-face modalities were still the most appropriate for this kind of participatory exercise. The project team initially allocated at least four months for this activity, but it was put on hold in Makati following lockdown in Metro Manila for most of 2020 and 2021. The main stakeholders were supposed to receive a face-to-face training on contingency plan preparation before the planning process could begin. On 6 May 2022, the project team had its second mentoring session with the Makati stakeholders to aid them with their contingency planing. In Lautoka, the contingency planning process started after the stakeholders conducted a training workshop on 23 March 2022.

While preparing the DWM contingency plan in Makati City, it became apparent that much of the information needed was not readily available. The core group in Makati eventually agreed that their initial DWM contingency plan would need to be updated once the necessary information became available. This is consistent with the principle that contingency plans are living documents that must be regularly revised or updated.

3.3. Missed opportunities

In 2020 and 2021, the Philippines was hit by a series of strong typhoons, resulting in the generation of a large volume of disaster waste. Unfortunately, due to safety concerns related to the COVID-19 pandemic, project team members were unable to visit the disaster-affected areas to conduct documentation and data-gathering, which would have been very useful for the capacity building project. For example, in December 2021, Typhoon Rai (locally known as Typhoon Odette) ravaged a vast area in central and southern Philippines. The typhoon caused widespread destruction, and it would have been another opportunity to document the disaster waste generated by a typhoon and observe how local and national government officials manage disaster debris if there had not been a pandemic.

3.4. Ways forward: Post-project activities

Thanks to this project, our team members were able to broaden their networks and establish partnerships with organisations that will continue to promote disaster waste management after the end of the APN project. The following are some of the activities:

- Expansion of the membership of the newly established Philippine Association for Disaster Waste Management (PADWM) and preparation of documents needed for the formal registration of the non-government organisation under the Securities and Exchange Commission.

- In October 2022, a proposed project titled "Science Advice on Disaster Waste Management: Enabling Local Governments to Practice and Promote Building Back Better, Circular Economy, and Climate Change Mitigation" submitted by the project leader was chosen by the International Network for Government Science Advice (INGSA) Asia chapter as one of the winners of its Grassroots Science Advice Promotion Awards 2022. Part of the award is a seed grant as well as guidance and mentorship from a distinguished member of the INGSA-Asia Steering Committee to organise science advice workshops. The new project will build on the accomplishments made under the APN project.
- The project team reprised the session "Disaster Waste Management Capacity Development in the Global South", organised for the SRI Congress 2022 at the 2022 Conference of the Solid Waste Management Association of the Philippines (SWAPPCon 2022) on 17 November 2022.
- The project leader has been involved as a resource person on "Forecasting Types and Amount of Disaster Wastes" in the quarterly Disaster Waste Management Training organized by the Development Academy of the Philippines (DAP). Three DAP staff were among those who participated at the DWM training of trainers organised by the project team in January 2020.
- The project team, together with new partnerships developed during the implementation of the project, created a Sendai Framework Voluntary Commitment to conduct capacity development training activities and seminars in the coming two years.

4. CONCLUSION

This capacity development project is an example of an inter- and transdisciplinary endeavour that showcases multistakeholder involvement, including local and national government offices, academia, NGOs, the private sector and international organisations. The project emphasises the importance of preparing in advance for post-typhoon disaster waste management. Addressing training and policy gaps in disaster waste management, including deficiencies in existing financial, technical, institutional and human resource capacities, will assist participating cities in their disaster recovery efforts, even beyond the end of the project.

This project has been designed to support the efforts of the participating cities in achieving the Sustainable Development Goals (SDGs), with a particular focus on Goal 11 (Make cities and human settlements inclusive, safe, resilient and sustainable), Goal 12 (Ensure sustainable consumption and production patterns), and Goal 17 (Strengthen the means of implementation and revitalize the Global Partnership for Sustainable Development). It is hoped that this project will also contribute to Priority 4 of the Sendai Framework for Disaster Risk Reduction 2015–2030, which aims to enhance disaster preparedness for effective response and to "Build Back Better" in recovery, rehabilitation, and reconstruction. Furthermore, the waste sector is one of the largest contributors to greenhouse gas emissions. By reducing the amount of disaster waste going to landfills, the participating cities can make a significant contribution to reducing greenhouse gas emissions. While it is still too early to determine the full impact of the project, it is hoped that it has laid the groundwork for continued efforts to promote disaster waste management and sustainable development in the participating cities and beyond.

Disaster waste management is well-aligned with the concept of circular economy. By effectively implementing disaster waste management, material consumption can be reduced and waste can be minimised, thus alleviating pressures on the environment for virgin raw materials. The increased focus on DWM generated by this project is expected to contribute to the documentation of best practices and the development of policies that can enhance DWM in the participating cities as well as in other urban areas.

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Mapping groundwater resilience to climate change and human development in Asian cities

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ABSTRACT

Groundwater resources in major Asian cities, including Bangkok and its vicinity, Ho Chi Minh City, Kathmandu Valley, and Lahore, confront escalating challenges due to climate change and human development. Over-extraction has led to groundwater depletion, causing socio-environmental and economic issues. This study investigates the combined impacts of climate change and urban development on groundwater resources and assesses the resilience of these cities' groundwater systems that are essential for sustainable management strategies. Employing a model-based approach, the study analyses climate and land use changes, groundwater recharge, levels, and resilience. Three land-use and extraction scenarios—high, medium and low—are examined to evaluate their effects on groundwater. The results suggest that all four Asian cities are expected to be warmer in future. Results predict warmer conditions across all cities, with Ho Chi Minh City experiencing the most significant temperature increases. All cities anticipate increased rainfall under both Representative Concentration Pathway (RCP) scenarios, notably Bangkok. Groundwater recharge is projected to decrease in high urbanisation settings and both RCPs, contrasting with a rise in low to medium urbanisation contexts. Under a high urbanisation scenario, the outskirts of all four Asian cities are resilient to climate change and human development, whereas the centre or urban areas are not resilient.

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KEYWORDS

Groundwater resiliency, climate change, human development, Asian cities

HIGHLIGHTS

- We estimated groundwater resiliency to climate change and human development in four Asian cities.
- Modelling method assessed climate change and human development influence on groundwater.
- All four Asian cities will be warmer in future, which is in line with the global temperature trend.
- Groundwater resources in the outskirt part of cities will be resilient to climate change and human development.
- Groundwater in the central part of all four cities will not be resilient to climate change and human development.

1. INTRODUCTION

Groundwater makes up 94% of the world's freshwater supplies and is portrayed as the true hidden wealth of the planet (Koundouri & Groom, 2010). The most ideal resource of water supply is groundwater since it is less susceptible to drought and quality deterioration than surface water (Schwartz & Ibaraki, 2011). Groundwater is one of the main drinking water sources for around 2 billion people residing in rural and urban areas (Kemper, 2004; Foster, 2022). It accounts for 32% of the drinking water supply (Morris et al., 2003). Major Asian cities rely entirely or partially on groundwater for their daily water supply, and groundwater plays a very vital role in the sustainable development of the major Asian cities. For instance, groundwater dependency in Bangkok and its vicinity, Thailand, is nearly 30%; in Ho Chi Minh City, Vietnam is 45%; in Lahore, Pakistan, is 100% and in Kathmandu Valley, Nepal, is 50% (Basharat, 2015; Gautam & Prajapati, 2014; Khatiwada, Takizawa, Nga, & Inoue, 2002; Lorphensri, Nettasana, & Ladawadee, 2016; Shrestha, Neupane, Mohanasundaram, & Pandey, 2020; Vuong, Long, & Nam, 2016). Future climate change and human development (population growth and rapid urbanisation) are projected to have a greater impact on groundwater availability for the city's water supply (Ghimire, Shrestha, Neupane, Mohanasundaram, & Lorphensri, 2021). The risks posed by intense climate change events are observed to be enormous, even with a 1°C increase in maximum temperature. In several tropical and subtropical regions, water availability is projected to change (IPCC, 2022). Under these conditions, the hydrological cycle experiences erratic changes in precipitation and evaporation, which will have a serious impact on surface and groundwater resources. Therefore, evaluating the groundwater's resilience to climate change and anthropogenic growth is crucial to strategically plan and manage the city's water supplies.

Mapping groundwater resiliency, as defined by National Groundwater Association [NGWA] (2016) is the capability of the groundwater system to endure either long-term shocks (e.g., climate change) or short-term shocks (e.g., drought) can be a useful tool for comprehending the groundwater system, which will ultimately help with groundwater resource management. The ability of an ecosystem to tolerate long-term harm and recover swiftly from disruptions is referred to as resilience (Gunderson, 2000). In the context of climate change, the ability of a system to absorb disturbances while preserving its essential structure and ways of functioning, as well as its capability to adjust to stress and change, is widely explored (IPCC, 2007). Peters, van Lanen, Torfs, and Bier (2004) defined resilience as "how quickly a system is likely to recover once a failure has occurred, while vulnerability is the severity of the failure". Sharma and Sharma (2006) defined groundwater resilience as the "ability of a system to maintain groundwater reserves despite major disturbances".

Climate change and human growth significantly impact water resources and the environment, which also results in changes to the hydrological cycle, the surface energy budget, and water yield (Wada, 2016). According to Mirchi, Madani, Roos, and Watkins (2013), the main factor affecting water availability is climate change, and the significant increase in the global population has raised water demand globally. This has further pressured the water supply (Gain & Giupponi, 2015). In many places, groundwater is the main water supply, disappearing at an alarming rate (Li, Rodell, & Famiglietti, 2015). For better water management, measuring how human growth and climate change have affected groundwater supplies is crucial. Further, the impacts of climate change and variabilities have risen as challenging issues to the present generation, which are likely to worsen in the future due to anthropogenic interventions with nature (Guptha, Swain, Al-Ansari, Taloor, & Dayal, 2021, 2022; Swain, Mishra, Pandey, & Dayal, 2022a; Swain, Mishra, Pandey, & Kalura, 2022b).

Despite the importance of groundwater for the sustainable development of major Asian cities, there has not been as much study done on it as on surface water resources in scenarios involving human development and climate change. This is also true for Asian cities like Bangkok and its vicinity, Ho Chi Minh City, Lahore, and Kathmandu Valley. Therefore, there is an urgent need to research how human growth and climate change affect the groundwater system in Asian cities to evaluate the existing situation and foresee potential future developments. Mapping groundwater resources to climate change and anthropogenic growth in Asian cities can be an effective tool for analysing areas where preventive actions are required and comprehending groundwater system behaviours, which eventually aids in managing and conserving groundwater resources and developing strategies for sustainable use.

The research aims to analyse the groundwater system's resilience to climate change and anthropogenic growth and design the adaptation solutions to minimise the vulnerability of groundwater resources in Asian cities, namely Bangkok and its vicinity, Thailand, Ho Chi Minh City, Vietnam, Lahore, Pakistan, and Kathmandu Valley, Nepal.

1.1. Objectives

The study's overarching goal is to analyse the resilience of groundwater systems in Asian cities to climate change and anthropogenic development.

The specific objectives are:

1. To evaluate regional climate models (RCMs) for projections of future climate change in Asian cities.
2. To forecast future land usage and land cover in Asian cities and examine possible future climatic scenarios.
3. To assess the spatiotemporal distribution of groundwater recharge in Asian cities under several climatic change scenarios and anthropogenic development.
4. To estimate the aquifers' groundwater levels in Asian cities under various scenarios of climatic change and anthropogenic development.
5. To develop groundwater resiliency indicators that consider climate change and human growth scenarios and analyse groundwater resiliency in Asian cities.

2. METHODOLOGY

2.1. Study area

The study area includes four rapidly expanding Asian cities: Bangkok and its vicinity, Ho Chi Minh City, Lahore, and Kathmandu Valley (Figure 1). The four Asian cities were selected based on

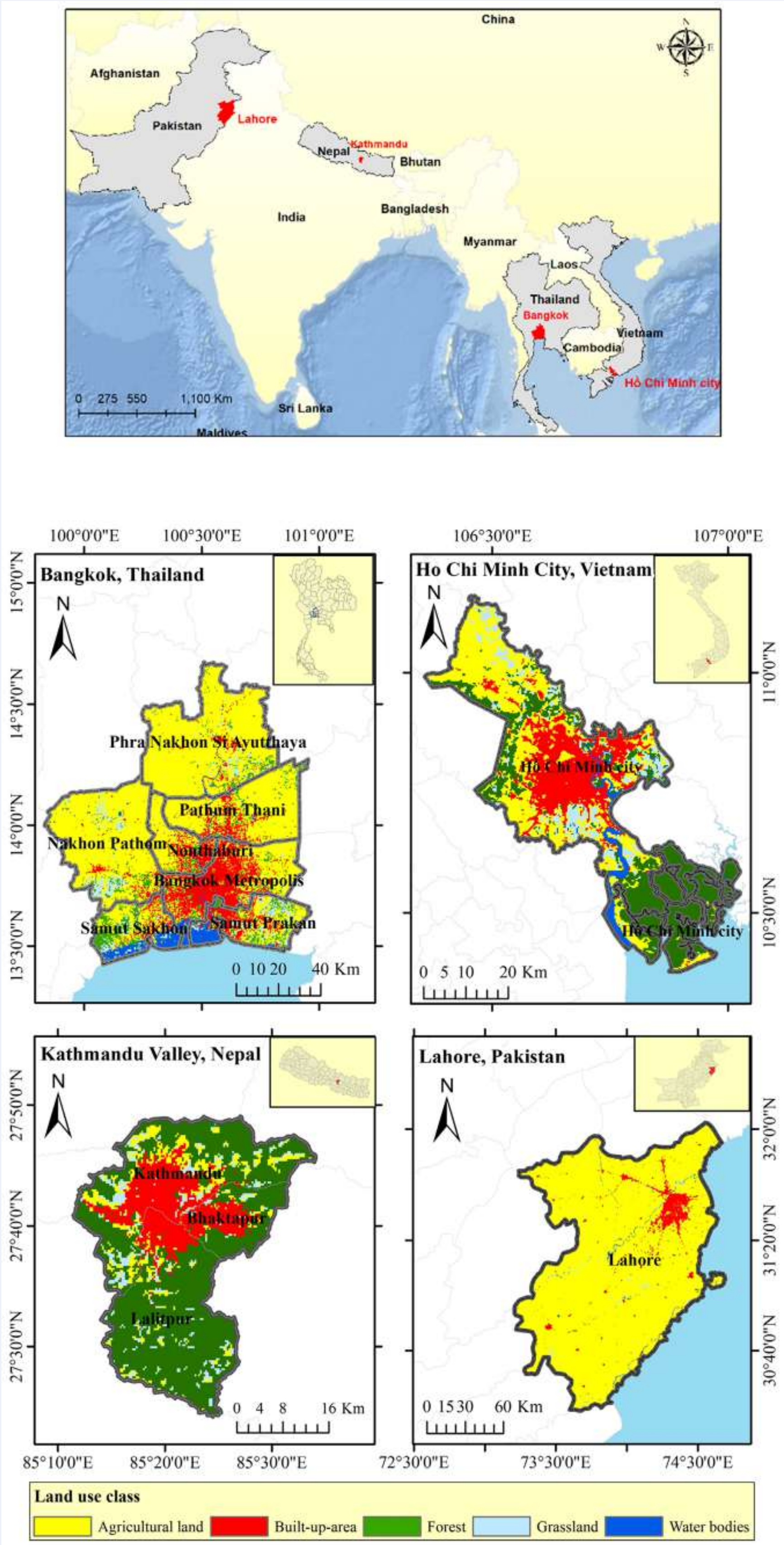


FIGURE 1. Location map of Asian cities (Bangkok, Ho Chi Minh City, Lahore, and Kathmandu Valley) with their respective land use classes.

their groundwater dependence which ranges from 30–100%.

Bangkok and its environs comprise seven provinces in Thailand: Bangkok, Samut Prakan, Samut Sakhon, Nakhon Pathom, Nonthaburi, Pathum Thani, and Phra Nakhon Si Ayutthaya. Bangkok is in the humid tropics and has a tropical wet-and-dry climate throughout the year. The average temperature is 30°C, and the annual rainfall is 1500 mm. The water supply for the city's demand comes from both surface and groundwater sources. Groundwater is mostly used in the water supply systems near Bangkok. In the study area, 11.3 million (in 2015) people are living at a density of 300 to 3,600 people/km². Eight confined aquifers exist in Bangkok and its environs, with Phra Pradaeng, Nakhon Luang, and Nonthaburi being the most exploited because of their higher production, accessibility, and excellent water quality. In the mid-1950s, the extensive use of groundwater was started, and there was a continuous increase in groundwater use until 1997. Land subsidence (1.0 cm/yr between 2006 and 2012), groundwater level depletion and recovery, and groundwater quality deterioration are the main groundwater-related problems.

Ho Chi Minh City (HCMC), the biggest city in Vietnam, is located 1760 kilometres south of Hanoi. HCMC had a population of around 7.35 million (in 2015) and a total area of 2095 km², making up roughly 8.79% of its total populace and 0.6% of Vietnam's total land. The average humidity is 75%, and the average temperature is 27°C. The climate is classified as tropical, more precisely tropical wet and dry. The total annual rainfall is 1946 mm, 1130 mm, lost due to evaporation. Both the surface and groundwater resources are used to deliver water. The fast growth in groundwater abstraction began in 1990 when Vietnam's economic policies were implemented. It is planned that groundwater's portion of the overall water supply, which was 44.7% in 2012, will be reduced to 15.5% in 2015 and 2.7% in 2020. Major groundwater-related problems include a decline in groundwater level (rate: 0.5–1.0 m/yr), saltwater intrusion in some areas, groundwater quality degradation (NO_3 content is four times the permissible value; iron content is 100 times the permissible value), and land subsidence of a few centimetres per year in heavily pumped areas.

Kathmandu, Nepal's capital and largest metropolitan city, is in central Nepal and has a total area of 656 km². The Kathmandu Valley's population is 2.8 million (in 2015) and the population density is 29 persons per km², which includes both the urban and rural areas of Kathmandu Valley. Kathmandu Valley is in the mild temperate zone, with an elevation range of 1205–2713 masl and a significant contrast in typical summer (28–30°C) and winter (10°C) temperatures. On average, it receives 1455 mm of rain annually, 65% of which falls from June to August. Kathmandu Valley has a closed reservoir system with a gentle slope towards the Valley's centre. The groundwater flow is assumed to be slow, particularly in the deeper aquifer. The water supply system is hugely dependent upon monsoon rain, the stream, and the rainfed recharge system, as 25–30% of the water demand is mitigated through groundwater abstraction. Due to an unfavourable geological characteristic of the Valley, surface runoff is high in volume during the monsoon period. The natural recharge in the swallow aquifers during the high monsoon periods occurs along the basin margin, although the presence of the clay bed significantly restricts natural recharge in deep aquifers.

With a total area of 1772 km², Lahore is one of the largest metropolitan regions in South Asia. The population was 10.37 M in 2015, and a population density of 14,000 persons per km². Lahore has a subtropical semi arid climate, with an average annual rainfall of 712 mm for the 30 years from 1971 to 2000. The majority of the yearly rainfall (roughly 75%) falls between June and September, recharging the groundwater by around 40 mm on average each year. The average yearly temperature is roughly 24.3°C, with monthly variations between 33.9°C (in June) and 12.8°C (in January). The only source of water in the city is groundwater. The Water and Sanitation Agencies (WASA) tube well infrastructure is used by about 89% of Lahore's entire land area. These tube wells, which have various capacities and are situated between 150 and 200 m deep,

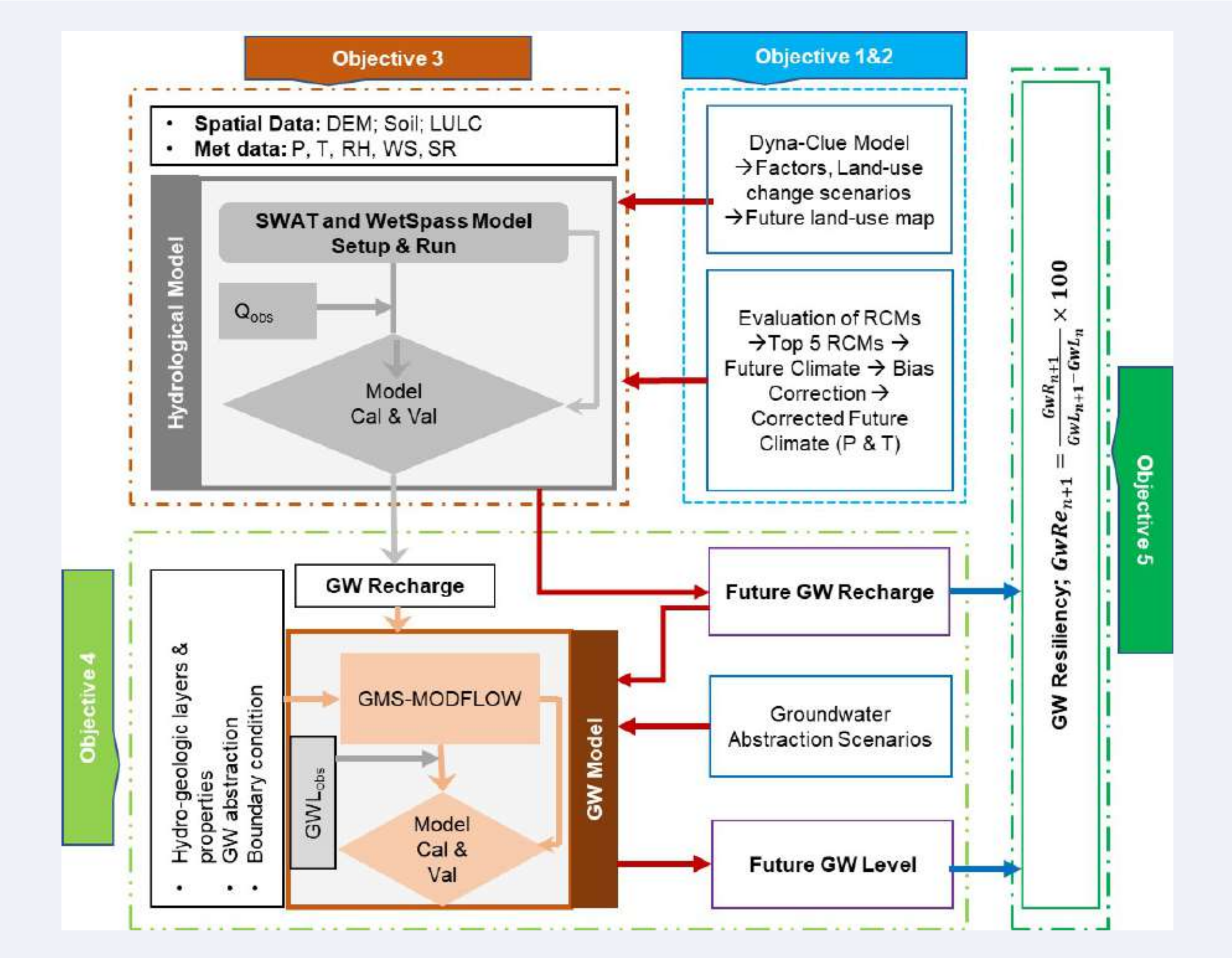


FIGURE 2. Overall methodological framework.

continuously pump 800 cubic feet of water per second (cusecs). Water levels between 2003 and 2011 are falling at a rate of 0.57 m/yr to 1.35 m/yr due to excessive groundwater consumption, and well productivity is also declining.

2.2. Methods and data

The overall methodological framework required to accomplish the stated objectives is shown in Figure 2.

"DEM is a digital elevation model; LULC is land use/cover; P is precipitation; T is Temperature; RH is Relative Humidity; WS is Wind Speed; SR is Solar Radiation; Q_{obs} is Observed River Discharge; Cal is Calibration; Val is Validation; GWL_{obs} is Observed Groundwater Level; GW is Groundwater; RCM is a Regional Climate Model; GwRe is the groundwater resiliency; GwR is groundwater recharge; GwL is groundwater level; and *n* is the base year"

The key objective of the study is to assess groundwater resiliency in four Asian cities; Bangkok and its vicinity, Ho Chi Minh City, Lahore, and Kathmandu Valley under climate change and human development scenarios Firstly, the evaluation of Regional Climate Models (RCMs) in each city was done based on their ability to replicate the observed climate datasets. The top 5 best-performing RCMs, along with two Representative Concentration Pathway (RCP) scenarios (RCP 4.5 and RCP 8.5), were then used to project the future climate of the study area. From the time perspective, the RCP scenarios differ in radiative forcing and greenhouse gas intensity. The main objective of the RCP scenarios is to identify future uncertainties without forecasting them, with different socioeconomic hypotheses used in their development (Moss et al., 2010; Rogelj, Meinshausen, & Knutti, 2012). RCP 4.5 is described by the Intergovernmental Panel on Climate Change (IPCC) as a moderate emission scenario in which emission peaks around 2040 and then declines. RCP 8.5 is the highest baseline emission scenario in which emission continues to rise throughout the 21st century. RCP 8.5 gives a much more rapid warming and more pronounced change in important indicators such as river flow, temperature, and precipitation. On the other hand, the RCP 2.6 scenario will result in the least amount of global warming and only limited climate change and the difference between RCP 2.6 and 4.5 will remain relatively small until the end of the century. Therefore, in this study, two scenarios: RCP 4.5 and RCP 8.5 are used. A quantile mapping technique was used to remove the bias from the climate data sets. The land use change model Dyna-CLUE was used to project the future land use change of the study area. The baseline climatic data, future projections from climate models, and land use change scenarios conceived by Dyna-CLUE were fed into the hydrological model SWAT and WetSpass to forecast future groundwater recharge. The hydrological modelling of Bangkok and its vicinity was done using the WetSpass model, whereas, for three other Asian cities, the SWAT model was used. The WetSpass model was chosen in Bangkok since it was challenging to include the city within a hydrological watershed. The future groundwater abstraction computed using population and water demand forecasting and future groundwater recharge was then input into calibrated steady-state groundwater model GMS-MODFLOW to obtain future groundwater level. Finally, based on the findings, a groundwater resilience indicator was created, which was then utilised to create a groundwater resilience map for the research region.

The data used for the study include the time series observations (rainfall, wind speed, maximum and minimum temperature, solar radiation, river discharge, relative humidity, groundwater level and groundwater abstraction), physical characteristics of catchments (DEM, soil map, land use map, slope, aspect ratio, distance from road, distance from river, population density), hydrogeologic properties of aquifers (specific storage (S_s), hydraulic conductivity (K_x, K_y), specific yield (S_y)) and future climate projection from climate models (adopted from Neupane, Shrestha, Ghimire, Mohanasundaram, & Ninsawat, 2021).

2.3. Land use change scenarios

Three land use change scenarios, namely: high urbanisation (HU), medium urbanisation (MU) and low urbanisation (LU) scenarios, were considered for all four Asian cities to project the future land use map. In high urbanisation scenarios, there will be a significant increase in built-up land or urban areas. In medium urbanisation scenarios, there will be a medium increment in a built-up area and low urbanisation scenarios, forest conservation is given priority and there will be no change in built-up land. A detailed description of the future land use scenario is presented in Supplementary Table 1.

2.4. Groundwater abstraction scenarios

To calculate future groundwater abstraction, three scenarios (like land use change scenarios) were analysed for all four Asian cities. The groundwater abstraction scenarios for Bangkok and its vicinity, Ho Chi Minh City and Lahore are mentioned below:

- High Urbanisation: Groundwater abstraction will be increased in future by 10%, 20%, 30% and 40% in 2035, 2055, 2075 and 2095, respectively (we assume that there will be very high increase in the built-up areas due to rapid population growth and hence the abstraction will increase in future).
- Medium Urbanisation: Groundwater abstraction will be decreased in future by 10%, 20%, 30% and 40% in 2035, 2055, 2075 and 2095, respectively (we assume that there will be very small increment in urban land and small reduction in agricultural land, and there will be some policies intervention to prevent groundwater abstraction or transboundary water diversion from different river basin).
- Low Urbanisation (safe-yield pumping): Groundwater abstraction will be decreased in future by 15%, 30%, 45% and 60% in 2035, 2055, 2075

Resiliency Indicator (RI) or Percentage of Recovery (%)	Resiliency Class	Interpretation
0 to 2	Not resilient	Less groundwater recharge, higher reduction of groundwater level.
2 to 4	Fairly resilient	Less groundwater recharge, fair reduction of groundwater level
4 to 6	Moderately resilient	Moderate groundwater recharge, moderate reduction of groundwater level
6 to 8	Highly resilient	Higher groundwater recharge, less reduction of groundwater level
>8	Very highly resilient	Higher groundwater recharge and very less reduction of groundwater level

TABLE 1. Resiliency classification.

and 2095, respectively (we assume that there will be no change in the area occupied by built up land or urban land and agricultural land. This suggests that the area occupied by forest will be increased, therefore in low urbanisation groundwater abstraction will be decreased in future).

Likewise, the groundwater abstraction scenarios for Kathmandu Valley are mentioned below:

- High Urbanisation: Groundwater abstraction meets 40% of overall water demand (is the pessimistic scenario where the groundwater abstraction further increases in future).
- Medium Urbanisation: Groundwater abstraction meets 20% of overall water demand (is the business as-usual scenario).
- Low Urbanisation (optimistic): Groundwater abstraction meets 10% of overall water demand (is the optimistic scenario which designates the reduction in groundwater abstraction for the implementation of policies to prevent groundwater abstraction or transboundary water diversion from different river basins).

The reason behind two different scenarios between Kathmandu and other three Asian cities is because of very less groundwater abstraction in Kathmandu as compared to other three Asian cities. And if we adopt similar methodology as of three Asian cities, there will not be much change in groundwater abstraction volume for Kathmandu.

2.5. Groundwater resiliency indicators

Based on the existing resilience document and definition (as discussed in literature review section) following methods have been suggested for the resilience indicators and resilient index calculation of a groundwater system.

2.5.1. *Resilience based on groundwater level data and recharge*

Groundwater resilience to climate change and human development is the percentage recuperation to total groundwater depletion at a distinct period and can be expressed as follows:

$$GwRe_{n+1} = \frac{GwR_{n+1}}{GwL_n - GwL_{n+1}} \quad (1)$$

"Where *n* denotes the base year, GwRe denotes groundwater resilience, GwR denotes groundwater recharge, and GwL denotes groundwater level."

Groundwater resilience (GwRe) was further classified into 5 categories to create a groundwater resiliency map of four Asian cities (Table 1). The greater the proportion of recovery over overall depletion, the more groundwater resilience.

Groundwater system is very highly resilient if the groundwater level increases in future. Also, for higher groundwater recharge and lesser reduction in groundwater level, groundwater system will be highly resilient (decrease in groundwater level is less than 20 times the groundwater recharge). Similarly, for lesser groundwater recharge and

Rank	Selected RCMs			
	Bangkok and its vicinity	Ho Chi Minh city	Kathmandu Valley	Lahore
1	WAS44-SMHI-RCA4-IPSL-CM5A-MR	WAS44-SMHI-RCA4-MIROC5	WAS44-IITM-REGCM4-4-CSIRO-MK3-6-0	WAS44I-CSIRO-CCAM-MPI-ESM-LR
2	WAS44-SMHI-RCA4-NCC-NorESM1-M	WAS44-SMHI-RCA4-CCCma-CanESM2	WAS44-SMHI-RCA4-MIROC5	WAS44-IITM-REGCM4-4-MPI-ESM-MR
3	WAS44-SMHI-RCA4-CCCma-CanESM2	WAS44-IITM-REGCM4-4-MPI-ESM-MR	WAS44-SMHI-RCA4-IPSL-CM5A-MR	WAS44-IITM-REGCM4-4-CERFACS-CNRM-CM5
4	WAS44-SMHI-RCA4-ICHE-EC-EARTH	WAS44-SMHI-RCA4-IPSL-CM5A-MR	WAS44-SMHI-RCA4-CCCma-CanESM2	WAS44-SMHI-RCA4-NOAA-GFDL-ESM2M
5	WAS44-SMHI-RCA4-MPI-ESM-LR	WAS44-SMHI-RCA4-MPI-ESM-LR	WAS44-IITM-REGCM4-4-MPI-ESM-MR	WAS44-IITM-REGCM4-4-CSIRO-MK3-6-0

TABLE 2. Top five ranked RCMs in four Asian cities.

higher reduction in groundwater level, groundwater system is not resilient (decrease in groundwater level is greater than 50 times the groundwater recharge).

2.6. Quantification of uncertainties

In climate change impact assessments studies, uncertainty quantification is an important issue because meteorological variables, such as precipitation and temperature must be projected several decades into the future. It is quite impossible to remove the uncertainties, however we can quantify it using several tools and techniques. This study also follows some uncertainty quantification techniques such as evaluation of regional climate models and finding the best RCMs for the study region. The main source of the uncertainty in climate impact analysis is emission scenarios and climate models and the uncertainty coming from the hydrological and groundwater model is very small compared to it coming from climate models. As we are reducing and quantifying the uncertainties from climate models it also helps in reducing the uncertainties from the models. We have used a physically-based hydrological model and this kind of model helps to reduce the parameter uncertainties. Also, the input data are the main source of uncertainties in modelling work. Since we have used the most efficient input data sets from respective organisations of each city, it also helps to reduce uncertainties.

3. RESULTS AND DISCUSSION

3.1. Evaluation of RCMs

The evaluation of Regional Climate Models (RCMs) in each city was done based on their ability to replicate the observed climate datasets. This study assesses the capability of 21 RCMs from the Coordinated Regional Climate Downscaling Experiment (CORDEX) to simulate climate extremes in the rapidly developing Asian cities (Bangkok and its surroundings, Ho Chi Minh City, Kathmandu Valley, and Lahore) that are highly vulnerable to climate change. A detailed description of the evaluation of RCMs can be assessed by Neupane et al. (2021). Table 2 shows the list of top five better performing RCMs in four Asian cities, which in turn were used to project the future climate of respective Asian cities.

3.2. Projected future climate of Asian cities

The future climate of four Asian cities is projected using the top five better-performing RCMs obtained from the evaluation study (Table 2) for three future periods: 2010 to 2039 or near future (NF), 2040 to 2069 or mid future (MF), and 2070 to 2099 or far future (FF) relative to the baseline period (1976–2005) under two emission scenarios (RCP 4.5 and RCP 8.5). A quantile mapping technique was used to remove the biases from future climate data.

3.2.1. Temperature trends

The study's findings indicate that future temperatures are predicted to rise in all four Asian cities for both RCPs scenarios, which aligns with the global temperature trend. By the end of the twenty-first century, the average annual maximum temperature for Bangkok and the surrounding area is predicted to rise by 0.4°C to 1.5°C under RCP 4.5 and by 0.5°C to 3.1°C under RCP 8.5. Similarly, it is anticipated that the average annual minimum temperature would rise by 0.8°C to 2°C in RCP 4.5 and 0.9°C to 4.3°C in RCP 8.5.

By 2099, the average annual maximum temperature in Ho Chi Minh City, Vietnam, is projected to rise by 0.52°C to 2.71°C under RCP 4.5 and 0.75°C to 5.13°C under RCP 8.5. Similarly, it is anticipated that the average annual minimum temperature would rise by 0.73°C to 5.13°C in RCP 4.5 and 0.97°C to 6.68°C in RCP 8.5.

The average annual maximum temperature is predicted to rise in the Kathmandu Valley by 0.22°C to 2.44°C by the end of the twenty-first century under RCP 4.5 and by 0.60°C to 5.38°C under RCP 8.5. Similar to this, it is estimated that the average annual minimum temperature would rise by 0.48°C to 3.52°C in RCP 4.5 and 0.57°C to 5.60°C in RCP 8.5.

By 2099, Lahore's average annual maximum temperature is anticipated to rise by 0.16°C to 2.85°C under RCP 4.5 and by 0.31°C to 4.43°C under RCP 8.5. Similarly, it is anticipated that the average annual minimum temperature would rise by 0.46°C to 3.72°C in RCP 4.5 and 0.62°C to 6.07°C in RCP 8.5. The yearly maximum and lowest temperature trend for four Asian cities is shown in Figure 3.

3.2.2. Rainfall trends

As for rainfall, all four Asian cities are expected to receive more rainfall in future. All RCMs and both RCP scenarios agree that rainfall is expected to increase annually throughout all time periods. For Bangkok and its vicinity, the relative increase in future rainfall ranges from 12.04% to 36.64% for RCP 4.5 scenario and 17.19% to 57.42% for RCP 8.5 scenario. For Ho Chi Minh City, the relative increase in future rainfall ranges from 10.18% to 24.83% under RCP 4.5 scenario and 11.52% to 28.40% under RCP 8.5 scenario. Likewise, the relative increase in future rainfall for Kathmandu Valley ranges from 21.44% to 25.12% for RCP 4.5 and 18.97% to 37.41% for RCP 8.5 scenario. For Lahore, the relative increase in future rainfall ranges from 11.39% to 15.67% under RCP 4.5 scenario and 13.1% to 15.38% under RCP 8.5 scenario. The maximum increase in future rainfall is expected for Bangkok and its vicinity, Thailand. Projection shows that the amount of rainfall is going to increase significantly during both dry and wet seasons for all four Asian cities. For four Asian cities, Figure 4 displays the yearly rainfall trend and an overview of the absolute change in annual, dry- and wet-season rainfall.

3.3. Projected future land-use of Asian cities

Future land-use change in all four Asian cities was projected using the Dyna-CLUE model. Three land use scenarios (HU, MU and LU) were developed for Bangkok and its vicinity, Ho Chi Minh City, Kathmandu Valley and Lahore to analyse its impact on groundwater. For Bangkok and its vicinity, in a high urbanisation scenario, agricultural land decreases from 69% of total land area to 33% from 2015 to 2099. Whereas built-up area increases from 15% to 52% of total land area. For medium urbanisation scenario, built up area increases from 15% of total land area to 25% from 2015 to 2099 and in low urbanisation scenario, forest area increases from 7% to 25% of total land area from 2015 to 2099 whereas, built up area is constant in all the future period.

For Ho Chi Minh City, in a high urbanisation scenario, agricultural land decreases from 32% of total land area to 2% from 2015 to 2099. Whereas built-up area increases from 26% to 62% of total land area. For medium urbanisation scenario, built up area increases from 26% of total land area to 35% from 2015 to 2099 and in low urbanisation scenario, forest area increases from 29% to 50% of total land area from 2015 to 2099 whereas, built up area is constant in all the future period.

Likewise for Kathmandu Valley, in a high urbanisation scenario, agricultural land decreases from

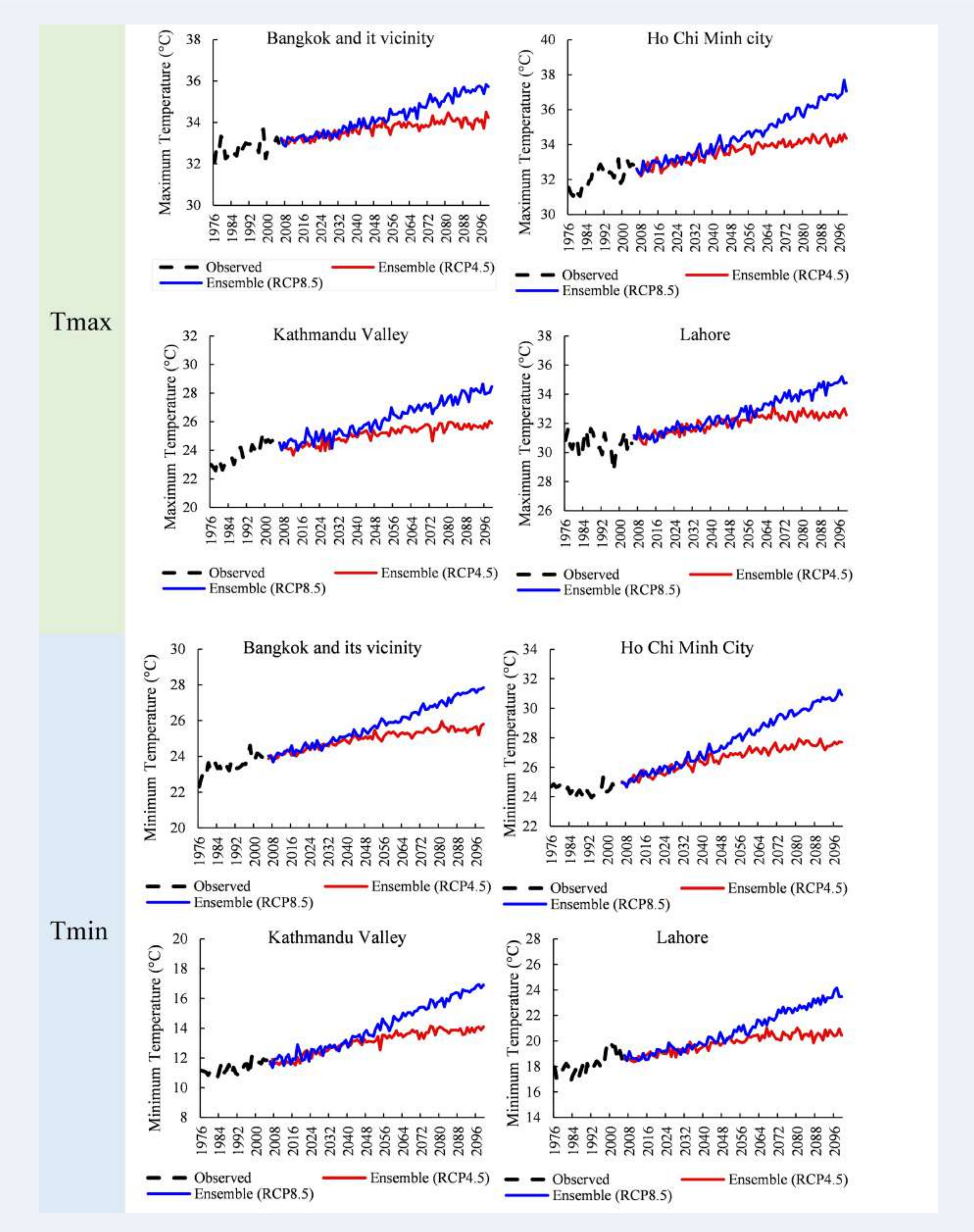
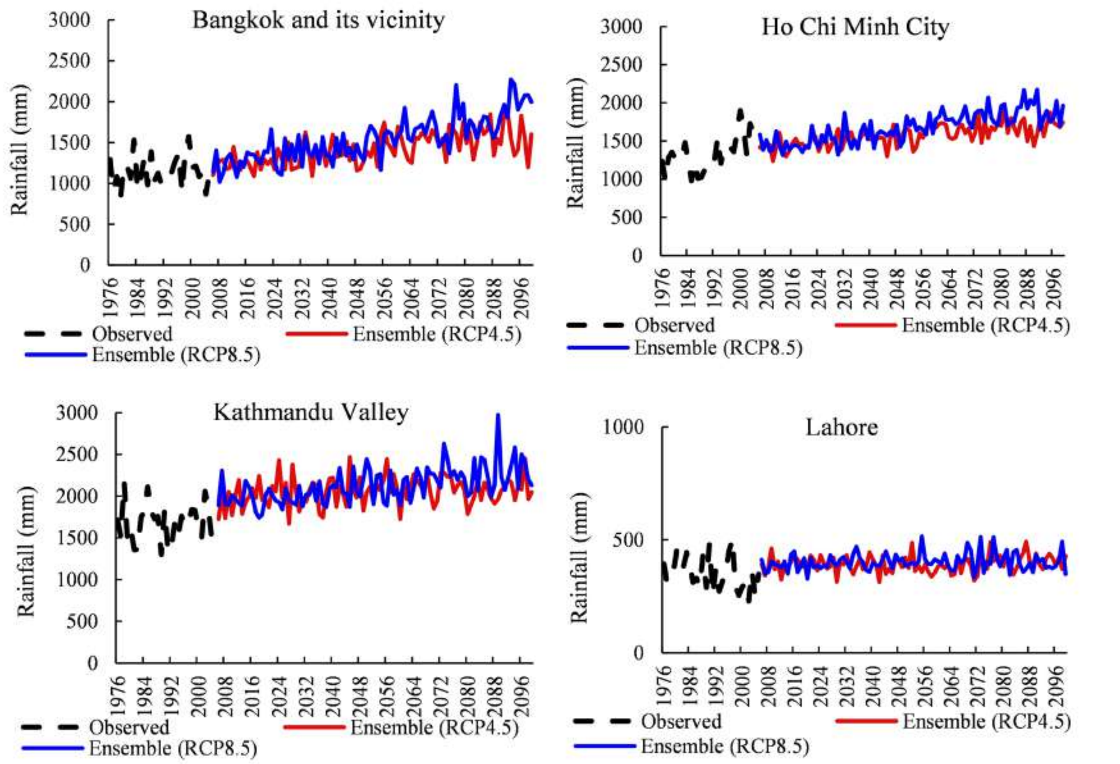


FIGURE 3. Annual maximum and minimum temperature trend for four Asian cities.

10% of total land area to 2% from 2015 to 2099. Whereas built-up area increases from 21% to 51% of total land area. For medium urbanisation scenario, built up area increases from 21% of total land area to 25% from 2015 to 2099 and in low urbanisation scenario, forest area increases from 62% to 75% of total land area from 2015 to 2099 whereas, built up area is constant in all the future period.



		Annual				Wet				Dry			
		Baseline	NF	MF	FF	Baseline	NF	MF	FF	Baseline	NF	MF	FF
Bangkok and its vicinity, Thailand													
Baseline	Average Rainfall (mm/year)	1146				997				149			
RCP 4.5	Average Rainfall (mm/year)		1284	1429	1566		1108	1202	1280		176	227	286
	Change (mm)		138	283	420		111	205	283		27	79	137
RCP 8.5	Average Rainfall (mm/year)		1343	1528	1804		1156	1300	1464		188	227	340
	Change (mm)		197	382	658		158	303	467		39	78	191
Ho Chi Minh City, Vietnam													
Baseline	Average Rainfall (mm/year)	1345				1174				170			
RCP 4.5	Average Rainfall (mm/year)		1482	1584	1678		1304	1395	1474		178	189	205
	Change (mm)		137	239	334		129	221	299		8	19	35
RCP 8.5	Average Rainfall (mm/year)		1500	1696	1727		1318	1518	1682		182	179	200
	Change (mm)		155	352	382		144	343	508		12	9	30
Kathmandu valley, Nepal													
Baseline	Average Rainfall (mm/year)	1660				1508				152			
RCP 4.5	Average Rainfall (mm/year)		2016	2096	2077		1733	1812	1798		283	284	279
	Change (mm)		356	436	417		225	304	289		131	132	127
RCP 8.5	Average Rainfall (mm/year)		1975	2133	2282		1690	1856	2012		285	276	269
	Change (mm)		315	472	621		182	348	504		133	124	117
Lahore, Pakistan													
Baseline	Average Rainfall (mm/year)	351				264				87			
RCP 4.5	Average Rainfall (mm/year)		391	384	406		284	276	281		107	107	125
	Change (mm)		40	33	55		20	12	17		20	20	38
RCP 8.5	Average Rainfall (mm/year)		397	409	405		267	271	260		129	137	145
	Change (mm)		46	58	54		3	7	-4		42	50	58

FIGURE 4. Yearly rainfall trend and an overview of the absolute change in annual, dry and wet-season rainfall for four Asian cities.

In Lahore, agricultural land decreased from 95% of total land area to 75% from 2015 to 2099 under a high urbanisation scenario. In contrast, built-up area rises from 4% to 25% of total land area. Built-up area increases from 4% to 12% of total land area in the medium urbanisation scenario from 2015 to 2099, while forest area increases from 0.1% to 25% of total land area in the low urbanisation scenario from 2015 to 2099.

Figure 5 shows the land use map of four Asian cities in different future periods under a high urbanisation scenario. The land use map of four Asian cities for medium and low urbanisation scenario is represented in Supplementary Figures 1 and 2, respectively.

3.4. Groundwater recharge trends

For all four Asian cities, the groundwater recharge for the reference period 2001–2005 (Bangkok

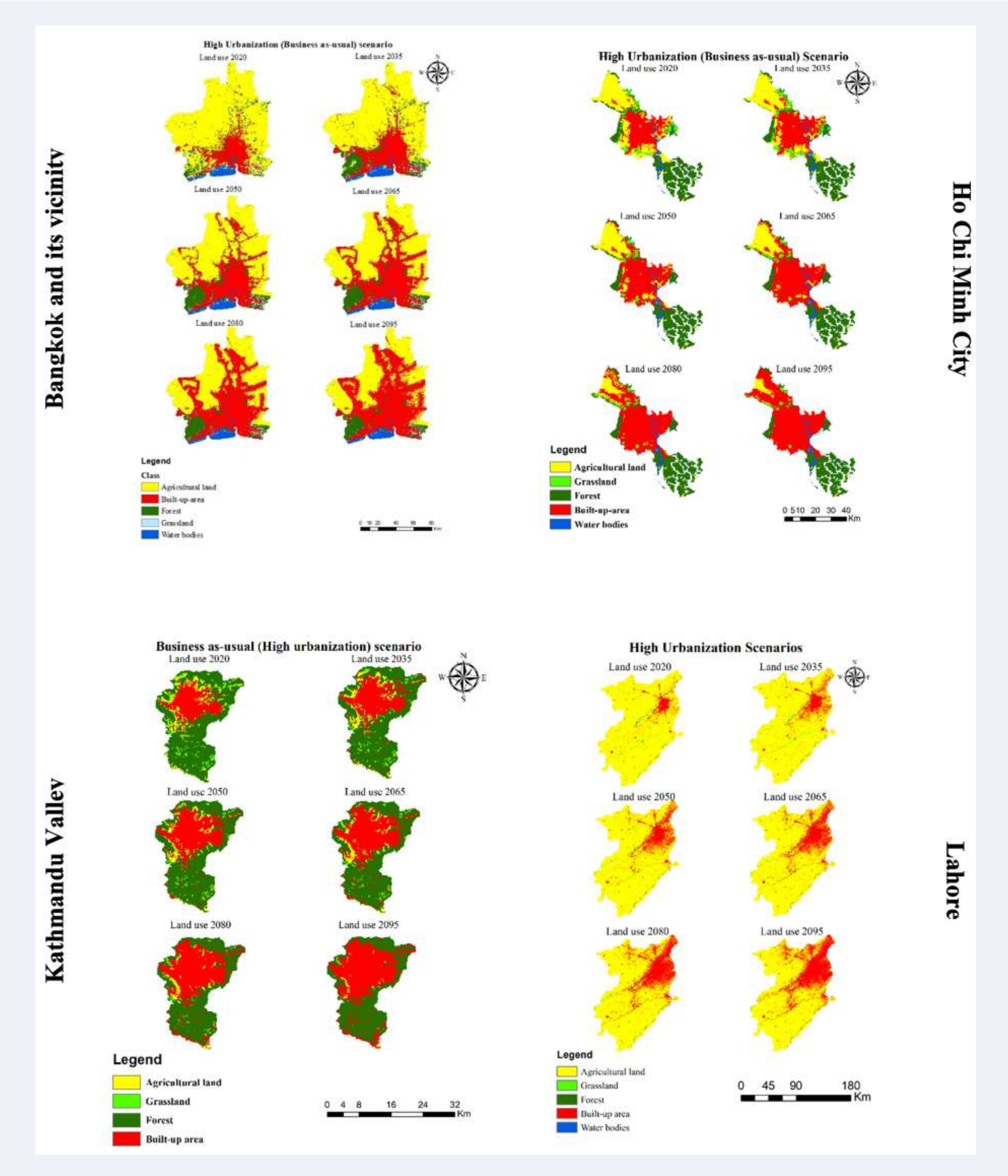


FIGURE 5. Land use map of four Asian cities in different future periods under high urbanisation scenario.

and its vicinity), 1989–2002 (Ho Chi Minh City), 1979–2005 (Kathmandu Valley) and 2000–2005 (Lahore) and for three future periods: 2010 to 2039 or near future (NF), 2040 to 2069 or mid future (MF), and 2070 to 2099 or far future (FF) were approximated seasonally and yearly (wet season from May–October and dry season from November–April). In the high and medium urbanisation scenarios, groundwater recharge is predicted to decrease, whereas it will rise in the low urbanisation scenario in both RCP scenarios. Future recharge in groundwater is anticipated to rise further during the dry season. The decline in future groundwater recharge is expected to be significant in the wet season.

For Bangkok and its vicinity, in a high urbanisation scenario, according to RCP 4.5 and RCP 8.5, the rate of fall in groundwater recharge will be between 28.3 mm/yr to 44.7 mm/yr and 22 mm/yr to 41.1 mm/yr, respectively. In a similar manner, future groundwater recharge for the medium urbanisation scenario is anticipated to decrease from 22.6 mm/yr to 33.3 mm/yr for RCP 4.5 and RCP 16.7 to 30.2 mm/yr for the RCP 8.5. In contrast, the expected increase in future groundwater recharge for low urbanisation scenarios ranges from 19.6 mm/yr to 35.8 mm/yr and 27.4 mm/yr to 40.1 mm/yr for RCP 4.5 and RCP 8.5, respectively.

In the high urbanisation scenario for Ho Chi Minh City, according to RCP 4.5 and RCP 8.5, the rate of fall in groundwater recharge will be between 22.1 mm/yr and 50.6 mm/yr and 29 mm/yr to 57.8 mm/yr, respectively. In a similar manner, future groundwater recharge for the medium urbanisation scenario is anticipated to decrease from 18.9 mm/yr to 46.1 mm/yr for RCP 4.5 and from 13.9 mm/yr to 42.1 mm/yr for RCP 8.5. In contrast, the expected increase in future groundwater recharge for low urbanisation scenarios ranges from 16 to 33.9 mm/yr for RCP 4.5 scenarios and 22.4 to 36.8 mm/yr for RCP 8.5 scenarios.

In Kathmandu Valley, for a low urbanisation scenario, the anticipated upsurge in future groundwater recharge ranges from 57.3–104.9 mm/yr and 65.7–116 mm/yr for RCP 4.5 and RCP 8.5, respectively. For the high urbanisation scenario, the drop in future groundwater recharge is anticipated to vary from 43.7–115.8 mm/yr and 28.2–104.1 mm/yr for the RCP 4.5 and RCP 8.5 scenario, respectively. For medium urbanisation scenario, groundwater recharge is expected to increase by 10.3 mm/yr and 1.4 mm/yr in near and mid future, whereas it is expected to decrease by 13.4 mm/yr in far future under RCP 4.5 scenario and for RCP 8.5 scenario, groundwater recharge is projected to increase by 15.1 mm/yr, 5.8 mm/yr and 2.4 mm/yr in near, mid, and far future, respectively.

For Lahore, in a high urbanisation scenario, the drop in future groundwater recharge is anticipated to differ between 12.4–34.3 mm/yr and 8.9–28 mm/yr for the RCP 4.5 and RCP 8.5, respectively. Future groundwater recharge for the medium urbanisation scenario is anticipated to decrease from 6.4 mm/yr to 23.2 mm/yr for RCP 4.5 and RCP 4.8 to 20 mm/yr for RCP 8.5. Whereas, for a low urbanisation scenario, the expected upsurge in future groundwater recharge ranges from 11.3 mm/yr to 27.2 mm/yr for RCP 4.5 scenario and 20.3 mm/yr to 34.4 mm/yr for RCP 8.5.

The findings show a progressive rise in groundwater recharge from the near future to the distant future in low urbanisation scenarios, with the lowest recharge found in high urbanisation scenarios. This is due to increased impervious surface induced by rapid urbanisation (Adhikari, Mohanasundaram, & Shrestha, 2020). It may also be established that changes in land-use patterns contribute much more to or less to groundwater recharge than changes in climate.

Figure 6 depicts the combined consequences of climate change and land use change under RCP 4.5 and RCP 8.5 scenarios and high urbanisation scenario on groundwater recharge across three future time periods: NF, MF and FF relative to the baseline period in four Asian cities. Medium and low urbanisation scenariosis presented in Supplementary Figures 3 and 4, respectively.

3.5. Groundwater level trends

Following a comparison with the baseline year 2001, projections were made for four future periods: 2035, 2055, 2075, and 2095 under two RCP scenarios and three land-use change scenarios (high, medium, and low urbanisation). Three abstraction scenarios (similar to land-use scenarios) were also examined in order to compute future groundwater abstraction, which was then utilised to forecast future groundwater levels in all aquifer layers.

For Bangkok and its environs, the results show that average groundwater levels are anticipated to fall under high urbanisation scenarios and all RCPs scenarios. Whereas, for medium and low urbanisation scenarios and both RCPs scenarios it is expected to increase in future. The amount of change in groundwater level through the Bangkok city is

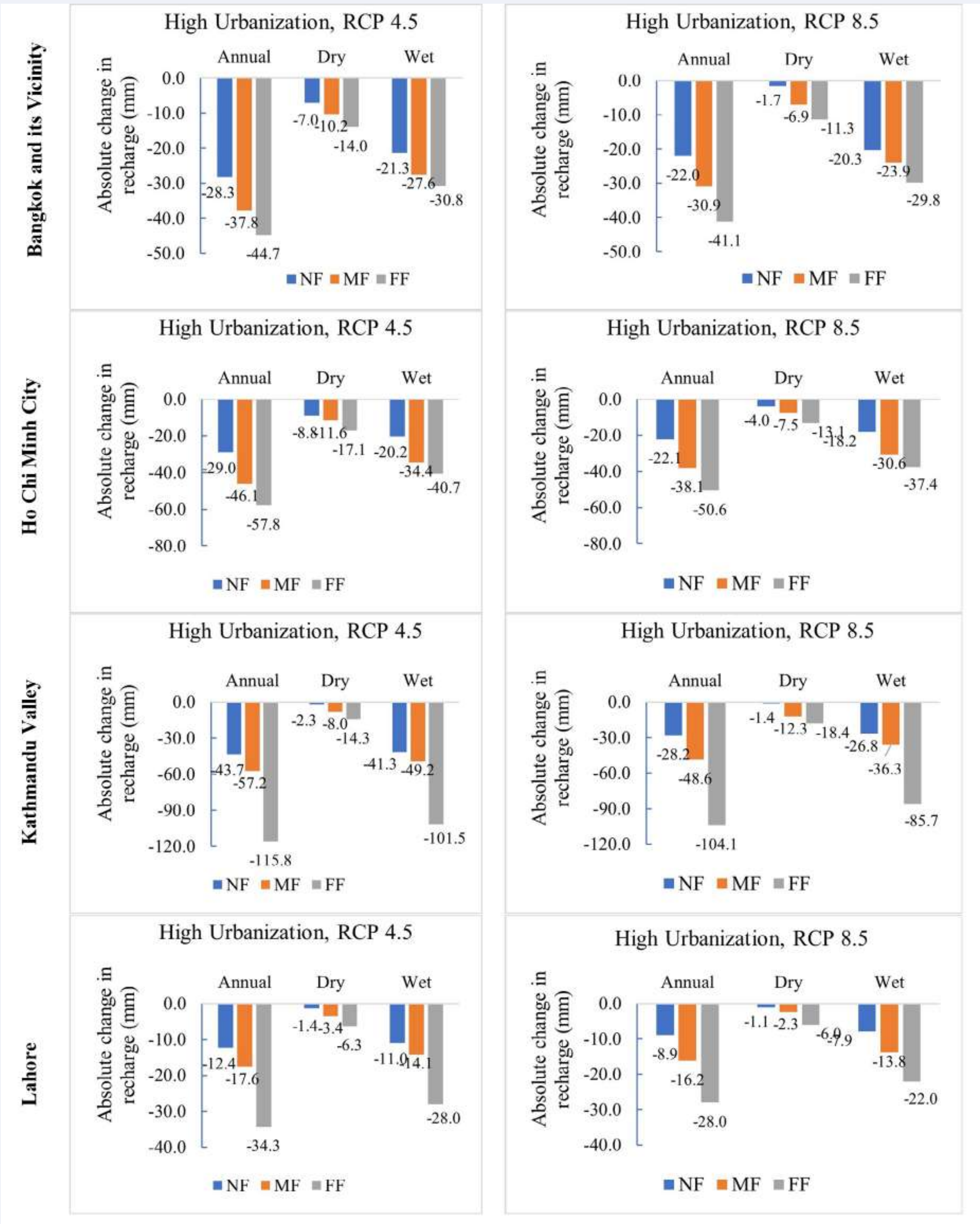


FIGURE 6. Combined consequences of climate change under RCP 4.5 and RCP 8.5 scenarios and land use change under high urbanisation scenario on groundwater recharge during three future periods; NF, MF and FF relative to the baseline period in four Asian cities.

not uniform. All RCPs cause a fall in groundwater level in the city and high urbanisation scenario with the central part experiencing noteworthy reduction in groundwater level as compared to western and eastern part. Under the high urbanisation scenario, the highest fall in groundwater level was 30.5 m and 29.5 m by 2095 in the NB aquifer for RCP 4.5 and RCP 8.5 scenarios, respectively. Under all RCPs, the groundwater level in Bangkok increased for medium and low urbanisation scenario with the increment higher in western and eastern part as compared to central part and maximum increase in groundwater level by 31.06 m and 32.06 m by 2095 was seen in NB aquifer for RCP 4.5 and RCP 8.5 scenarios, respectively under low urbanisation.

In Ho Chi Minh City, the average groundwater level is expected to fall under high urbanisation scenarios and all RCPs. In contrast, it is expected to rise in the future for medium and low urbanisation scenarios, as well as both RCPs. The amount of change in groundwater level is not uniform throughout Ho Chi Minh City. Under all RCPs and high urbanisation scenarios, the city experiences a decrease in groundwater level, with the central part experiencing a significant decrease in groundwater level as compared to the northern (Chu Chi) and southern parts (Can Gio). Under the high urbanisation scenario, the upper middle Pleistocene aquifer experienced the greatest decrease in groundwater level of 56.9 m and 53.5 m by 2095, respectively. Ho Chi Minh City experienced an upsurge in groundwater level for all RCPs, medium and low urbanisation scenarios, with the increase being greater in the northern (Chu Chi) and southern (Can Gio) parts of the city than the central part, and the maximum increase in groundwater level by 21 m and 22.5 m by 2095 was seen in the middle Pleistocene aquifer for RCP 4.5 and RCP 8.5 scenarios, respectively, under low urbanisation.

The average groundwater level in Kathmandu Valley will decline in the future under all three pumping scenarios: high, medium, and low urbanisation, as well as both RCP scenarios. The average decline in groundwater level was greater in the high urbanisation scenario than in the medium and low urbanisation scenarios. The pace of decline in groundwater level is not uniform throughout the Valley. The fall in groundwater level in the Valley's centre is considerable, and it is considerably greater than in the northern and eastern parts. The maximum decrease in groundwater level of 70 m and 66.7 m by 2095 was seen in well M4 (Lubhoo) for RCP 4.5 and RCP 8.5 scenarios, respectively under high urbanisation scenario. Whereas minimum decrease of 1.5 m and 1.3 m by 2095 was seen in well GK4 (Nayapati) for RCP 4.5 and RCP 8.5 scenarios, respectively under low urbanisation scenarios.

The average groundwater level in Lahore is expected to fall under high urbanisation scenarios and all RCPs. In contrast, it is expected to rise in the future for medium and low urbanisation scenarios, as well as both RCP scenarios. The pace of decline in groundwater level in Lahore is not uniform. The fall in groundwater level in the city's centre is significant and much greater than in the outskirts. Under the high urbanisation scenario, the maximum decrease in groundwater level was 62.3 m and 57.2 m by 2095 in well Dhobi Ghat for RCP 4.5 and RCP 8.5 scenarios, respectively. Ghazi Mohala Children Park Ghari Shahu saw increases of 16 m and 18.9 m by 2095 for RCP 4.5 and RCP 8.5 scenarios, respectively under low urbanisation scenarios.

These regional disparities in groundwater level may be related to the amount of groundwater pumping caused by the intensity of the pumping wells. The core section of Asian cities is more densely inhabited, has the most abstraction wells, and draws the most water for home, industrial, and other commercial activity. Also, the centre areas of Asian cities are built-up, restricting groundwater recharge to aquifers.

Figure 7 shows the average change in groundwater level for both RCP scenarios (RCP 4.5, RCP 8.5), three land-use change and pumping scenarios (low, medium, and high urbanisation) for four future periods: 2035, 2055, 2075 and 2095 relative to the baseline in four Asian cities and Figures 8 and 9 shows absolute change in future groundwater level with respect to observed groundwater level in 2035, 2055, 2075 and 2095 for aquifer layers under high urbanisation scenario and RCP 4.5 (a) and 8.5 scenarios (b) in Bangkok and its vicinity and Ho Chi Minh City, Kathmandu Valley and Lahore. The results under medium and low urbanisation scenarios for Bangkok and its vicinity and Ho Chi Minh City are presented in Supplementary Figures 5 and 6, respectively.

FIGURE 7. The average change in groundwater level for both RCP scenarios (RCP 4.5, RCP 8.5), three land-use change and pumping scenarios (low, medium, and high urbanisation) for four future periods: 2035, 2055, 2075 and 2095 relative to the baseline in four Asian cities.

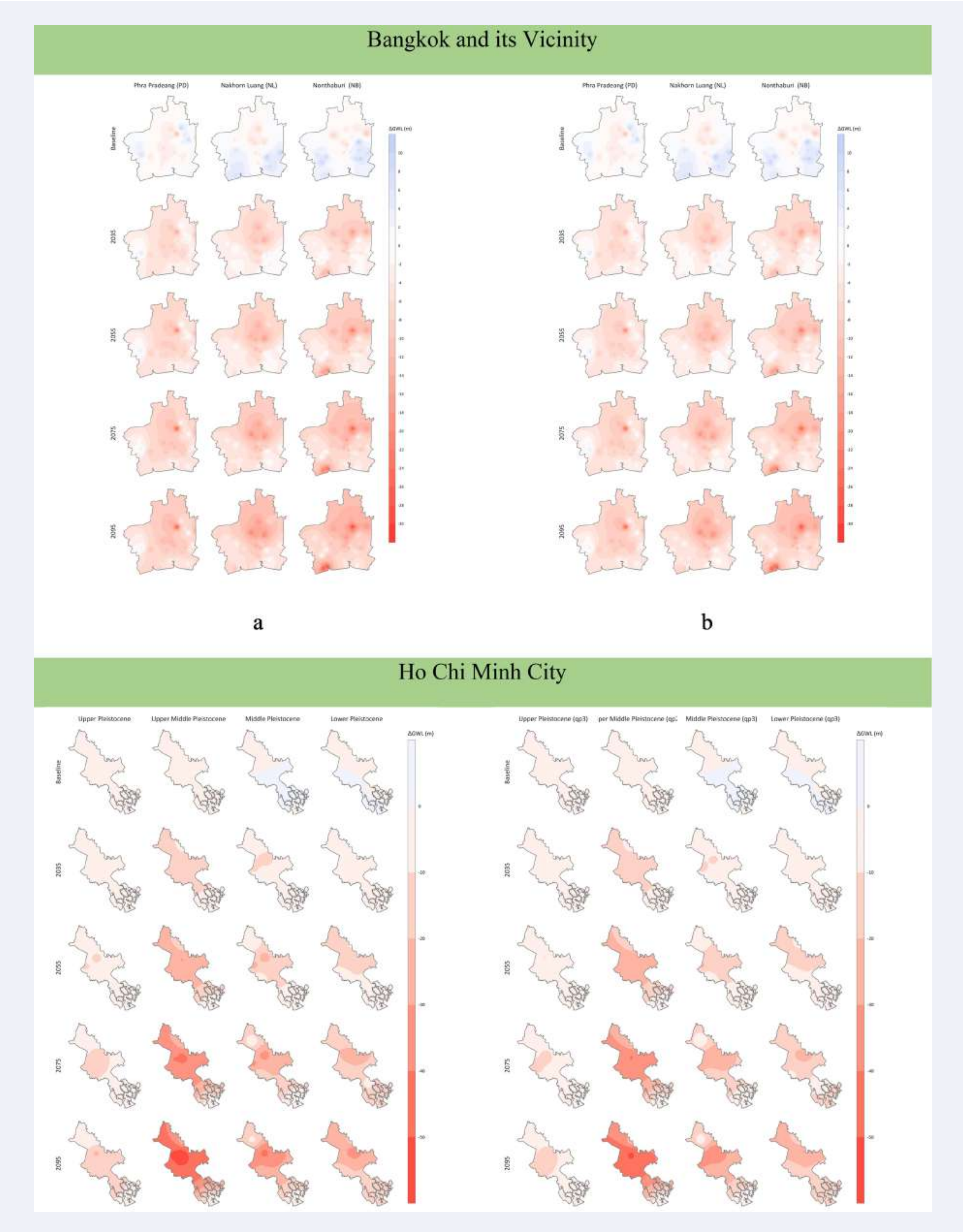


FIGURE 8. Absolute change in future groundwater level with respect to observed groundwater level in 2035, 2055, 2075 and 2095 for aquifer layers under high urbanisation scenario and RCP 4.5 (a) and 8.5 scenarios (b) in Bangkok and its vicinity and Ho Chi Minh City, respectively.

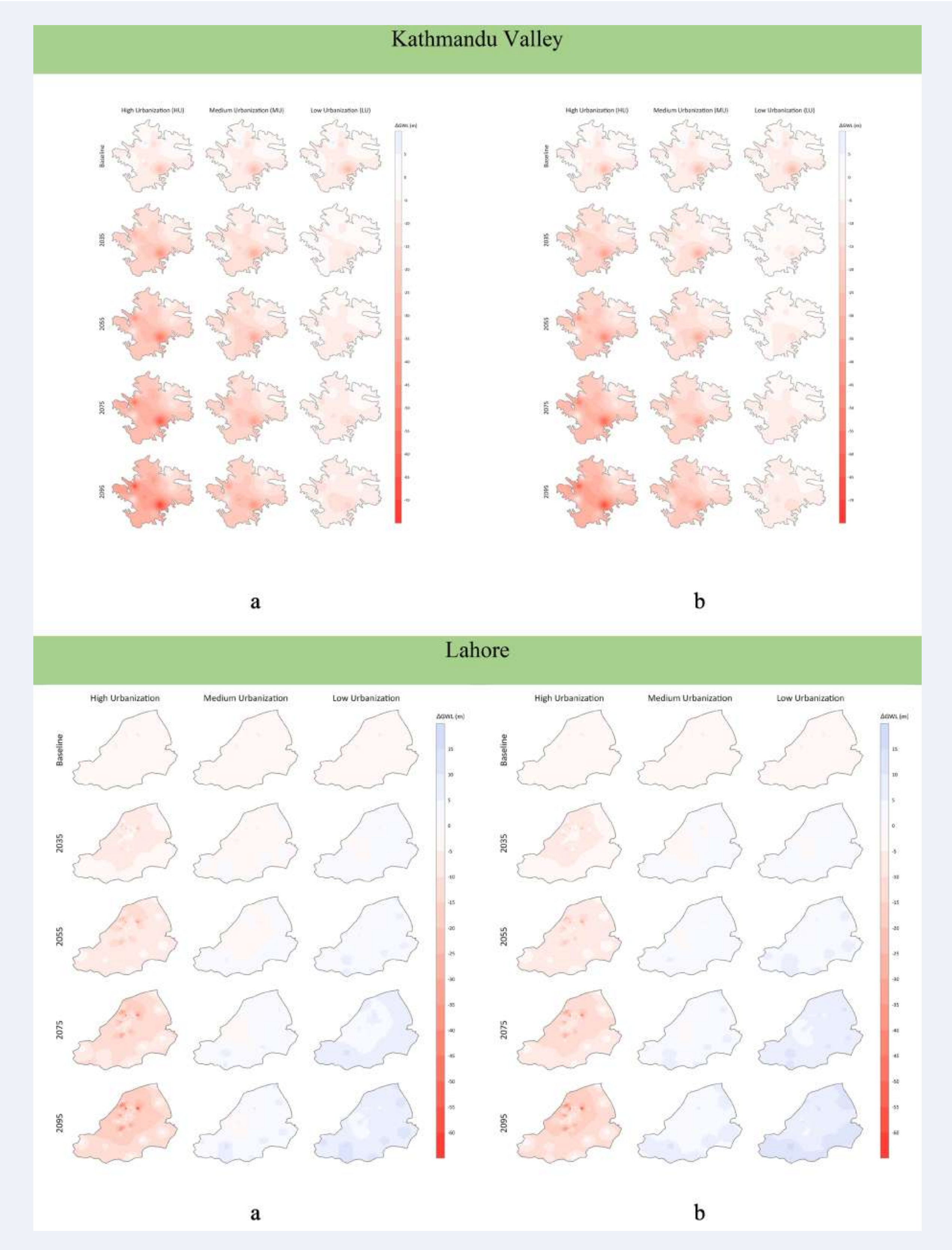


FIGURE 9. Absolute change in future groundwater level with respect to observed groundwater level in 2035, 2055, 2075 and 2095 under high, medium, and low urbanisation scenarios and RCP 4.5 and 8.5 scenarios for Kathmandu Valley and Lahore.

3.6. Spatial variation in groundwater resiliency

Based on the results of groundwater recharge from hydrological models and groundwater level from groundwater models, a groundwater resilience map of Asian cities was created. In this research groundwater resiliency is specified as the percentage recuperation over total depletion. The groundwater resiliency map of all four Asian cities was developed for five time periods (2025, 2035, 2055, 2075 and 2095) under three land use and pumping scenarios (low, medium, and high urbanisation scenario) and climate change scenarios (RCP 4.5 and RCP 8.5).

Under high urbanisation scenarios, it is anticipated that less land area will fall into the "very highly resilience class" in Bangkok and the surrounding area, while more land area will fall into the "not resilient class" as time goes on. This is true for all climate change scenarios and for all three aquifer layers. Central part of Bangkok and its vicinity (Bangkok metropolis, Pathum Thani, Nonthaburi, Samut Sakhon, Ayutthaya) are not resilient to climate change and human development. Due to the dense habitation in the city's centre, the aquifers receive less groundwater recharge. Besides this the central part of the Bangkok consists of underlying clay layer which forbid the water to enter the aquifers. Also, groundwater abstraction in these areas is very high due to high population density and industrial areas. Western part of Bangkok and its vicinity (Nakhon Pathom) is resilient to climate change and human development. Western part of the city is the major groundwater recharge zone for the Bangkok aquifer system. Under medium and low urbanisation scenarios the findings show an expected expansion in proportion of area under "very highly resilient class".

In Ho Chi Minh City, under high urbanisation scenarios, there is projected diminution in percentage of area under "very highly resilience class" while the area under "not resilient class" is increasing as we move to the future, and this is valid for all climate change scenarios and all four aquifer layers. Central part of Ho Chi Minh City (District 1-12, Binh Chan, Hoc Mon, Binh Tan) is not resilient to climate change and human development. For the Lower Pleistocene aquifer all part of HCMC is not resilient to climate change and human development. Due to the dense habitation in the city's centre, the aquifers receive less groundwater recharge. Also, groundwater abstraction in these areas is very high due to high population density and industrial areas. Northern part of Ho Chi Minh City (Chu Chi) and Southern part (Can Gio) is resilient to climate change and human development for three aquifer layers. Northern part of the city is the major groundwater recharge zone for HCMC aquifer system. Southern part consists of forest area (conservation area), increasing groundwater recharge to the aquifers. Under medium and low urbanisation scenarios the findings show an expected expansion in percentage of area under "very highly resilient class".

According to the data, the percentage of the Kathmandu Valley that falls into the "very highly resilient" class is predicted to decline over time, while the percentage of the "not resilient" class is predicted to rise. For areas with high urbanisation compared to those with medium and low urbanisation, there was a considerable decline in the area categorised as "very highly resilient" and an expansion in the area under "not resilient". Central part of the Kathmandu Valley (Lubhu, Kathmandu airport, Baneshwor, Swayambhu, Patan, Baluwatar) are not resilient to climate change and human development. Due to the dense habitation in the Valley's centre, the aquifers receive less groundwater recharge. Also, groundwater abstraction in these areas is very high due to high population density and industrial areas. Northern part of the Valley (Budhanilkantha, Sundarijal, Shakhu, Danchi, Gokarna) are resilient to climate change and human development. Northern part of the Valley is the major groundwater recharge zone for Kathmandu aquifer system. This part is a semi urban area with more agricultural area and forest as compared to built-up hence the groundwater recharge in these areas is high.

According to the high urbanisation scenario projections for Lahore, the proportion of area falling into the "very highly resilience" class is anticipated to decline over time, while the percentage of land falling into the "not resilient" category is projected to rise. Central parts of Lahore (Allama Iqbal town, Johar town, Shahadara, Badshahi mosque, Garhi Shahu) are not resilient to climate change and human development. Due to the dense habitation in the city's centre, the aquifers receive less groundwater recharge. Also, groundwater abstraction in these areas is very high due to high population density and industrial areas. The outskirts of the city (Lokhori, Jahman, Padhana, Wahqa, Manga mandi) are resilient to climate change and human development. Outskirts part of the city is a semi urban area with more agricultural land hence the groundwater recharge in these areas is high.

Figure 10 shows the groundwater resilience map of Bangkok and its vicinity and Ho Chi Minh City in five different time periods 2025, 2035, 2055, 2075, and 2095 under high urbanisation scenarios and RCP 4.5 (a) and RCP 8.5 (b) scenarios. For medium and low urbanisation scenarios, the results are presented in Supplementary Figures 7 and 8, respectively. Figure 11 shows the groundwater resilience map of Kathmandu Valley and Lahore in five different time periods 2025, 2035, 2055, 2075, and 2095 under high, medium and low urbanisation scenarios and RCP 4.5 (a) and RCP 8.5 (b) scenarios.

4. DISCUSSION

The results indicate a gradual increase in groundwater recharge in the low urbanisation scenarios from the near future towards the far future, with the lowest recharge observed in high urbanisation scenarios. This is due to a greater increase in the built-up area (impervious surface) caused by high urbanisation (Adhikari et al., 2020, Ghimire et al., 2021). It can also be concluded that land-use pattern changes significantly contribute to the increase or decrease in groundwater recharge in comparison to changes in climate.

Groundwater of good natural quality is an excellent source of drinking water. The reduction in groundwater recharge leads to a drop in the groundwater table, which can have a negative impact on human life by affecting the quality of groundwater. Groundwater is also one of the most important sources of water for irrigation and industrial purposes. Reduction in groundwater recharge may lead to the shortage of water for agricultural and industrial purposes affecting the economy of the whole country, living standard of the people and other social impacts such as displacement of population, loss of scarce agricultural land, etc. Besides this, reduction in groundwater recharge may cause land subsidence resulting in loss of properties and human life. Techniques like rainwater harvesting, artificial recharge techniques in addition to low urban development planning and adopting climate change strategies may lead to the sustainable aquifer in the Asian cities in the future.

The over extraction of groundwater induced by rapid population growth, rapid urbanisation along with climate change may lead to complete depletion of groundwater and other environmental problems like land subsidence, contamination of groundwater table, and depletion of surface water resources. These consequences of groundwater depletion are directly linked with human life. The lowering of the groundwater table causes wells to no longer be able to reach groundwater and hence affecting the availability of water for domestic, agricultural, and industrial purposes. As the water table lowers, the water must be pumped farther to reach the surface, using more energy. In extreme cases, using such a well can be prohibitive. Groundwater and surface water are connected. The depletion of groundwater lever can lower lake levels or in extreme cases intermittent or totally dry perennial streams. These effects can harm aquatic and riparian plants and animals that depend on regular surface flows. Excessive pumping in coastal areas can cause saltwater to move inland and upward, resulting in saltwater contamination of the water supply. The over extraction of groundwater might cause land subsidence and sinkhole formation in areas of heavy withdrawal. These changes can damage buildings, roads, and other structures as well as human life. Techniques like rainwater harvesting, artificial recharge techniques in addition to low urban development planning and adopting climate change strategies along with improving the groundwater governance of respective cities is

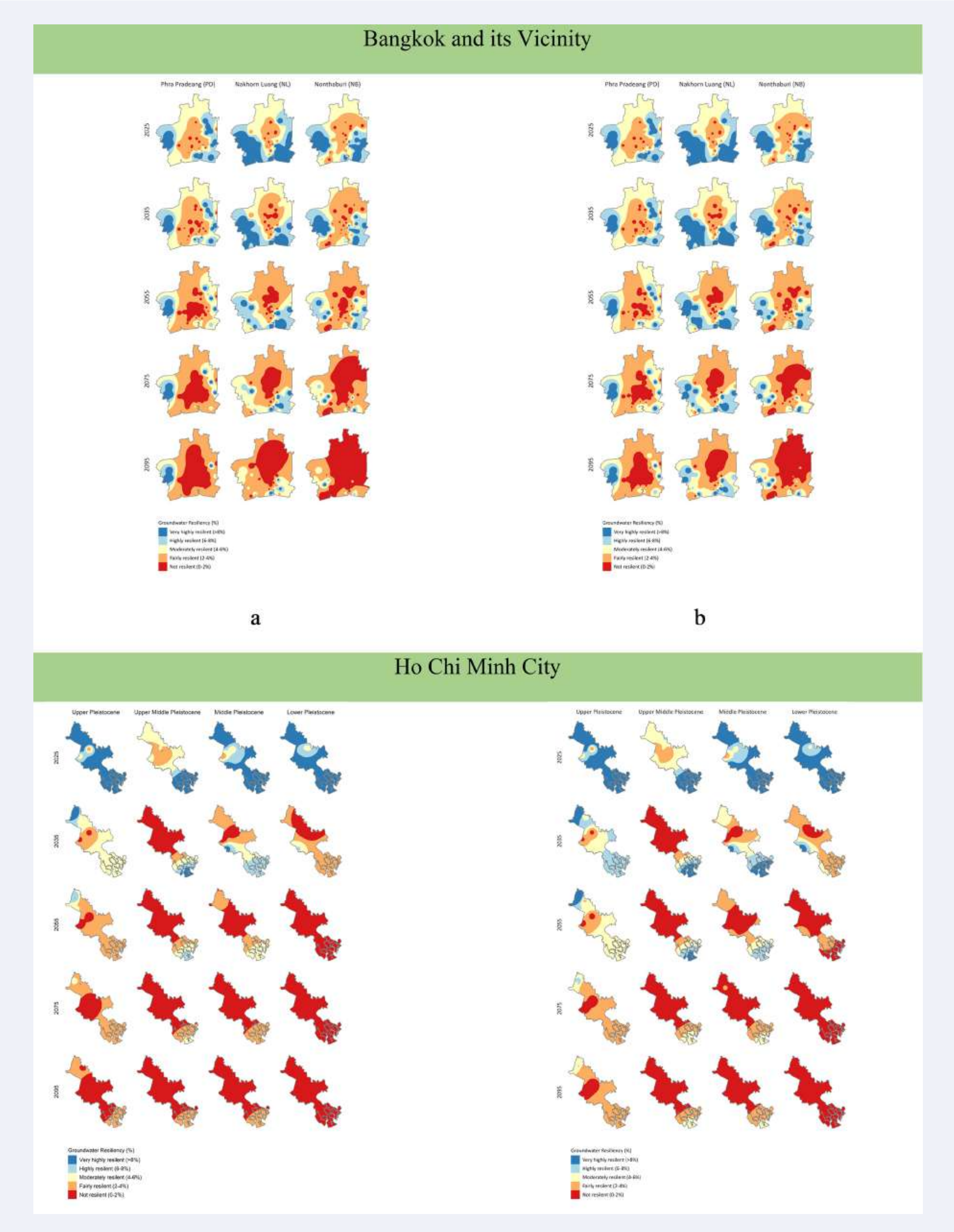


FIGURE 10. Groundwater resilience map of Bangkok and its vicinity and Ho Chi Minh city in five different time period 2025, 2035, 2055, 2075, and 2095 under high urbanisation scenarios and RCP 4.5 (a) and RCP 8.5 (b) scenarios.

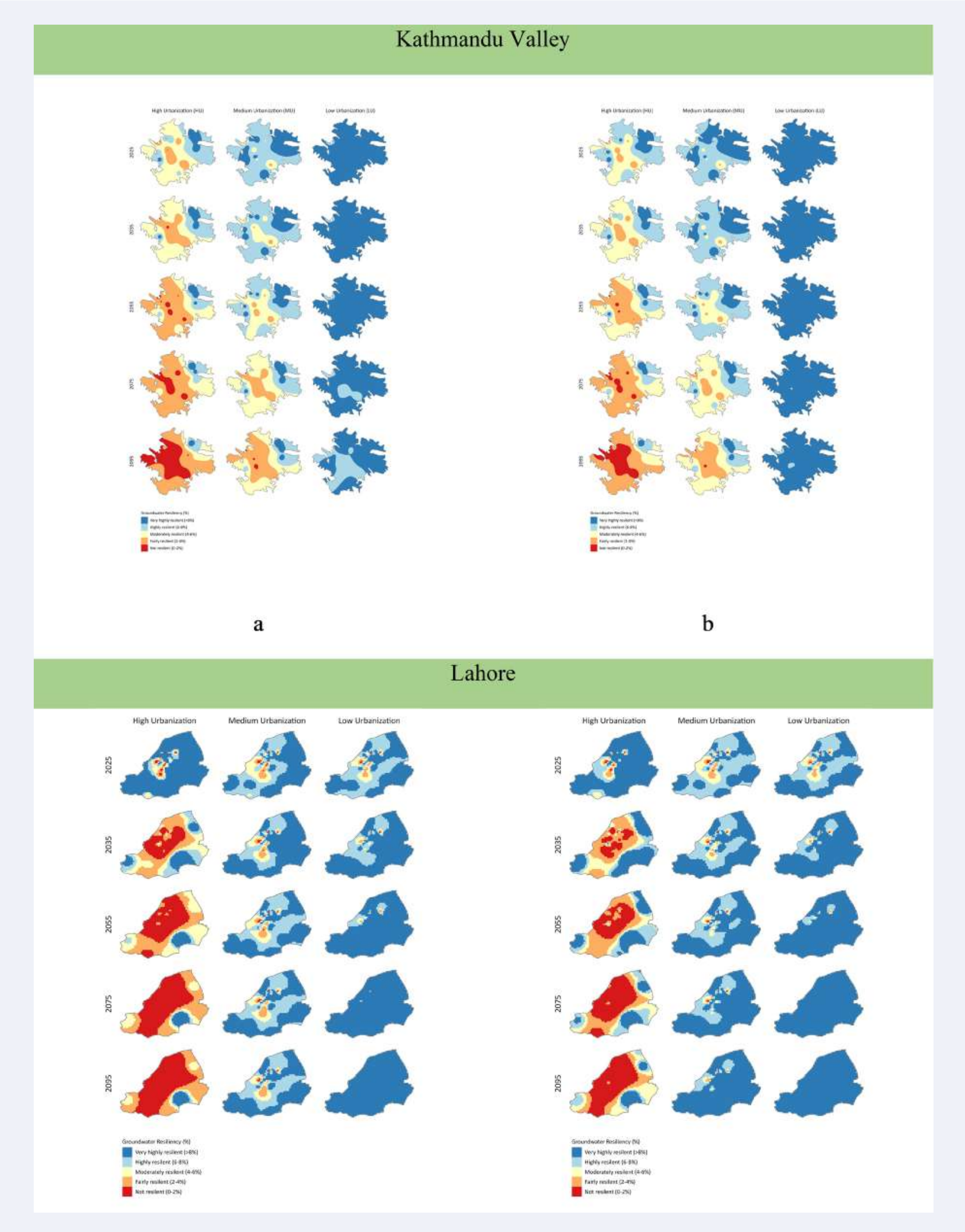


FIGURE 11. Groundwater resilience map of Kathmandu Valley and Lahore in five different time period 2025, 2035, 2055, 2075, and 2095 under high, medium, and low urbanisation scenarios and RCP 4.5 (a) and RCP 8.5 (b) scenarios.

for the protection and sustainable management of groundwater resources.

Based on the results and variability in terms of climate change and human development, it can be concluded that the groundwater resources in the Asian cities are at risk due to climate change and human development. The reduction in groundwater recharge and depletion of groundwater are both associated with decreasing resiliency of groundwater system in Asian cities. Asian cities are heavily dependent on groundwater resources for their daily water supply. The reduction in groundwater recharge and depletion in groundwater table can have serious impact on socio-economic aspect of the country due to contamination of groundwater, depletion of surface water resources and problem of land subsidence. Therefore, proper monitoring of the groundwater condition and development of adaptation is crucial for sustainable management of groundwater resources in the Asian cities.

5. CONCLUSION

Groundwater resources play a very crucial role in sustainable development of main Asian cities. The over extraction of groundwater caused by rapid growth in population, rapid expansion in urban land, economic development, tourism development alongside with climate change may lead to extensive reduction of groundwater level causing social, environmental, and economic problems. Therefore, this study objects to examine the resilience of groundwater system to climate change and anthropogenic development in Asian cities: Bangkok and its vicinity, Thailand, Ho Chi Minh City, Vietnam, Lahore, Pakistan and Kathmandu Valley, Nepal, which eventually helps in the management and protection of groundwater resources as well as to develop strategies for sustainable use. A unified methodology was used to conduct the study.

To assess groundwater resiliency in Asian cities, twenty-one CORDEX RCMs were evaluated based on their capacity to simulate climate extremes in fast-expanding Asian cities that are especially sensitive to climate change. The top five better performing RCMs along with two RCPs scenarios were used to project future climate in respective Asian cities for three future periods. All RCMs and both RCP scenarios project that the Asian cities are expected to be warmer in future. The maximum increase (by 4.1°C) in maximum temperature and (by 5.6°C) in minimum temperature is expected for Ho Chi Minh City. The results show that all the Asian cities will receive more rainfall under both RCP scenarios with Bangkok and its vicinity experiencing maximum increase in future rainfall by 658 mm.

An empirical land use projection model Dyna-CLUE was used to project the future land use change of the study area. Dyna-CLUE was used to create land-use maps of Asian cities up until 2099 based on three future land-use scenarios: LU, MU, and HU. These scenarios focused on the growth of built-up areas. The effects of climatic change and human development on groundwater recharge and level were also investigated. Groundwater recharge is expected to decline in all four Asian cities under the high urbanisation scenario and both RCP scenarios (by up to 115 mm in Kathmandu Valley), but it is anticipated to increase in all future scenarios under the low and medium urbanisation scenarios and both RCP scenarios. In the case of Bangkok, Ho Chi Minh City and Lahore, the average groundwater level is projected to decrease under high urbanisation scenarios and all RCP scenarios. Whereas, for medium and low urbanisation scenarios and both RCP scenarios it is projected to increase in future. For Kathmandu Valley, on average, the groundwater level will decrease in future for all three pumping scenarios: high, medium and low urbanisation and both RCP scenarios. The average decrease in groundwater level was higher for high urbanisation than medium and low urbanisation scenarios. Spatially, the central part of all the Asian cities experiences maximum decrease in groundwater level. These spatial differences in groundwater level might be linked to the level of groundwater abstraction by the density of the pumping wells. In contrast, the central part of the Asian cities is a highly built-up area, reducing groundwater recharge to the aquifers.

For Bangkok and its vicinity, Ho Chi Minh city and Lahore, the results show a projected increase in percentage of area under "very highly resilient class", for medium and low urbanisation scenarios, and for high urbanisation scenario, there is projected decrease in percentage of area under "very highly resilience class" while the area under "not resilient class" is increasing, which is valid for all climate change scenario and all three aquifer layers. For Kathmandu Valley, results show a projected decrease in the percentage of area under "very highly resilient" class and a projected increase in the "not resilient" class towards the future periods. The decrease in the area classified as "very highly resilient" and an increase in the area under "not resilient" was significant and higher for high urbanisation than medium and low urbanisation.

According to the findings and variance in climate change and human development, it is possible to conclude that groundwater supplies in all four Asian cities are threatened by climate change and human growth. As a result, appropriate groundwater monitoring and adaptive development are vital for the sustainable management of groundwater resources in Asian cities.

6. ACKNOWLEDGEMENT

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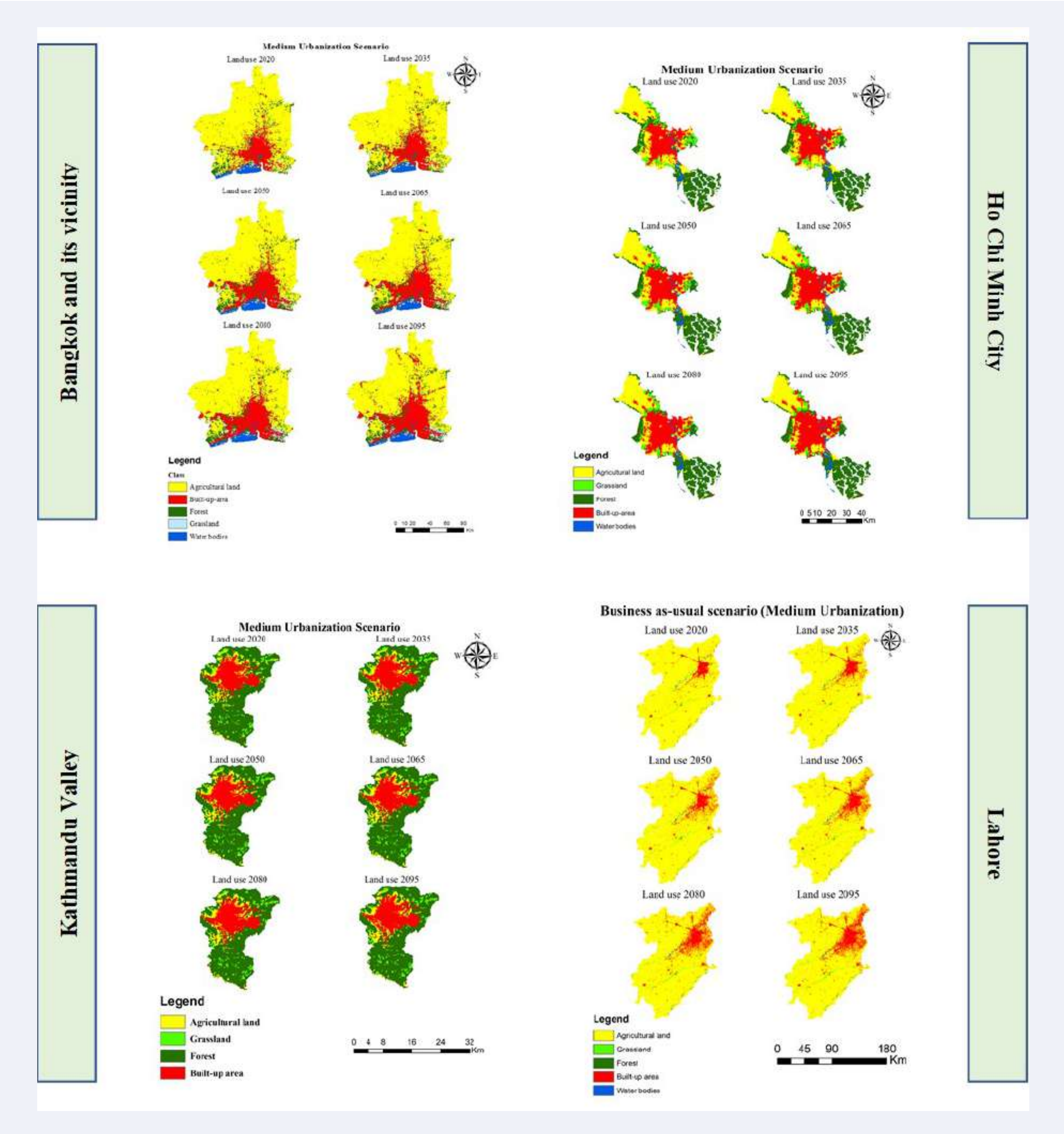
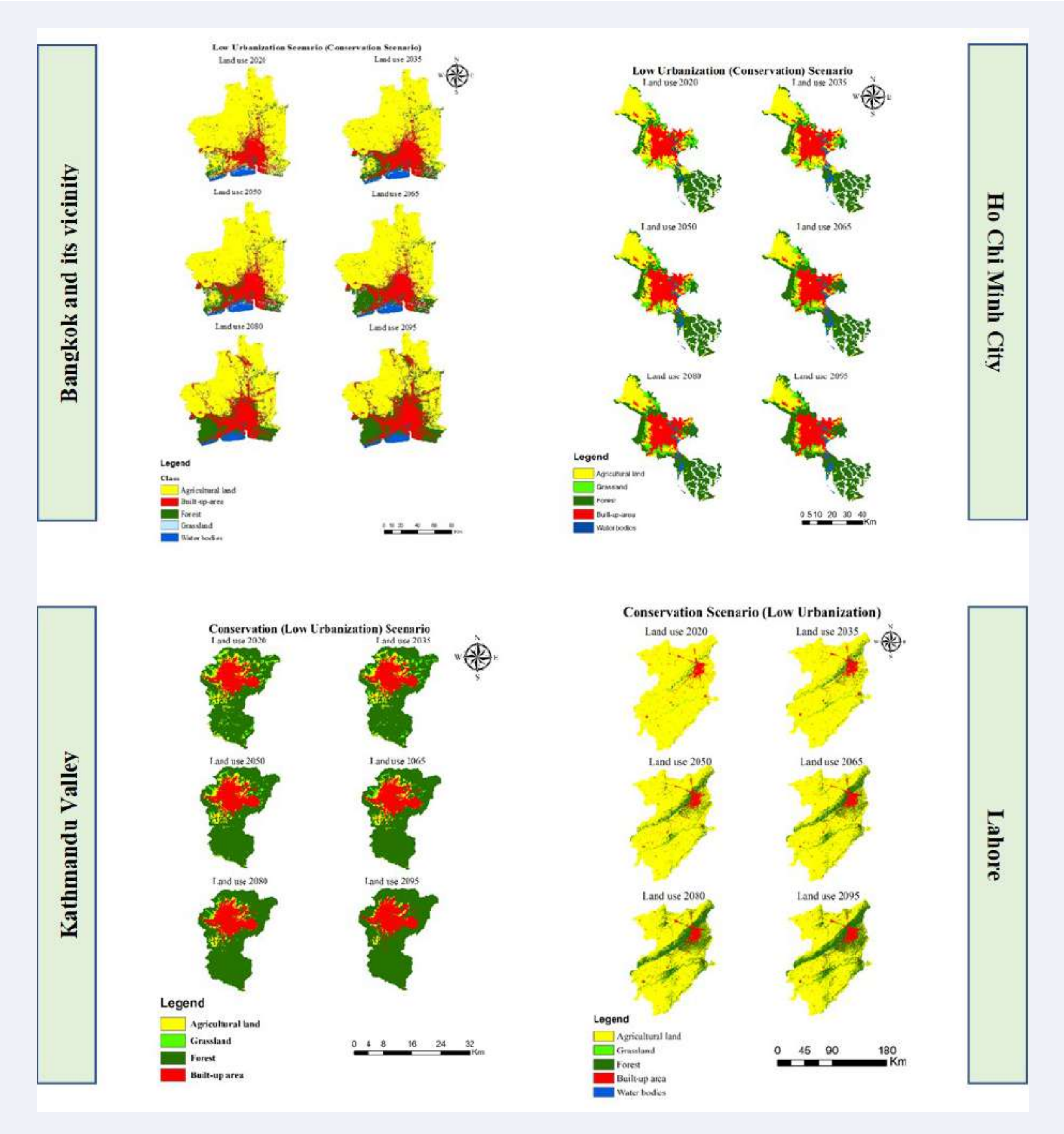
A. APPENDIX

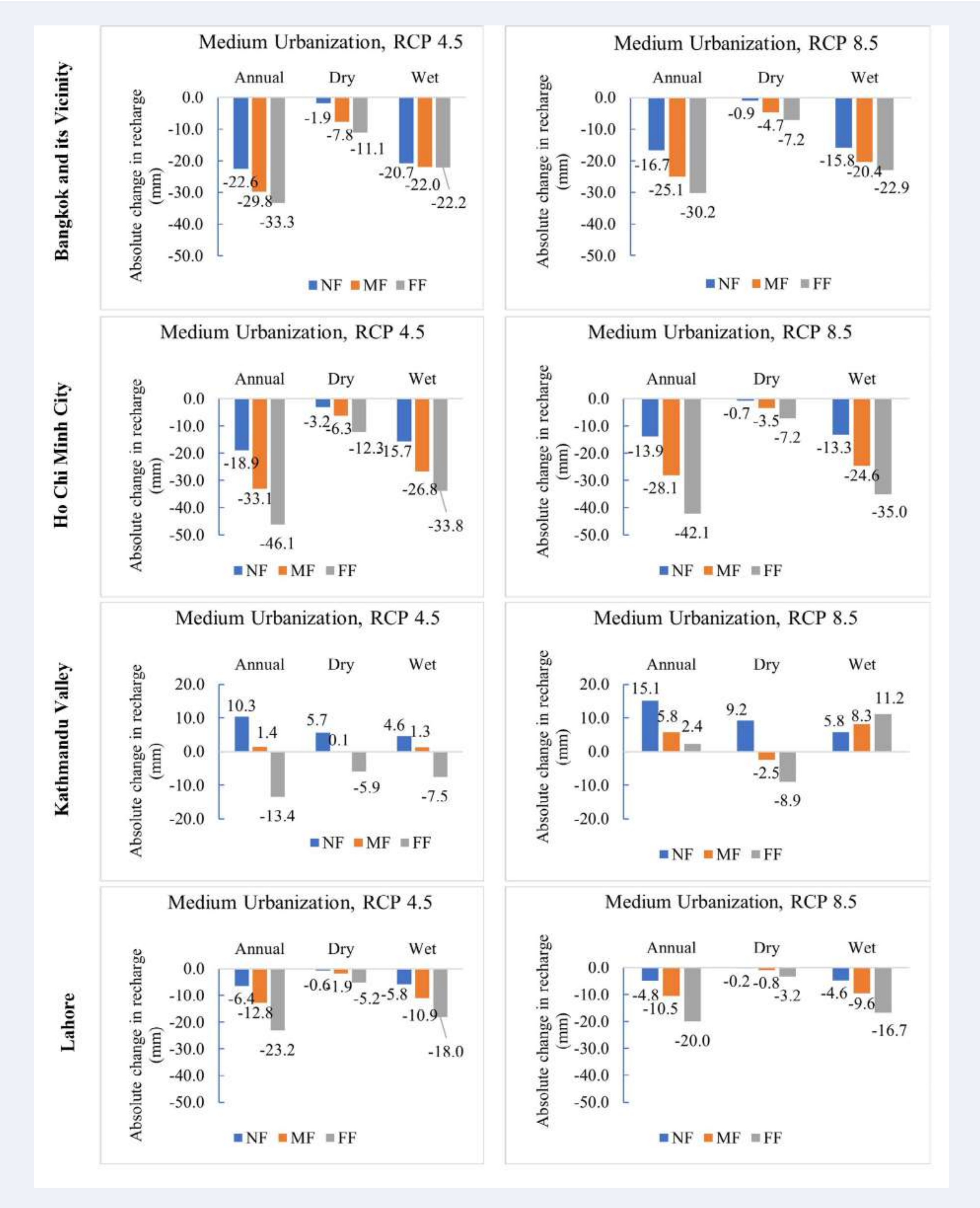
A.1. Supplementary Figures and Tables



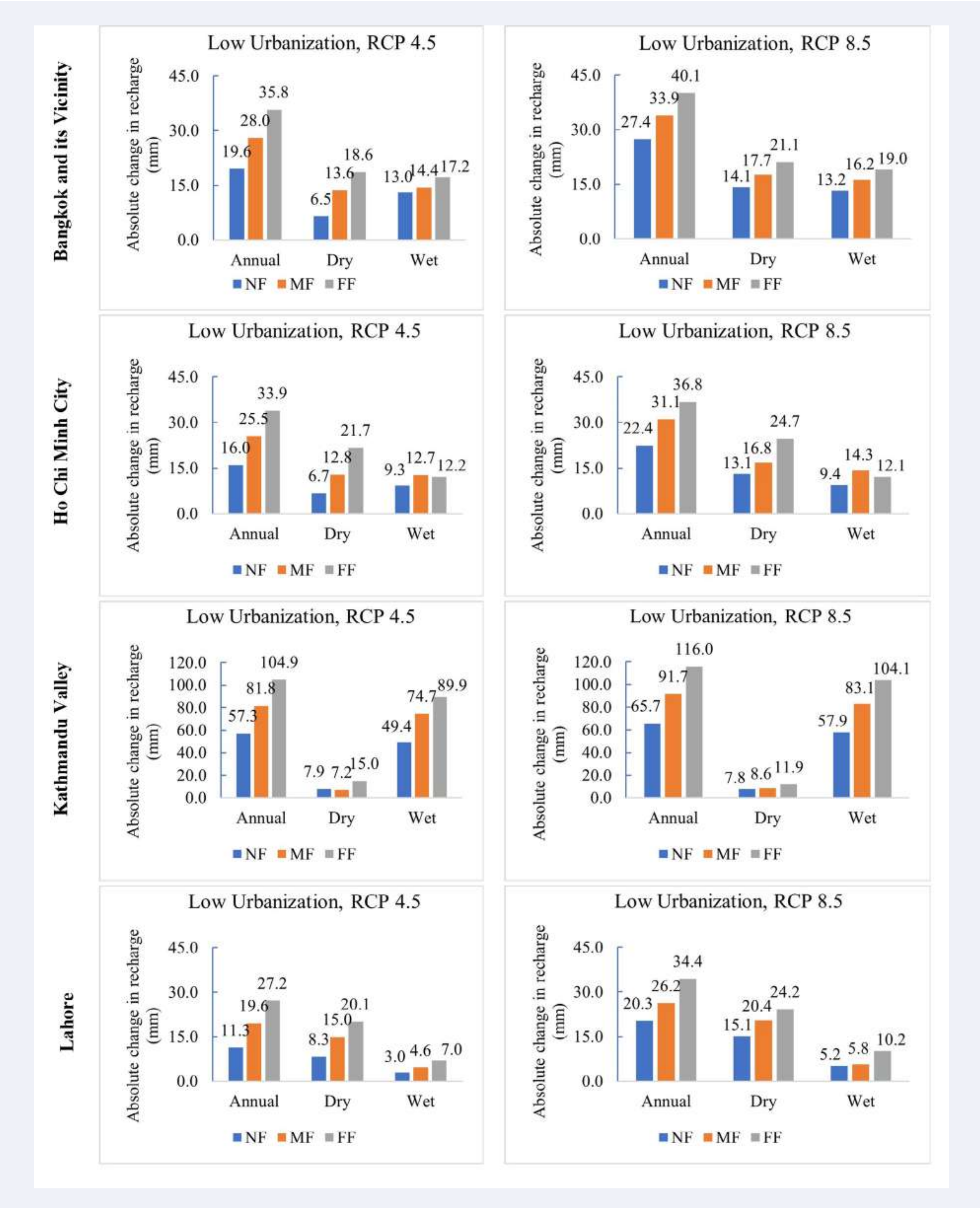
SUPPLEMENTARY FIGURE 1. Land use map of four Asian cities in different future periods under medium urbanization scenario.



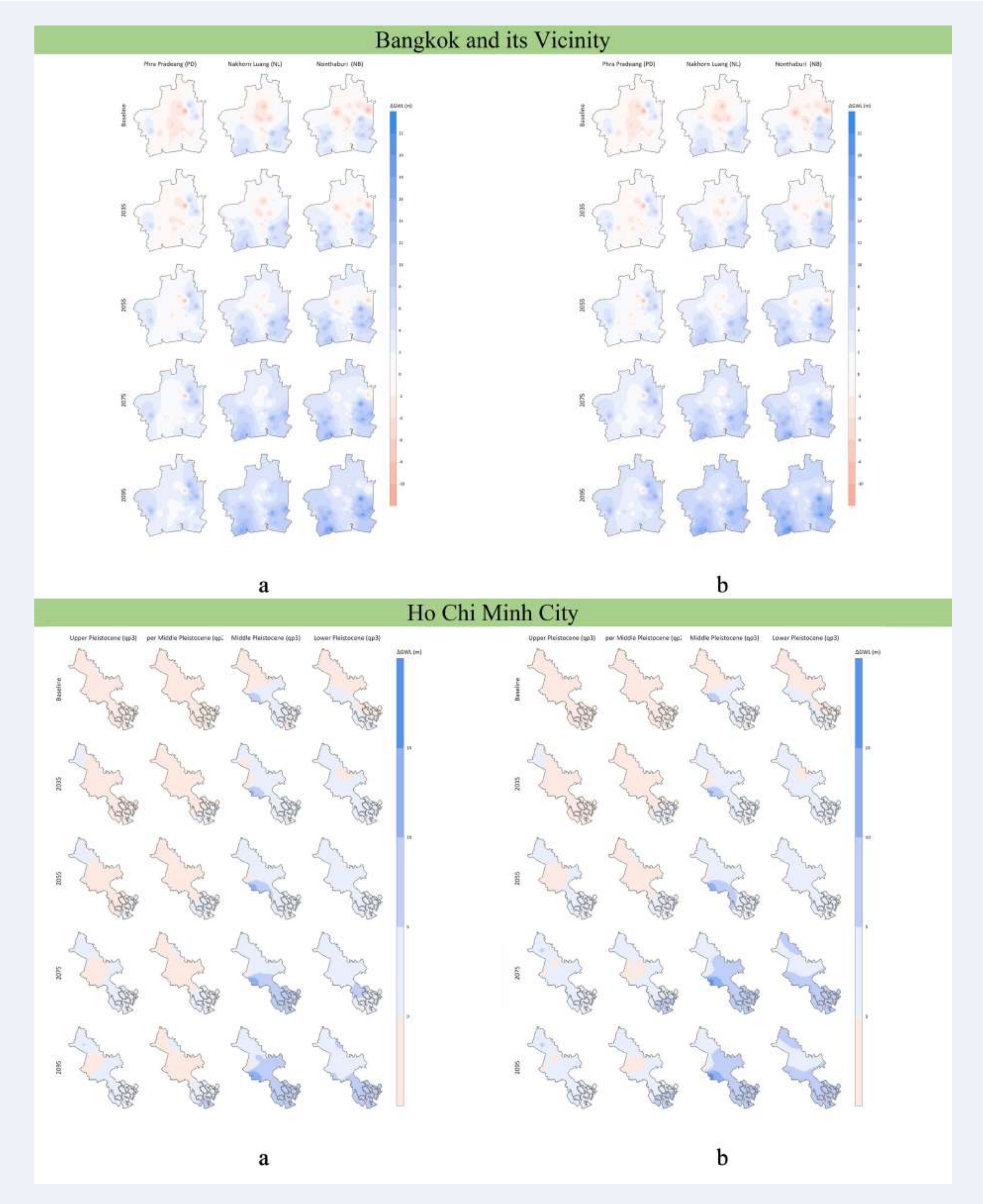
SUPPLEMENTARY FIGURE 2. Land use map of four Asian cities in different future periods under low urbanization scenario.



SUPPLEMENTARY FIGURE 3. Combined impacts of climate change under RCP 4.5 and RCP 8.5 scenarios and land use change under medium urbanization scenario on groundwater recharge during three future period; NF, MF and FF relative to the baseline period in four Asian cities.



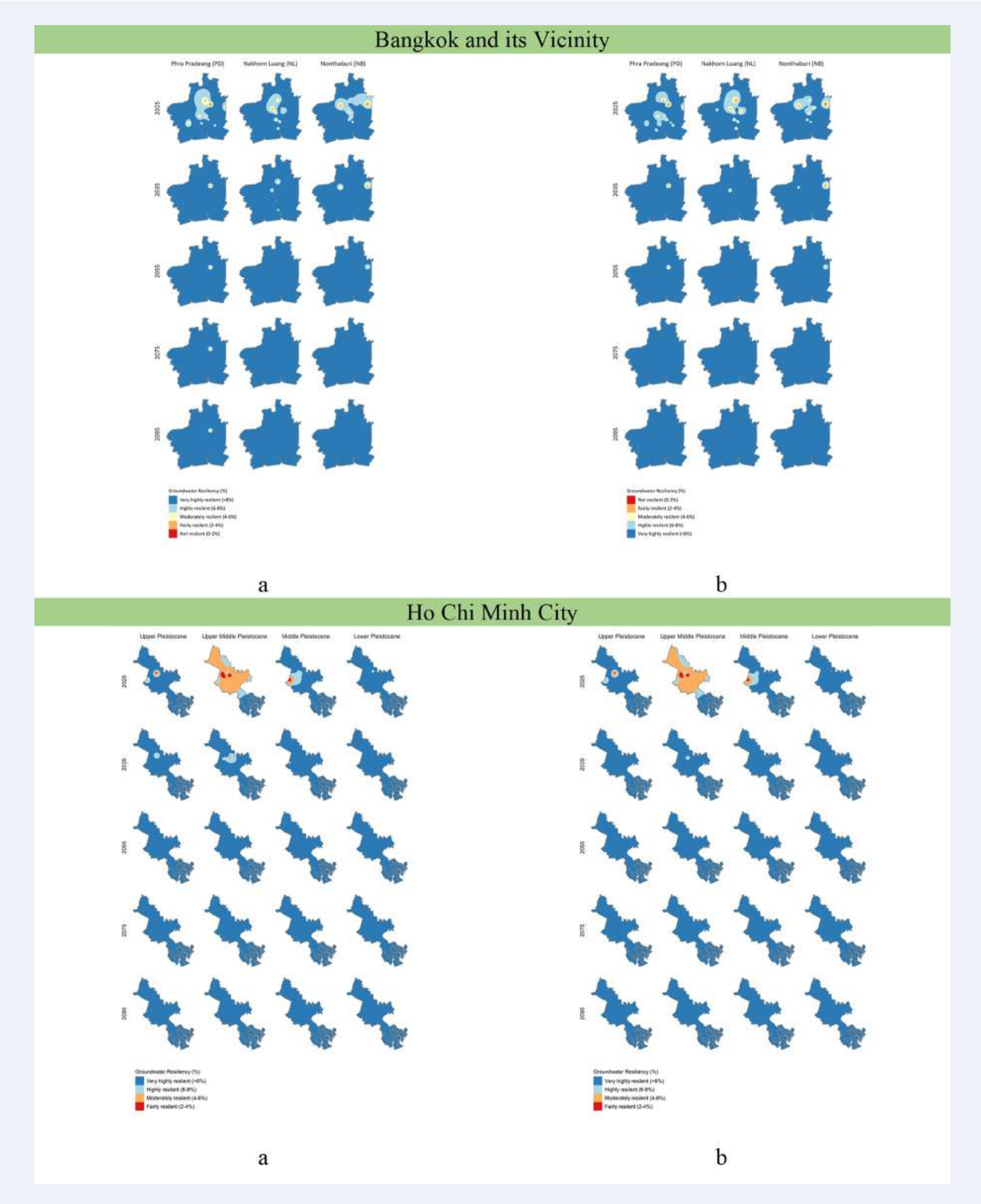
SUPPLEMENTARY FIGURE 4. Combined impacts of climate change under RCP 4.5 and RCP 8.5 scenarios and land use change under low urbanization scenario on groundwater recharge during three future period; NF, MF and FF relative to the baseline period in four Asian cities.



SUPPLEMENTARY FIGURE 5. Absolute change in future groundwater level with respect to observed groundwater level in 2035, 2055, 2075 and 2095 for aquifer layers under medium urbanization scenario and RCP 4.5 (a) and 8.5 scenarios (b) in Bangkok and its vicinity and Ho Chi Minh city respectively.

SUPPLEMENTARY FIGURE 6. Absolute change in future groundwater level with respect to observed groundwater level in 2035, 2055, 2075 and 2095 for aquifer layers under low urbanization scenario and RCP 4.5 (a) and 8.5 scenarios (b) in Bangkok and its vicinity and Ho Chi Minh city respectively.

SUPPLEMENTARY FIGURE 7. Groundwater resilience map of Bangkok and its vicinity and Ho Chi Minh city in five different time period 2025, 2035, 2055, 2075, and 2095 under medium urbanization scenarios and RCP 4.5 (a) and RCP 8.5 (b) scenario.



SUPPLEMENTARY FIGURE 8. Groundwater resilience map of Bangkok and its vicinity and Ho Chi Minh city in five different time period 2025, 2035, 2055, 2075, and 2095 under low urbanization scenarios and RCP 4.5 (a) and RCP 8.5 (b) scenario.

Land use change scenario	Bangkok and its vicinity	Ho Chi Minh City	Kathmandu Valley	Lahore
High urbanization (HU)	Future land demand was assumed to follow the historical trend.	Future land demand was assumed to follow the historical trend.	Future land demand was assumed to follow the historical trend.	The built-up areas were assumed to increase up to **25%** of total land area by 2099 followed by small decrease in agricultural land, forest, and grassland.
Medium urbanization (MU) scenario	The built-up areas were assumed to increase up to **25%** of total land area by 2099 followed by small decrease in agricultural land, forest, and grassland.	The built-up areas were assumed to increase up to **35%** of total land area by 2099 followed by small decrease in agricultural land, forest, and grassland.	The built-up areas were assumed to increase up to **25%** of total land area by 2099 followed by small decrease in agricultural land, forest, and grassland.	Future land demand was assumed to follow the historical trend.
Low urbanization scenario (LU) or conservation scenario	The forest was assumed to increase up to **25%** of total land area by 2099 followed by small decrease in agricultural land and grassland.	The forest was assumed to increase up to **50%** of total land area by 2099 followed by small decrease in agricultural land and grassland.	The forest was assumed to increase up to **75%** of total land area by 2099 followed by small decrease in agricultural land and grassland.	The forest was assumed to increase up to **25%** of total land area by 2099 followed by small decrease in agricultural land and grassland.

SUPPLEMENTARY TABLE 1. Land use change scenarios in four Asian cities.

Land-use and Groundwater Abstraction Scenarios	Change in Groundwater Recharge (mm/yr)						Average Change in Groundwater Level (m)							
	RCP 4.5			RCP 8.5			RCP 4.5				RCP 8.5			
	NF	MF	FF	NF	MF	FF	2035	2055	2075	2095	2035	2055	2075	2095
Bangkok and its Vicinity, Thailand														
Baseline	259.64 mm						Range = (9.44 to 85.56 m below ground surface; Nonthaburi Aquifer)							
HU	−28.3	−37.8	−44.7	−22	−30.9	−41.1	−4.7	−6.29	−7.80	−9.29	−4.41	−5.08	−7.03	−8.29
MU	−22.6	−29.8	−33.3	−16.7	−25.1	−30.2	2.07	3.74	5.47	7.04	2.88	4.34	6.32	8.48
LU	19.6	28	35.8	27.4	33.9	40.1	5.25	7.77	9.93	12.24	5.76	8.65	11.28	14.41
Ho Chi Minh City, Vietnam														
Baseline	139.3 mm						Range = (1.94 to 39.72 m below ground surface; Upper Middle Pleistocene)							
HU	−29	−46.1	−57.8	−22.1	−38.1	−50.6	−11.78	−20.79	−30.53	−39.65	−11.11	−19.38	−28.44	−36.72
MU	−18.9	−33.1	−46.1	−13.9	−28.1	−42.1	−1.47	−0.9	−0.33	0.24	−1.24	−0.34	1.31	1.37
LU	16	25.5	33.9	22.4	31.1	36.8	−0.03	2.04	4.04	6.12	0.31	2.59	4.94	7.22
Kathmandu Valley, Nepal														
Baseline	796.7 mm						Range = (1280.88 to 1341.79 m above sea level)							
HU	−43.7	−57.2	−115.8	−28.2	−48.6	−104.1	−16.1	−20.9	−25.4	−30	−13.7	−18.7	−23.5	−28.3
MU	10.3	1.4	−13.4	15.1	5.8	2.4	−9.9	−12.9	−16	−19	−8.6	−11.8	−14.5	−17.9
LU	57.3	81.8	104.9	65.7	91.7	116	−4.1	−5.4	−6.7	−8.1	−2.4	−4.1	−5.4	−6.8
Lahore, Pakistan														
Baseline	119.24 mm						Range = (11.7 to 45.93 m below ground surface)							
HU	−12.4	−17.6	−34.3	−8.9	−16.2	−28	−5.93	−10.31	−15.39	−19.74	−5.40	−9.19	−13.71	−17.49
MU	−6.4	−12.8	−23.2	−4.8	−10.5	−20	0.02	0.90	1.78	2.67	0.22	1.43	3.66	3.72
LU	11.3	19.6	27.2	20.3	26.2	34.4	1.46	3.86	6.18	8.58	1.82	4.44	7.13	9.74

SUPPLEMENTARY TABLE 2. Summary of change in future groundwater recharge and groundwater level under RCP 4.5 and RCP 8.5 scenarios and land-use and abstraction scenarios during respective future period in four Asian cities.

Case study

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Farmers' perceptions on the impact of climate change: Case study of the agricultural sector of Cambodia

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ABSTRACT

This research aimed to assess the perception of farmers on climate change impacts and to find out existing coping mechanisms for climate change adaptation. Quantitative and qualitative approaches were adopted with a sample size of 320 using IBM's statistical software SPSS version 21, which was used to analyse data, mainly descriptive statistics (frequency and percentage). Results show that climate change was anticipated to seriously impact agricultural production, particularly rice crops, at a high perceived level. It is evident from the survey results that drought occurrences have the most significant impact on the economic destruction of households in the target areas due to their frequency, and damage is higher if compared to other disaster types. Followed by drought, flood is also one of the significant disaster effects on livelihoods. Based on the farmers' practices, changing planting/harvesting data is the best choice for climate change adaptation. This low-cost option minimises the risk of climate change in agricultural practices. Changing crop variety is also one of the popular strategies for coping with climate change as it could tolerate current climate conditions and market situations. Other strategies, such as changing the level of inputs and investing in irrigation systems, were the secondary adaptation option in the target area because it is a high-cost option and some farmers could not afford it. In another case, even perceiving climate change, farmers did nothing because they did not have sufficient capacity to cope. Some challenges in climate change adaptation among Cambodian farmers include lack of money, poor potential for irrigation, shortage of land, lack of information and shortage of labour.

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KEYWORDS

Impact of climate change, farmers' perception, agricultural sector

HIGHLIGHTS

- Cambodia is an agrarian country that mostly depends on climatic condition.
- Cambodia farmers perceived climate change impacts on daily livelihood and agricultural practices.
- Some adaptation options were found; however, more farmers do nothing to respond to climate change.
- Future intervention on cropping calendars appropriate for climate change adaptation should be prioritised.

1. INTRODUCTION

Cambodia is an agricultural country in Southeast Asia that frequently faces the challenges of climate change. The impacts of climate change have manifested in various ways, notably through rising sea levels, increasing temperatures, and shifts in precipitation patterns. Consequently, Cambodia has experienced far-reaching effects across all sectors, with some areas being particularly severely affected, such as agriculture, water resources, forest ecology, coastal regions, public health and infrastructure. The Ministry of Environment (MoE) survey in 2011 and 2015 regarding climate change impacts indicated that 98% of total respondents had experienced climate variabilities and extreme weather change, such as increasing temperatures and irregular rainfall in their regions (Ministry of Environment [MoE], 2016).

However, climate change has impacted many countries globally, and Cambodia is one of the most vulnerable countries due to limitations on adaptation capacity, particularly in the agricultural sector (De Young, Soto, Bahri, & Brown, 2012). Although many people sense climate change, the number of people who understand the causes and adaptation to climate change is relatively low (MoE, 2016; NCSD/MoE, 2020). Since Cambodians are likely to experience the anticipated increase of effects from climate change directly, it is crucial to understand how they have encountered and responded to climate change. Rice production and livestock are the most susceptible to climate change disasters such as floods, drought, and pest and disease outbreaks (Ros, Nang, & Chhim, 2011).

This study seeks to evaluate the perception of farmers regarding the impacts of climate change and to identify the coping mechanisms they currently employ for climate change adaptation. The result of this assessment will contribute to climate change risk reduction, strengthening climate change adaptive capacity and adaptation planning.

2. METHODOLOGY

The main approaches for data collection were inclusive, participatory and rights-based. Household surveys were utilised as a key tool for this research. Quantitative and qualitative approaches were employed using questionnaires, with closed and open-ended questions and observation, which were used for interpreting and clarifying results. The samples were selected from villagers living in a target area longer than ten years using a random sampling technique with 320 sample sizes based on the number of households in the target area. The sites selected for the study were eight districts in the following four provinces: Preyveng, Kampot, Kratie, and Preahvihear. The sample size was applied equally to each targeted province (80 sample/province). These provinces were identified as Cambodia's most vulnerable to climate change (Yusuf, 2010). These provinces frequently face flooding, drought, pest outbreaks, and lightning strikes, which are signs of vulnerability to climate change. IBM's statistical software, SPSS version 21, was used to analyse data, mainly descriptive statistics (frequency and percentage). Microsoft Excel was used for creating tables and figures.

3. RESULTS AND DISCUSSION

Table 1 represents the demographic characteristic of respondents and other independent variables. Male-headed and female-headed households accounted for 80% and 20% of the total respondents, respectively. Female-headed households included widows, divorcees, those with sick or disabled husbands, or husbands who migrated for employment outside the village/province. Although the agricultural population of males (48%) and females (52%) are not significantly different (FAO/GSO/MoP, 2010), climate change affected men and women differently, with women seeming to be the more vulnerable (CDRI, 2021). For example, research showed that men tended to be stronger physically, allowing them to do heavier work, such as the ability to carry water for greater distances during times of drought. As a result, women's farms suffered damage due to insufficient water to irrigate. In short, that research concluded that women's climate change adaptive capacity was limited in comparison to men. It was also noted by various research outputs that women experienced greater vulnerability due to generally having less access to education (Ikeda et al., 1995; Miller & Rodgers, 2009; Vyas & Watts, 2009).

The proportion of 43% of respondents were above 50 years, 26% were between 19–30 years, and the rest were between 30–50 years. FAO/GSO/MoP (2010) reported that the age group between 30–50 years is active age Cambodian agriculture due to their experience in farming, power, education, and so on. Similarly, this research found that those aged above 50 years had limited access to education and information and experienced problems with health (e.g., illness). We found that while some young respondents aged 19–30 faced job shortages in farming, they had some experience in cultivation.

The household size shows 63%, 19%, and 18% of the respondents had four to six members, more than seven members, and less than three members, respectively (Table 1). In this research, the average number of people per family is 5.1, which seemed higher than in other research (4.7 persons per family), with average female-headed households as four people per family, while the male-headed average was 4.9 (NIS, 2015; San, Sriv, Spoann, Var, & Seak, 2012).

Furthermore, the average land size held by respondents was 2.38 hectares, with 57% having 1–5 hectares and 10% greater than five hectares (Table 1), which is higher than the average domestic farming area was only 1.4 hectares reported in NIS (2015). The higher average in the study can be caused by the site selection of the province (Battambang province) with the most significant agricultural land size in Cambodia. However, 33% of respondents held less than 1 hectare for farming.

The respondents' education shown in Table 1 indicated that 45% were educated in primary school, 22% in secondary school, 9% in high school, and 2% in university. From the analysis, 22% of respondents identified as illiterate and having difficulties in reading or writing. Moreover, illiteracy poses challenges in understanding information on new agricultural technologies and strategies to adapt to climate change.

The general perception of respondents on long-term changes in temperature over the years showed that 92% noticed the temperature change, while 8% said that the temperature stayed the same (Table 1). Regarding the perception of long-term precipitation, 92% claimed that the precipitation has changed in their community, while the rest (8%) noticed no change (Table 1). Therefore, the majority of farmers expressed experiencing climate change in their community.

The accessibility of respondents to the irrigation system (Table 1) was 64%, but not sufficient water for their farming needs, while 36% could not access

Item		Frequency	Percentage (%)	Max	Min	Mean	Std.
Household head sex	Male	256	80				
	Female	64	20	-	-	-	-
	Total	320	100				
Age	19–30 years	26	8				
	31–40 years	73	23				
	40–50 years	85	27	80	19	46.64	12.27
	Above 50 years	136	43				
	Total	320	100				
Household size	1–3 Persons	56	18				
	4–6 Persons	203	63				
	Over 7 Persons	61	19	12	1	4.87	1.73
	Total	320	100				
Land size	Less than 1 hectare	104	33				
	1-5 hectares	183	57	14.50	0.01	2.38	2.14
	More than 5 hectares	33	10				
	Total	320	100				
Education	Illiterate	68	22				
	Primary School	144	45				
	Secondary School	71	22	15	0	4.34	3.15
	High School	27	9				
	University	8	2				
	Total	320	100				
Perceptions of temperature change	Temperature changed	295	92				
	Temperature not changed	25	8	-	-	-	-
	Total	320	100				
Perceptions of precipitation change	Precipitation changed	293	92				
	Precipitation not changed	27	8	-	-	-	-
	Total	320	100				
Access to irrigation	Accessible	206	64				
	Inaccessible	114	36	-	-	-	-
	Total	320	100				
Access to water extension service	Accessible	135	42				
	Inaccessible	186	58	-	-	-	-
	Total	320	100				
Access to credit	Available	158	49				
	Unavailable	162	51	-	-	-	-
	Total	320	100				
Access to climate information	Accessible	141	44				
	Inaccessible	179	56	-	-	-	-
	Total	320	100				

Note: Max = Maximum Value: Min = Minimum Value: Std. = Standard Deviation.

TABLE 1. Household demographic and other independent variables.

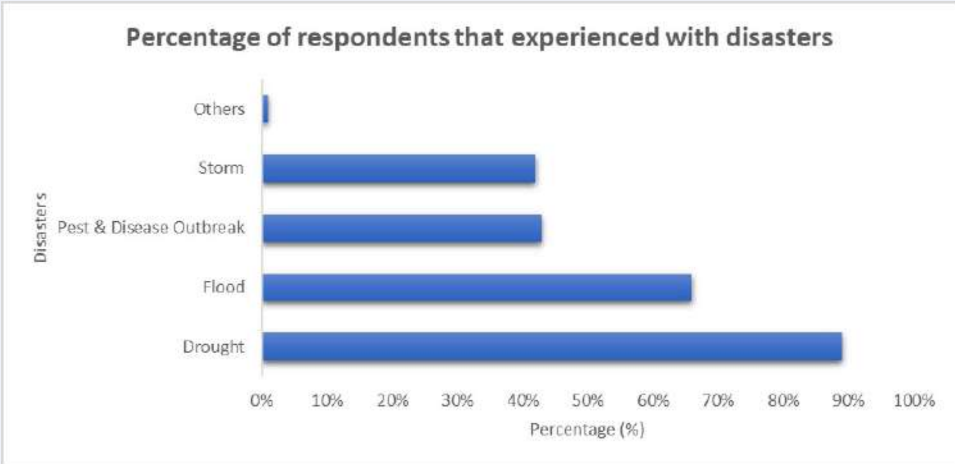

FIGURE 1. Percentage of respondents experienced with disasters.

the irrigation system. The result indicated that their farming solely depended on rainfall. An extension service was said to be very important for improving farming productivity in the community. However, 42% of respondents mentioned that they had never received an agricultural extension service, while 58% used to access it (Table 1). Access to credit was necessary in farming when farmers wanted to expand production or faced unexpected circumstances. In this case, the research found that half of the respondents could not access credit to improve their farming. Table 1 also illustrates respondent perceptions of climate change information, such as meteorology information. More than half of respondents (56%) reported difficulties accessing climate information, limiting their ability to adapt to climate change.

Respondents acknowledged that they experienced disaster impacts. The negative impact of the disaster on the following factors: food availability, agricultural production, health, education, water resource, and infrastructure. Multiple disasters and their effects on communities were reported during the survey in target areas, with at least three types of disasters reported. Drought and flood were the most common disasters that occurred in the target areas and were reported by the majority of the respondents (89% and 66%, respectively). Pest and disease outbreaks were also reported by (43%) of the respondents, followed by storms (42%). Regarding the frequency of the occurrences encountered by households, the average incidents were reported 3 to 4 times drought (range from 1 to 6 times) and 2 to 3 times Flooding (range from 1 to 5 times) within the last ten years (Figure 1).

From 2009 until 2018, there were notable increases in the number of reported disaster incidents encountered by households in the target area (Figure 2). In 2011, a steady increase in drought was observed from 5% to around 73%, pest and disease outbreak was nil to 17%, and the storm was nil to 14%. However, floods were steady from 2009 to 2015 and rapidly increased from 10% to 71% by 2018. These reported variations and increases cause significant negative impacts on households in target areas' living and economic conditions.

Regarding seasonal variation in disaster occurrence, a relatively higher proportion of households reported that disasters were more frequent in the wet season than in the dry season (Figure 3). However, drought and flood were experienced in similar proportions. Pest and disease outbreaks and storms were reported throughout the year. Drought commonly extended from May to September (peaking in August), whereas floods frequently lasted from August to October (peaking in September).

Perceived general impacts were also captured during the survey by asking respondents to list

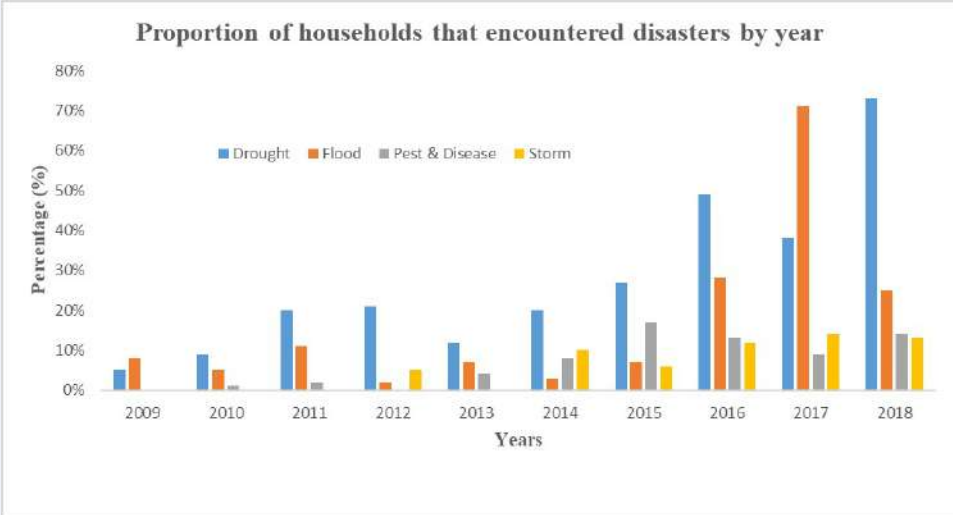

FIGURE 2. Proportion of households that encountered disasters by year.

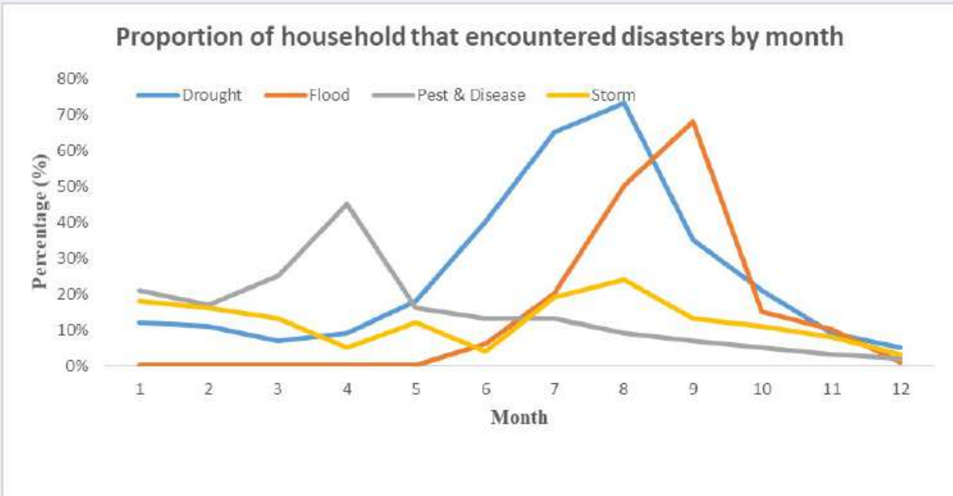

FIGURE 3. Proportion of households that encountered disasters by month.

and rank impact areas by disaster type. The level of disaster impact seemed to be very high across all types of disasters according to different sectors, including agricultural production, livestock production, health issues, water utility (use, quality, and availability), household assets, and educational access for children.

All households (100%) in the target areas reported negative impacts from disaster occurrences. Nearly all respondents (98%) encountered loss of crop products from disaster impacts (mainly drought and flood). Around 40% claimed crop loss, a negative impact of pest and disease outbreaks. Approximately half of the households were concerned by a lack of water due to drought and flood. In addition, nearly one-third of respondents mentioned human health incidents and animal loss, describing storms as a source of these issues. Out of all respondents, almost half reported that drought had the most severe impact on crop loss and similar proportions with crop loss due to flooding. Drought was considered the primary source of negative impacts due to water scarcity and affected human health. At the same time, the flood was considered

Type of impact			Percentage by disasters			
	N	Percent	Drought	Flood	Pest and disease	Storm
Crop loss	314	98	88	70	41	17
Animal loss	86	27	22	20	3	3
Human health incidents	118	37	32	26	2	34
Lack of water	170	53	49	19	2	1
Loss of household assets	16	5	3	4	1	56
No access to education	26	8	5	7	1	1

TABLE 2. Proportion of the households by different types of impact and disasters.

Adaptation strategies	Respondents' percentage (%)
No adaptation	8.1
Changing the planting/harvesting date	35
Change Varieties	20
Change the level of input	19.2
Invest in an irrigation system	17.7
Total number of respondents	320

TABLE 3. Respondents' adaptation strategies.

the main cause of animal loss. Overall, disasters such as drought and flood significantly impact household economic status due to the destruction of crops, scarcity of water utility, and incidents of human disease (Figure 2, Table 2).

Table 3 describes strategies that farmers used to adapt to climate; as a result, those who mentioned that they had taken action in adapting to climate change indicated the following varieties of adaptation strategies: changing in planting/harvesting date, change of rice varieties, investment in the irrigation system, changing level of input. These adaptation strategies were similar to findings from research conducted in the region near Cambodia (Afifi et al., 2016; Dharmarathna, Herath, & Weerakoon, 2014; Mainuddin, Kirby, & Hoanh, 2011). The results indicated that 35% of surveyed farmers decided to change the planting/harvesting date to minimise the impact of climate change. Furthermore, 20% of respondents choose to change their rice variety, such as using those tolerant to drought, flood, and pests. Changes to input levels for rice production were reported by 19.2% of respondents as an option, and 17.7% mentioned investment in an irrigation system as their choice. It was also revealed that 8.1% of experienced respondents do nothing despite them realising how climate had already affected their farming. Overall, farmers who apply changing planting/harvesting dates tend to adapt better to climate change as they can minimise the negative impact and reduce the risk.

Some barriers were reported by respondents in adaptation to climate change, as shown in Figure 4. Those who did nothing in response to climate change provided reasons such as insufficient resources (money), lack of irrigation system, shortage of land, limited information, and shortage of labour. Lack of money, lack of irrigation system, and shortage of land were mentioned by 24.3%, 23.4%, and 22% of respondents respectfully. Lack of information and shortage of labour was 15.3% and 15%, respectively. Thus, these findings point to a lack of choice for some farmers in adopting methods to respond to climate change. To deal with these

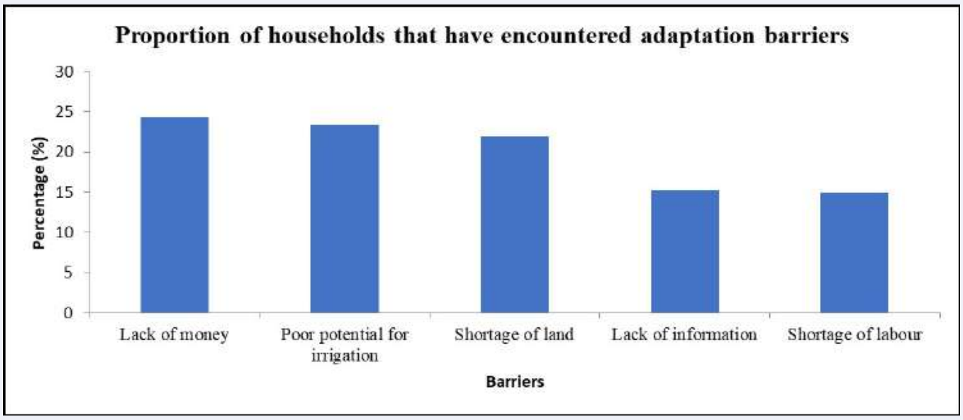

FIGURE 4. Proportion of Households that encountered adaptation barriers.

issues, the Royal Government of Cambodia have been developing and implementing some policies and strategic plan for climate change adaptation, such as the Cambodia Climate Change Strategic Plan 2014–2023.

4. CONCLUSION

Several types of disasters, such as drought, flood, storm, pest and disease outbreaks, were commonly experienced by most households surveyed in the target areas. Farmers already perceived these impacts. These impacts have a significant and serious effect on the livelihoods and social activities of target households due to the destruction of crop production, loss of livestock production, limit to availability and accessibility of water for household uses, destruction of household assets or property, increase in commodity prices, and poor access to social services. It is evident from the survey results that drought occurrences have the most significant impact on the economic destruction of households in the target areas due to their frequency, and damage is higher if compared to other disaster types. Followed by drought, flood is also one of the significant disaster effects on livelihood.

Based on the practices of farmers, changing planting and harvesting dates emerges as the most favourable choice for climate change adaptation. This option proves to be cost-effective and helps minimise the risks associated with climate change in agricultural activities. Another popular strategy among farmers is the adoption of different crop varieties that can better tolerate the current climate conditions and align with market demands. However, some farmers face challenges in implementing adaptation strategies. Changing the level of inputs and investing in irrigation systems are considered secondary options due to their high costs, which make them less accessible to some farmers who cannot afford such investments. Additionally, some farmers cannot take any action despite acknowledging climate change, primarily because they lack the capacity to cope with its effects.

For Cambodian farmers, the obstacles in adapting to climate change include financial constraints, limited potential for irrigation, land scarcity, lack of information and labour shortage. These challenges hinder their ability to effectively address and prepare for the impacts of climate change on their agricultural practices.

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Climate change impacts on spatiotemporal variation of extreme weather and its consequences on dam optimisation and risk management in the Cagayan basin, Philippines

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ABSTRACT

Extreme weather threatens livelihood and urban development in the Philippines. However, addressing their effects and occurrences is a significant challenge, particularly in the Cagayan River Basin (CRB), due to increasing population and the dilemma of dam operations for floods and droughts management. Therefore, this paper focuses on investigating the impact of climate change on extreme weather events and understanding flood characteristics by simulating Typhoon Ulysses on the Magat dam. The Mann-Kendall test was used to investigate the spatiotemporal variability and magnitude of change in extremes over historical and future periods. Furthermore, Rainfall-Runoff Inundation Model was evaluated with four different dam operation scenarios to investigate mitigation strategies for dam optimisation to reduce flood and drought risks. Findings indicate an increased risk of dry and wet spells in future, potentially increasing vulnerability to drought and flooding over CRB. We also discovered that each sub-basin had different hydrological responses and significantly higher runoff than others. However, with a modified Magat dam operation to start a flow rate of 700 m³/s and a discharge rate of 0.5, the water level at Buntun can be lowered by 0.5 m. In addition, a proposed dam at Cagayan Segment 1 is expected to reduce flood risk in downstream areas.

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KEYWORDS

Rainfall-runoff inundation, typhoon, flood risk, drought risk, dam optimisation, spatio-temporal climate impacts

HIGHLIGHTS

- Consistent increase in temperature and precipitation is likely to bring more prolonged dry and wet spells.
- Prolonged dry and wet spells may cause severe drought and flooding over some basins in Cagayan River Basin (CRB).
- Urgent need to optimis e dam pre-release to maintain the balance for required storage during the dry period, as well as appropriate strategies for reducing flood risk during the wet period at Magat dam in CRB.

1. INTRODUCTION

Climate change, largely due to anthropogenic warming, is a serious concern as it is predicted to have severe and widespread negative socioeconomic impacts worldwide. Consistent heavy precipitation and intense droughts are expected to increase due to the adverse effects of climate change and a higher fluctuation in rainfall and temperature (IPCC, 2007; IPCC-TGICA, 2007). The South-West Pacific (SWP) region recorded 1,407 severe disasters, which caused around 65,391 deaths and US$ 163.7 billion of economic losses during the recent period of 1970 to 2019 (WMO, 2021). The majority of them were associated with floods (39%) and storms (45%). The Philippines accounted for 75% of all deaths caused by climate and water hazards in the SWP region, with an average of 1,000 deaths per year. The national agricultural area affected by typhoons, floods and droughts in the Philippines increased from 683,440 hectares in 2000 to 977,208 hectares in 2010 (Israel & Briones, 2013).

The Philippines, located on the "typhoon belt," is one of the world's most cyclone-prone countries. Therefore, the Philippines has many natural hazard sources, including floods, drought, storm surges, landslides, and coastal erosions. Nearly 19–20 cyclones enter the Philippine Area of Responsibility every year, with 7–9 making landfall (Monjardin et al., 2021; WBG & ADB, 2021). Typhoons have already caused devastation in the Philippines, and the northern part experienced more cyclone frequency where the Cagayan River basin is located (Figure 1). Seven cyclones approached the Philippines in just two months, from October to November 2020 (UNOCHA, 2020). Especially the last Typhoon Ulysses came to Luzon Island and caused death and injured people (UNOCHA, 2020). In addition, Ulysses caused flooding downstream of the Cagayan River, the longest river in the Philippines, located on Luzon Island (UNOCHA, 2020). Climate change and urbanisation have increased the probability of these disasters, posing a rising threat to economies, peoples, and sustainable development (ICHARM & PWRI, 2013). The Philippines is experiencing more frequent heavy precipitation events and severe droughts due to climate change and a greater degree of fluctuation in precipitation and temperature and is considered one of the world's most disaster-prone countries (WBG & ADB, 2021). Floods, drought, and storms are severe problems in the Philippines and often cause catastrophic damage to properties and loss of lives (DPWH & JICA, 2002).

The most critical impacts are affecting water resources, especially the dam operation and effective river basin management. These directly affect agricultural systems, food, and livelihood security. Moreover, the Cagayan River Basin (CRB) in the Philippines is the central basin, covering a total land area of 27,493.49 km^2, presently facing critical issues of rapid climate variability, sedimentation,

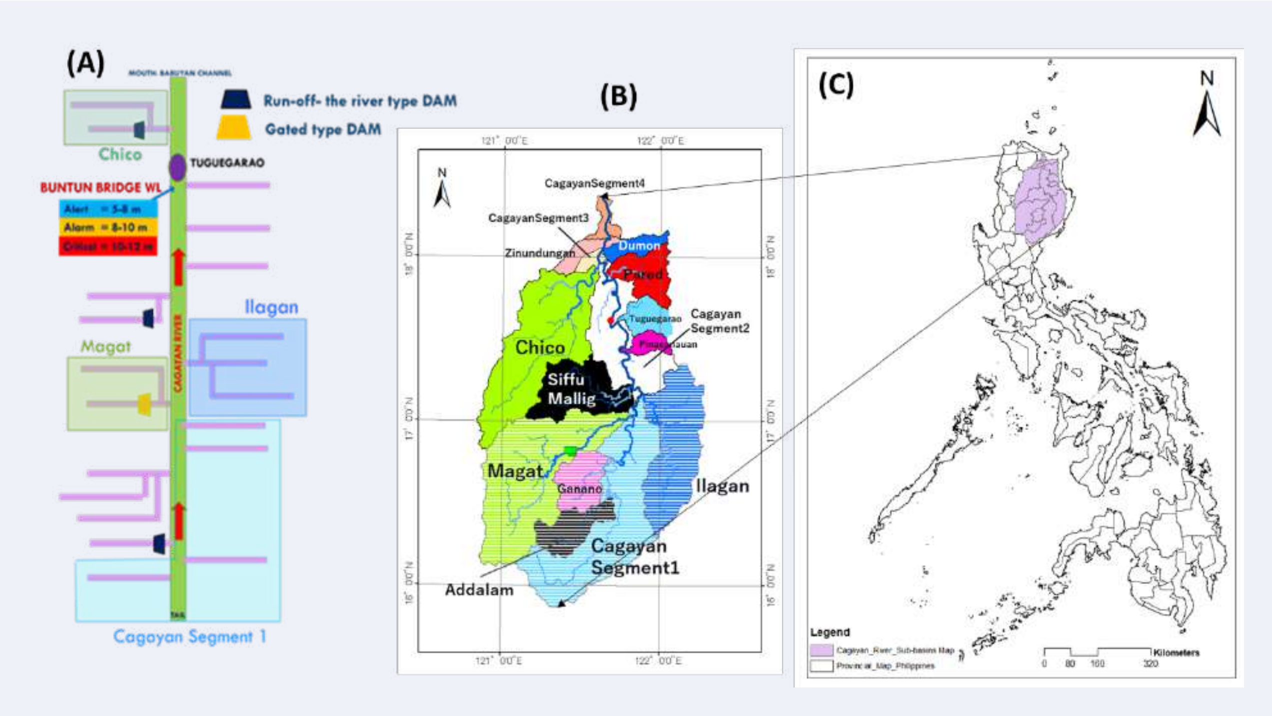

FIGURE 1. Index map showing the location of Buntun Bridge (A), Cagayan River Basin network (B) and location of CRB in the Philippines map (C).

and frequent occurrences of typhoons, floods, and droughts. These are the significant constraints that somehow prevent further development in CRB. Therefore, dams and reservoirs are essential to the sustainability of human civilisation because they collect and store water for irrigation and drinking, generate energy, and reduce flood and drought risks. Dams are still a crucial part of development today as a result of the world's rising energy and water demands, as well as their ability to secure the water environment and mitigate damage caused by climate change and variability. Therefore, safe dam operation (i.e. optimised dam operation) is always crucial and has equal importance as being able to control food, which is a short-term or almost near-real-time goal (i.e. when to store or when to release the floodwaters) and in contrast to restoring the appropriate amount of water for irrigation, drinking, and several other purposes which is a medium-to-seasonal-to-annual goal to save water for various purposes such as drinking, irrigation, industries, and hydroelectric power, etc. during the dry season/period. This is because sometimes the amount of precipitation received during the normal or El Niño year is insufficient to fill the dam, and water is needed to replenish the dams. Also, considerable rainfall is lost as surface runoff (42.85%), with only a small portion recharging the groundwater aquifer (10.65%). The geologic property of the watershed governs low groundwater recharge. Conversely, the Cagayan River's stream flow is approximately 55.04% of the annual rainfall (UPLB, n.d.). About 30% of the river basin is highly susceptible to drought. In comparison, only 14% of the river basin is susceptible to flood, covering most of the part from Isabela and Cagayan, and is one of the perennial problems existing in the CRB emphasised in the report of "climate-Responsive Integrated Master Plan for Cagayan River Basin". Also, the Philippine Atmospheric, Geophysical and Astronomical Services Administration (PAGASA) reported that the temperature is expected to increase from 0.8–1.1 °C in 2020 and 1.6–2.2 °C in 2050, which will cause the CRB to have drier summer months and a wetter rainy season. This will add extra pressure and difficulties in appropriate strategies for water resource management. By looking into climate change, the situation may worsen in the upcoming period over CRB, which is predicted to increase the magnitude and frequencies of such hazardous weather events (PAGASA, 2023; WBG & ADB, 2021). Understanding knowledge regarding identifying specific risks and their possibility will be more critical for managing climate-related risks (Weaver et al., 2017). Therefore, to be prepared and counter these changes, there is a strong need for an integrated approach to studying climate change, combining aspects of climate projections and predicting future potential impacts to understand the spatiotemporal changes of extreme weather events and their consequences on surface water resource management. Hence, this study has been undertaken with the following objectives:

1. Accessing the impact of climate change on the perception of occurrences of extreme weather events such as floods and drought at the CRB.
2. Conducting the exposure survey to validate the extreme weather analysis results, understanding the awareness and critical problems risk communication, and
3. Investigating the hydrological response under different dam release scenarios using the case of extreme Typhoon Ulysses on the Magat dam at the CRB.

These results would be an easy-to-use resource to tackle the extreme weather situation and guide the national and local disaster risk reduction and management offices in developing an appropriate decision for implementing adaptation strategies over high-risk zones.

2. METHODOLOGY

2.1. Study area mapping and datasets

Figure 1 shows the location map of the CRB with a total catchment area of 27,281 km^2 and a river length of 520 km. The Cagayan River flows from the Caraballo Mountains in the south to the north-northeast through the mountains, joining the Magat River on the left bank and the Ilagan River on the right bank. The main tributaries of the Cagayan River are the Chico River, with a catchment area of 4,550 km^2. The Siffu-Mallig River with a catchment area of 2,015 km^2, the Magat River with a catchment area of 5,110 km^2 from the left bank, the Pared River with a catchment area of 970 km^2, the Tuguegarao River with a catchment area of 660 km^2, the Tumauini River with a catchment area of 960 km^2, and the Ilagan River with a catchment of 3,130 km^2 joins from the right bank side (Alejandro, 2021). According to the report "Climate-Responsive Integrated Master Plan for Cagayan River Basin" by UPLB (n.d.); "Floods created by this river flow down very slowly due to surface retention across a large flood plain, a very gradual slope, and flood retardation by multiple gorges and river meanders, and the location from Tuguegarao to Aparrib should target for flood forecasting and warning system". The river basin has around 70 completed dams, two ongoing dams, and 63 proposed dams. These dams are divided into three types: diversion dams, water impounding systems, and small water impounding systems. The Magat Dam is the river basin's largest dam (UPLB, n.d.). It is also reported that the flood extent in the future (2050) period will likely be the same as the flood extent of current climatic conditions, and extreme weather situations like typhoons can bring torrential rains and cause disastrous floods. Hence, optimised dam operation is crucial in such a situation for effective pre-release to control the flood and maintain the appropriate storage to secure water during prolonged dry periods.

This study used long-term and high-spatial-resolution climate change projection data (MRI-AGCM3.2S) to comprehensively assess extreme rainfall and temperature indices for the spatiotemporal assessment of the probability of flood and drought events under the worst-case (RCP8.5) climate change scenarios. The dataset used in this study was developed by Mizuta et al. (2012) from the Meteorological Research Institute (MRI) based on the simulations from the Atmospheric General Circulation Model (AGCM) with a horizontal grid size of about 20 km. A detailed description of this dataset can be found in the DIAS data catalogue at http://metadata.diasjp.net/dmm/doc/CMIP6_MRI_AGCM3_2_S_HighResMIP-ja.html. Also, this study used other geospatial datasets such

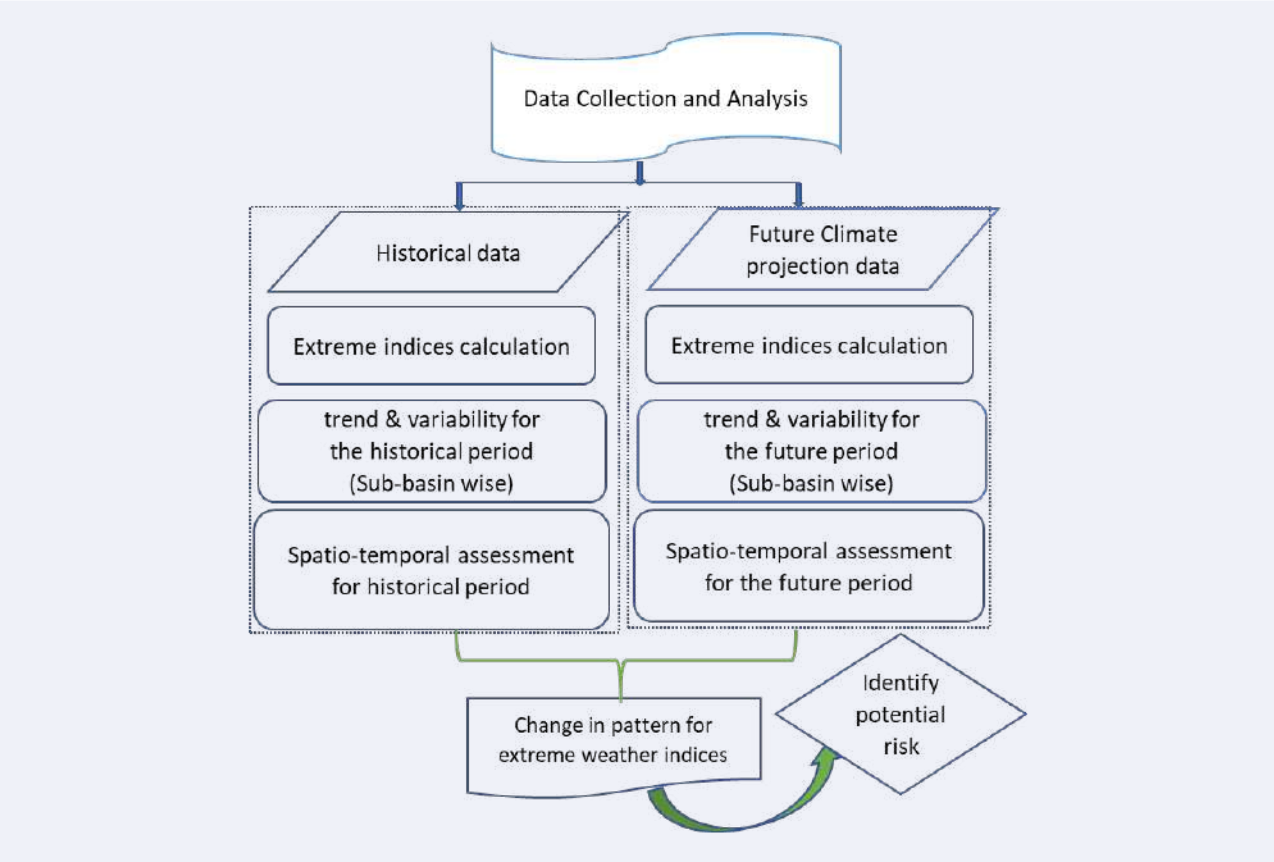

FIGURE 2. Flowchart for assessment and prediction of potential risk from extreme weather events.

as Digital Elevation Model (DEM), Rainfall, and other hydrological datasets, including reservoir inflow discharge, dam outflow, river discharge, dam operation rules, and power generation obtained from MERIT Hydro: global hydrography datasets, PAGASA, and NIA MARIIS (Yamazaki et al., 2019).

2.2. Estimation of extreme weather events and associated disaster risk for dam operation

The approach of spatiotemporal assessment by Sen's slope with Mann Kendall's test was applied to analyse the variability and magnitude of change in climate variables and key extreme climate indices, using the daily meteorological variables obtained from high-resolution CMIP6 simulation data produced by MRI-AGCM3.2S over historical (1951–2014) and future (2015–2099) period (Figure 2).

This study estimated the extreme climate indices CDD, CWD, r95p, Tx90p, and Tn90p, considering the most important and relevant for water resource protection from climate change risk (Table 1).

The relative changes over each sub-basin and different periods were estimated to investigate the impacts of climate change on various extreme weather events such as consecutive wet days leading to flooding, heavy precipitation events, dry days leading to drought, number of hot days, and tropical nights. Along with this, we also studied other natural and technological disasters, as well as cyclone tracks, to better understand their occurrences and the implications for dam operation and overall climate risk management. The climate analysis supports dam operations and emphasises multiple aspects of management, such as releasing water during heavy rainfall events to control floods and storing the required amount of water during extended long dry periods for appropriate water use management for various purposes such as drinking, industries, irrigation, and energy production. Therefore, we estimate and simulate dam operation

Precipitation Indices			Temperature Indices		
Indices	**Definition**	**Unit**	**Indices**	**Definition**	**Unit**
PRCPTOT	Total amount of annual precipitation	mm/yr	**Tx**	Mean daily max. temperature	°C
CDD	***Consecutive dry days***: Number of Spell of five consecutive days with rainfall < 1 mm per year	days	**Tn**	Mean daily min. temperature	°C
CWD	***Consecutive wet days***: Number of Spell of five consecutive wet per year with rainfall > 1 mm	days	**Tx90p**	***Amount of the hot days***: The percentage of days when Tx > 90th percentile	%
r95p	***Very wet days rainfall***: Annual total rainfall when daily rainfall exceeds the 95th percentile of wet days	mm/yr	**Tn90p**	***Amount of warm nights***: The percentage of days when Tn > 90th percentile	%

TABLE 1. Indices for characterising temperature and rainfall extremes (Zhang et al., 2011).

using the case of extreme Typhoon Ulysses, and the optimised dam operation rules have been estimated under different dam release scenarios and associated reservoir sedimentation impacts.

2.3. Estimation of dam optimisation using Rainfall Runoff Inundation (RRI) model

The RRI model can easily simulate the effect of a dam reservoir. Hence, this study has used the RRI model for hydrological simulation and optimisation of dam operation rules. As recommended by Alejandro (2021), the parameters of the dam model were settled for the maximum reservoir volume; flood control starts to release the total discharge and discharge rate for the Magat-dam, e.g., when the inflow is less than the flood control start discharge, the outflow is equal to the inflow, and when the inflow exceeds the flood control begins to discharge, the outflow = inflow × discharge rate. The dam is designed to release the same amount as the inflow when the water storage volume reaches the maximum storage volume (Figure 3).

Then, the dam operation is simulated using four different scenarios: (1) without a dam, (2) with only a Magat dam but a fixed amount of water released, (3) with only a Magat dam but a constant rate released, and (4) with a Magat dam supported by an additional proposed dam, and the results were compared for water level changes at Buntun bridge (Iwamoto, Nohara, Takemon, Koshiba, & Sumi, 2021; Sayama, Myo, Fukami, Tanaka, & Takeuchi, 2011). In this way, several scenarios have been conducted, including an evaluation of each sub-contribution catchment's and dam operations during the typhoon and an examination of additional proposed dams in the other sub-catchment. Then, the best feasible potential flood risk mitigation strategies have been evaluated.

3. RESULTS AND DISCUSSION

The relative changes for different periods and over each sub-basin were estimated and illustrated to investigate the variability and magnitude of change in rainfall and key relevant extreme climate indices over historical and future climate change. Temporally, the intra-annual rainfall has shown an increasing trend over the future, with a higher fluctuation rate in minimum and maximum annual rainfall (Figure 4). Overall, not many significant changes were observed for future annual rainfall changes. However, the amount of annual average rainfall varies across each sub-basin, with a significant difference observed between sub-basins even though they are close to each other (Figure 5). This will cause drought occurrences where precipitation

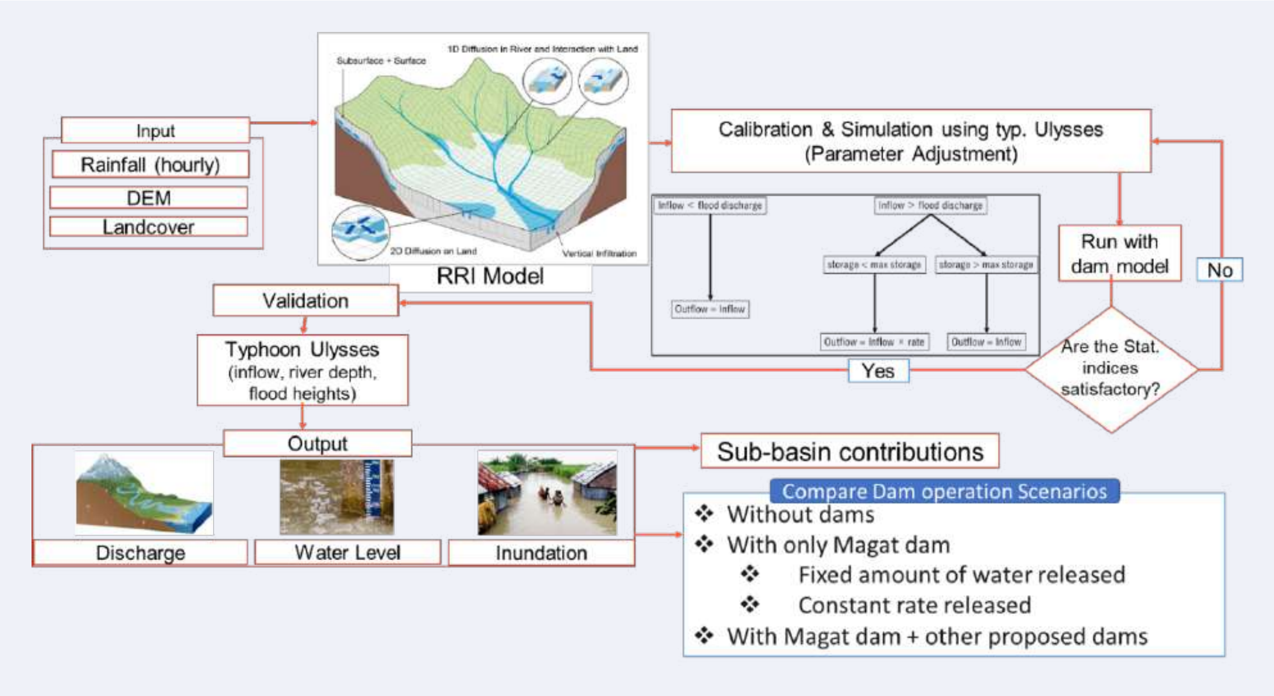

FIGURE 3. Methodology approach for dam optimisation using RRI model.

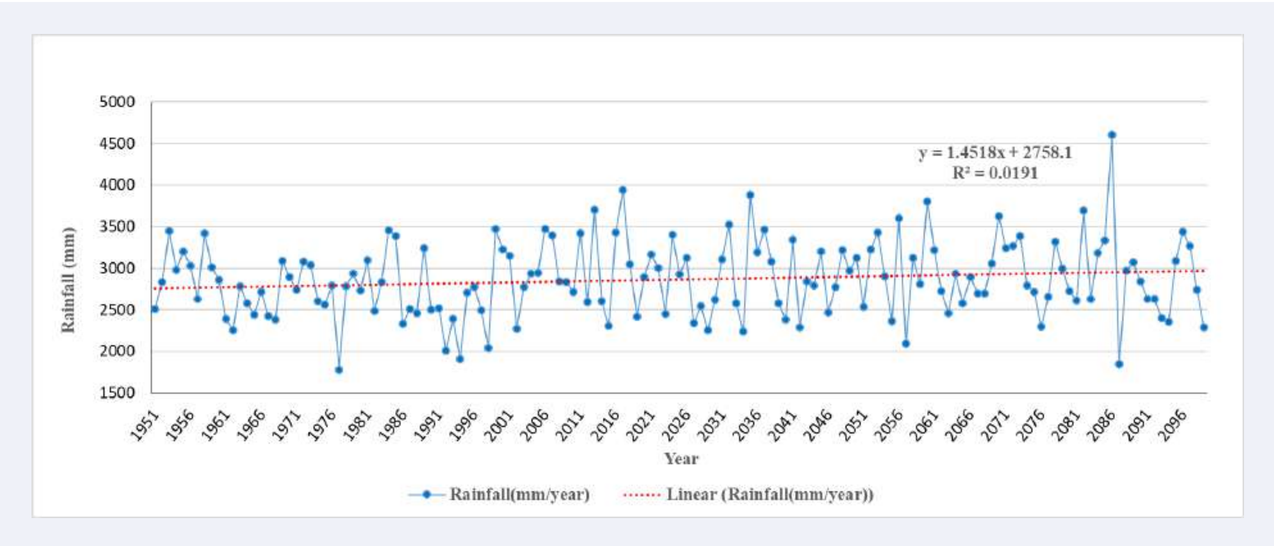

FIGURE 4. Temporal variability of rainfall at Cagayan River Basin, Philippines.

has shown a decreasing trend over the sub-basins Ilagan, Dumon, Pared, Cagayan Segment 4, etc. in the future. On the other hand, floods will likely occur where precipitation has shown an increasing trend over sub-basins like Siffu-Mallig, Ganano, Addalam and Cagayan Segment 2, etc., in the future over the CRB (Figure 5c). Hence, this study has analysed extreme weather situations such as the spell for consecutive dry days (dryness), consecutive wet days (wetness), and the number of hot days (warmness) as the most relevant factors in consideration of appropriate management of surface water resources such as dam and reservoir operations.

Interestingly, the findings also revealed that the sub-basin like Addalam would experience an increase in the percentage of consecutive dry days (CDD) as well as an increase in the percentage of consecutive wet days (CWD) in the future compared to the past (Figure 6a, and Figure 6b). This indicates the risk of intense dry spells and heavy precipitation

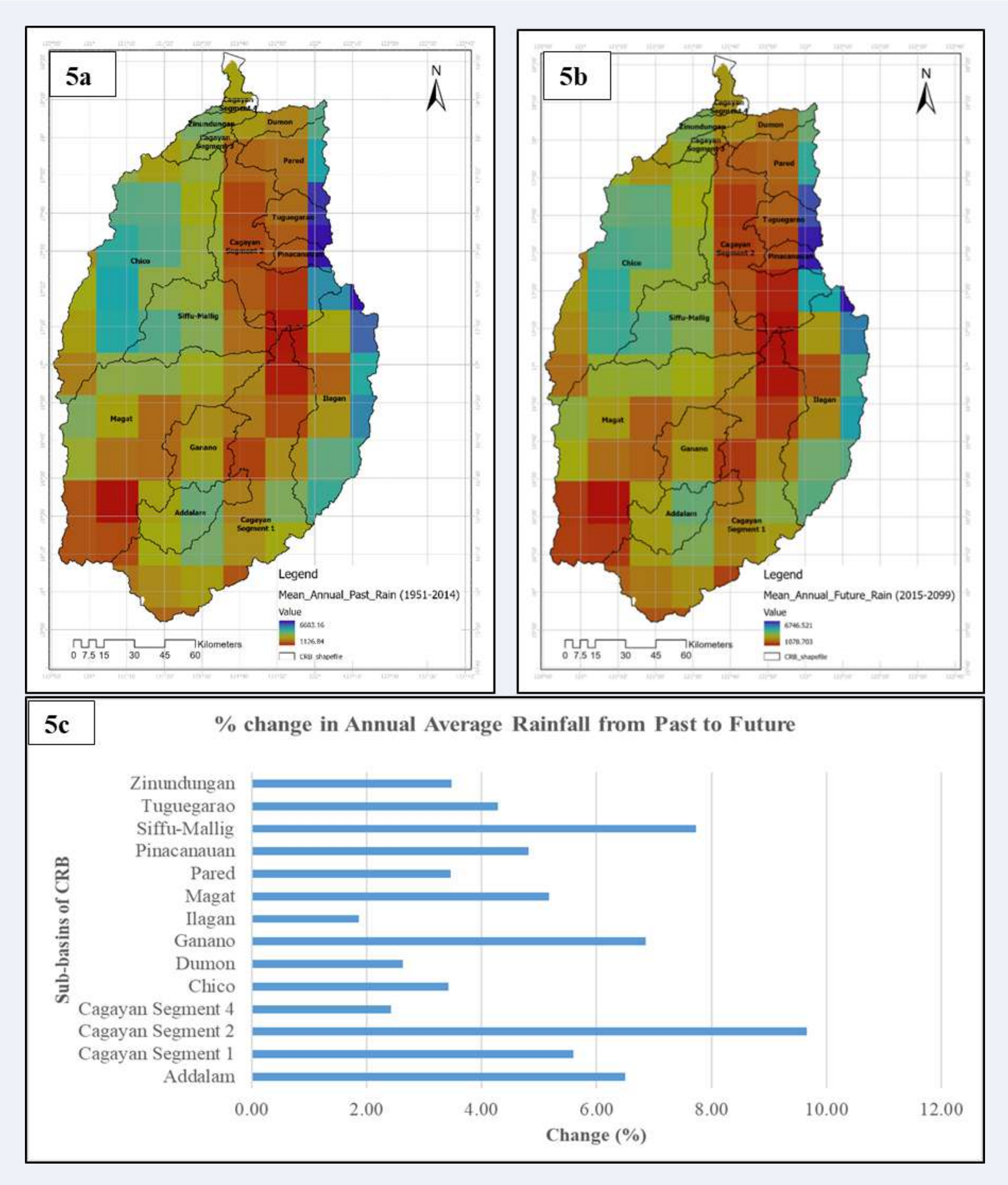

FIGURE 5. Spatial variability of rainfall at Cagayan River Basin, Philippines.

events, which may cause severe drought and flooding the upstream and downstream of the Addalam sub-basin, respectively (Figure 6c).

Furthermore, in terms of the impacts of temperature, the results have shown a significant increasing trend for the annual amount of hot days (Tx90p) continuously from past to the future (Figure 7). In contrast, the spatially, all sub-basins showed an increased amount of hot days in the future throughout the CRB (Figure 8). This indicates the probability of increasing warming over CRB in the future, which will likely cause an increase in evaporation. This will also affect the overall hydrological response of each sub-basin across the Cagayan River.

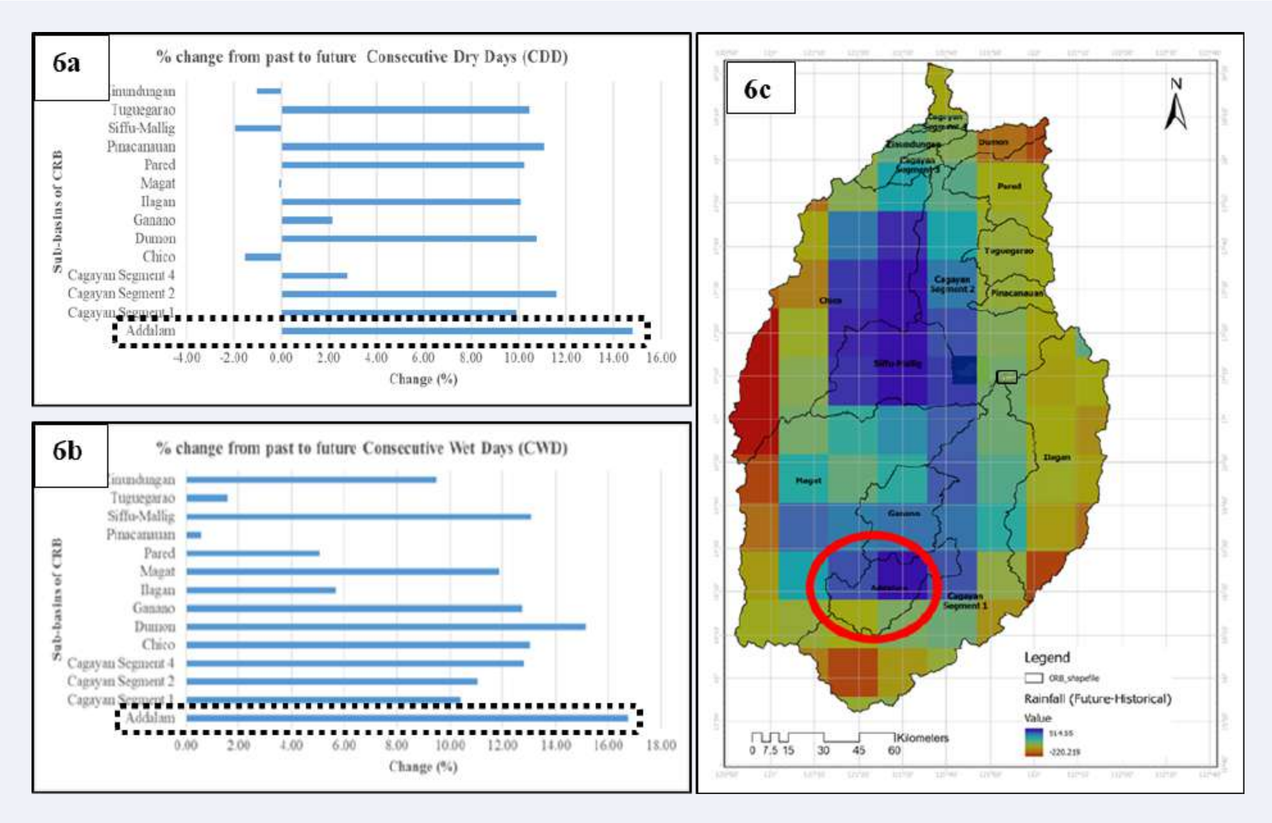

FIGURE 6. Spatiotemporal changes in future dryness and wetness at Cagayan River Basin.

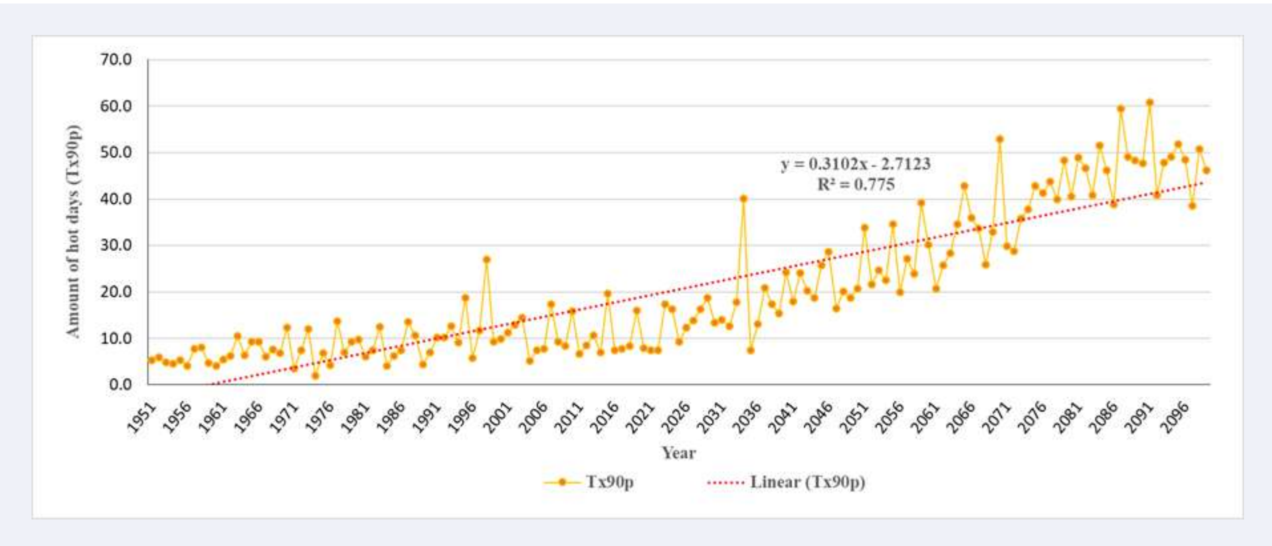

FIGURE 7. Temporal changes in warmness at Cagayan River Basin, Philippines.

Understanding knowledge about the identification and probability of occurrences of such extreme weather events is always critical for addressing climate-related risks and managing surface water resources appropriately. Furthermore, more extreme weather events can be expected as the world continues to warm. Hence, as a result, this study used other freely available reputable national disaster databases to analyse the effects of other disasters in the Philippines and their consequences for the Cagayan River basin. The global international catastrophe (EM-DAT) database was used to construct the outlook of water-related disasters in the Philippines. Floods and storms are the top natural

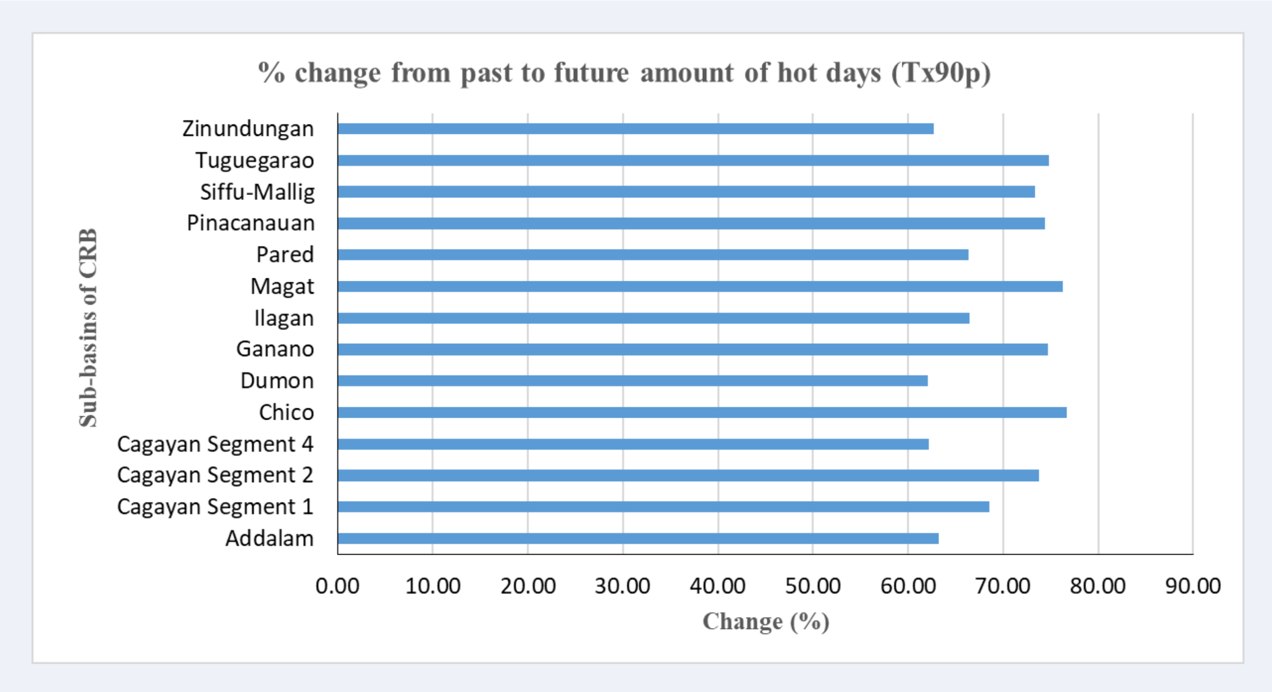

FIGURE 8. Spatial changes in warmness at Cagayan River Basin, Philippines.

disasters in the Philippines in terms of occurrences, people affected, and overall socioeconomic damages (CRED, 2022). The frequency of occurrence events for storms and floods increased in the recent decade (2011–2020) compared to the past four decades 1971–2020. The graph (Figure 9) visualises how sharply it has increased in the recent period and caused considerable economic damage in the Philippines.

Also, the time series tropical cyclone tracks (*NOAA's International Best Track Archive for Climate Stewardship (IBTrACS)*) data were used to construct a statistical outlook and to provide some context of the spatial distribution of impacts of typhoons across the Philippines (Knapp, Kruk, Levinson, Diamond, & Neumann, 2010). Figure 10 highlights the frequency and impacts of typhoon events over the Philippines during the past two decades, 2001–2021. It was observed that the overall cyclone frequency has increased over the northern Philippines, especially over the Cagayan River Basin, during the past two decadal periods, compared to the other parts of the country.

Furthermore, this study conducted an exposure field survey to validate our extreme weather analysis results and to understand the impacts and critical problems through a comprehensive community survey and institutional stakeholder interviews (Figures 11 and 12). It has been confirmed that the areas surrounding the Addalam sub-basin and Magat basin experienced frequent water shortages during the dry season and frequent floods during the wet season, respectively. This is because increased dryness (i.e. increased CDD) increases the risk for drought, whereas the increased amount of hot days (i.e. Tx90p) has increased the evaporation and added the risk for increased spells of heavy precipitation.

We visited several potential sites, institutes and households to learn about the key issues and the level of community risk awareness. The respondents indicated that they receive warnings and are fully aware of the situation when a typhoon occurs. However, the critical problem and key issues during such extreme weather situations revolve around whether to preemptively release water from the reservoir to control flooding or retain an adequate amount of water to address the risk of replenishing capacity during dry periods. Therefore, this study utilised the recent event (i.e. Typhoon Ulysses) as an example to simulate dam (i.e. Magat-Dam)

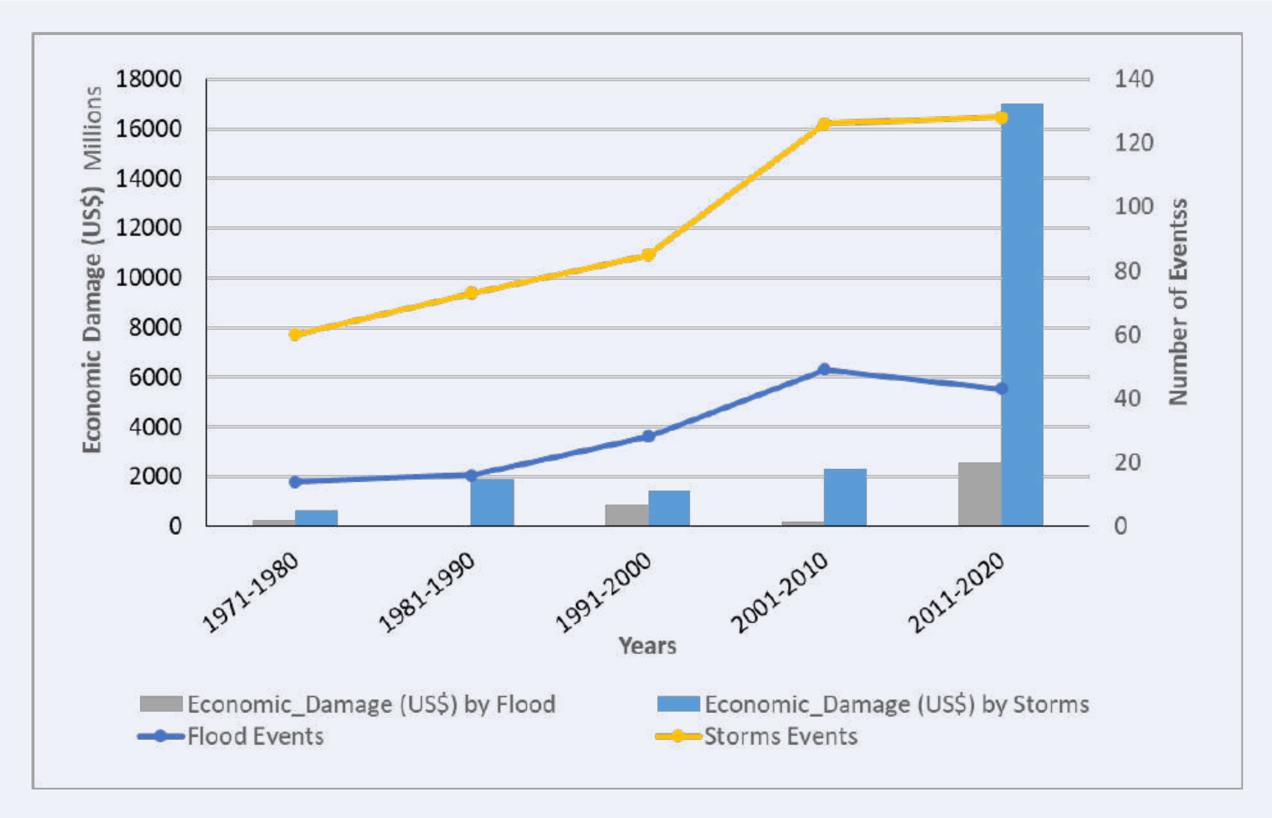

FIGURE 9. Occurrences and Economic Impacts of Floods and Storms, Philippines (CRED, 2022).

operations under different water management scenarios (such as with only Magat dams, without dams, with Magat dam + other proposed additional dam, etc.) to better optimise the dam operation to mitigate the problem of flood and drought risk and address the dilemma between releasing water during extreme weather/heavy rainfall events to control floods and storing the required amount of water to ensure water availability during extended long dry periods (i.e. how to operate the dam during synergies between two extreme weather (flood and drought) situations). Because the Magat dam is one of the major multi-purpose dams along the Cagayan River Basin that should be operated in order to control reservoir releases to ensure water availability for irrigation on a year-round basis, especially during January to May, which are normally dry months, and effective release of impounded water during the flood seasons due to occurrences of typhoons and/or heavy rains, such as the case of Typhoon Ulysses. Hence, this study investigated the hydrological response and compared each sub-basin runoff to quantify the tributary sub-basin contribution under the assumption of constant rainfall across the entire basin. It was discovered that each sub-basin had different hydrological responses and subsequently contributed to the runoff during the typhoon. The Cagayan Segment 1 sub-basin contributed higher runoff than other sub-basins under dam and without-dam scenarios. Therefore, a new scenario of proposing an additional dam for flood control was compared with other baseline scenarios, which can help reduce flood risk in downstream areas and restore water to reduce the risk of water availability during the dry season. This helped evaluate the best feasible mitigation strategy for the CRB.

The actual rainfall data was used in the RRI model to reproduce the inflow discharges. Figure 13 shows that the contributions of Cagayan Segment 1 to the downstream are 44% compared with the other tributaries and sub-basins. Furthermore, the same hydrological inputs were simulated for a new scenario where the Magat dam was included.

FIGURE 10. Spatial map showing cyclone tracks crossing the Philippines during 2001–2021.

FIGURE 11. Institutional stakeholder survey for results validation and interpretation.

It was found that the contributions of Cagayan Segment 1 are higher compared to Magat River with and without dam scenarios. Therefore, we can use the constant discharge and rate discharge models to simulate the dam pre-release scenarios, as shown in Table 2. In the case that there is no sedimentation in Magat dam and they could pre-release to reduce the dam's water level from 188.64 m to 180 m, the operation that does not store water total is only constant discharge of 1000 m^3/s, and this operation can reduce water level at Buntun bridge from 13.3 m to 12.1 m. If there is sedimentation in Magat dam and they cannot pre-release more, the best operation is the starting discharge for flood at 700 m^3/s and a discharge rate of 0.5. This operation can reduce the water level at Buntun bridge to 12.8 m (Table 2).

Finally, new scenarios were compared with the baseline scenarios such that a proposed additional dam for flood control will be constructed in Cagayan Segment 1 and Ilagan sub-basins. We selected the location referred from JICA's master plan, and our study result showed that Cagayan Segment 1 and Ilagan had high outflow (DPWH & JICA, 2002). The storages of the new dams are about 400 million m^3. Therefore, if they can use the dam at Typhoon Ulysses and Magat dam's operation, the starting discharge for flood is 700 m^3/s, and the discharge rate is 0.5, they could reduce the Buntun bridge's water level to 12.4 m (Table 2). The results of this study would probably be an easy-to-use resource to tackle extreme weather situations and guide the disaster risk and management offices in establishing

FIGURE 12. Exposure survey for understanding the gaps and community risk.

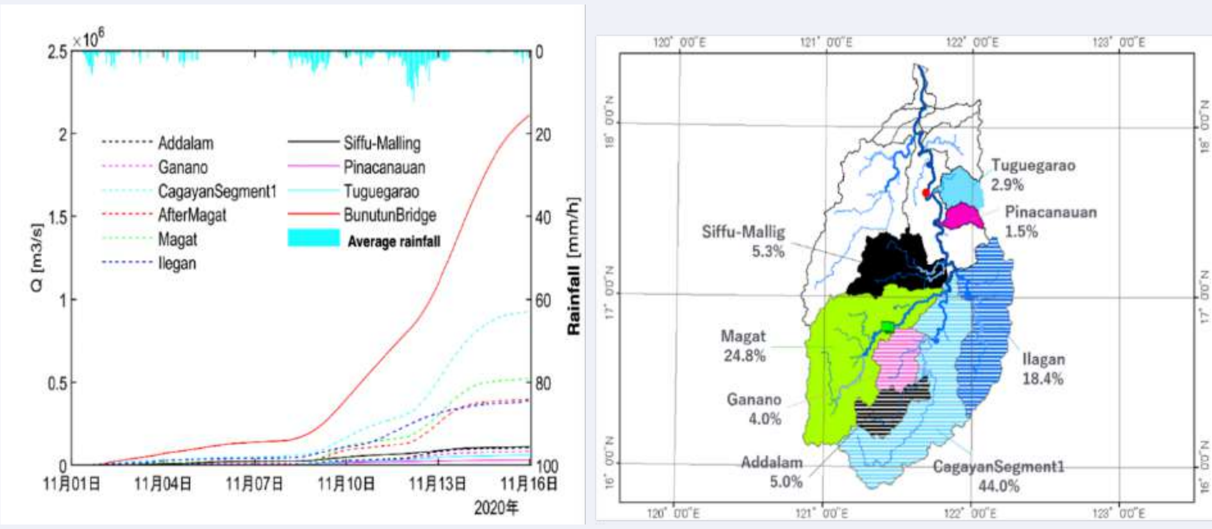

FIGURE 13. Result of the RRI model using actual rainfall at Ulysses.

an appropriate decision for implementing adaptation strategies over high-risk zones.

4. CONCLUSION AND FUTURE RECOMMENDATION

A consistent increase in temperature and precipitation is expected to result in prolonged dry and wet spells in some sub-basins, such as Addalam. Prolonged dry and wet spells may cause severe drought and flooding over CRB. Hence, the spatiotemporal assessment was helpful and recommended for analysing the specific risk of different hydroclimatic extremes.

Regarding Magat dam operation, sedimentation countermeasures and Magat dam pre-release have flood control effects, but they are insufficient.

Scenarios	Start Flood control discharge [m³/s]	Discharge rate	Water level at Buntun bridge [m]
No dam	-	-	13.3
Magat dam : Sedimentation, no pre-release	700	0.5	12.8
Magat dam : No sedimentation, pre-release	1000	0	12.1
Magat + CS1 + Ilagan	Magat: 700 CS1: 500 Ilagan 1: 300 Ilagan 2: 100	Magat: 0.5 CS1: 0 Ilagan1: 0 Ilagan2: 0	12.4

TABLE 2. Changes in Water Level at Buntun Bridge with Magat Dam and New Dam in Tributary Basin.

Therefore, there is an urgent need to optimise dam pre-release to target an appropriate balance between required storage during droughts and flood management strategies during floods. Moreover, optimising sediment management to recover reservoir volume and restore original functions is a high priority in the Cagayan River Basin, especially at Magat Dam. The simulation without a dam indicates that Cagayan Segment 1, Chico, Magat, had high outflow. Therefore, constructing an additional dam at the highly contributing tributaries is required to reduce floods in the lower CRB.

It is also recommended to start the discharge with a flow rate of 700 m³/s and a discharge rate of about 0.5 to lower the water level at Buntun Bridge and thus reduce the potential flood risk. It is also suggested that an ensemble rainfall forecast be used to optimise dam operations for pre-release before more than three days during the extreme typhoon prediction. Therefore, the effective use of an ensemble rainfall forecast system has been recommended to monitor the extreme weather situation and rainfall forecast for effective dam operation and maintain the optimised/maximum accumulated water storage volume, which can be secured and used effectively to address the water shortage/management issues to reduce drought risk during El Niño/normal climate condition. RRI models are suitable for science-based decision-making tools during extreme rainfall conditions. In addition, it is helpful for flood forecasting, early warning systems, evacuation planning, and emergency response.

5. ACKNOWLEDGEMENT

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Original article

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Dive industry perspectives on the threats to coral reefs: A comparative study across four Asia-Pacific countries

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ABSTRACT

The combined effects of climate change, marine tourism and other stressors threaten the ecological and economic sustainability of coral reefs. This study investigates dive industry stakeholder awareness of the threats to coral reefs through structured interviews with Dive Masters, company managers and marine management agencies in Vietnam, Australia, Malaysia and Indonesia. Stakeholders from all locations have observed degradation of local reefs. Destructive fishing was identified as the principal threat in all regions except Australia. Most participants identified threats from climate change and marine tourism. There was a lack of awareness about ocean acidification by all participants from Maluku, Indonesia. However, ocean acidification could make coral more fragile and, therefore, vulnerable to diver-induced damage. The majority of Dive Masters across all regions provide pre-dive briefings to reduce diver impacts and participate in environmental activities to protect local reefs. Stakeholders in three regions thought there was capacity to expand the local dive industry. However, in Nha Trang Vietnam, most industry stakeholders thought they were at, or exceeded, carrying capacity, whereas marine management employees thought there was room to expand. This study highlights an opportunity to improve diver education on the vulnerability of coral to damage in acidifying oceans. This study also identifies various non-regulatory and regulatory strategies used to reduce diver impacts, emphasising the value of multi-national knowledge sharing between the dive industry and regulatory agencies for adaptive management.

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KEYWORDS
Coral reefs,
diver impacts,
environmental stewardship,
marine tourism,
ocean acidification

HIGHLIGHTS

- Dive industry stakeholders are concerned about threats to coral reefs.
- Impacts from diving activities were recognised in three of four regions.
- There was great discrepancy between regions in the awareness of ocean acidification.
- Most dive industry stakeholders are engaged in marine conservation activities.
- Some marine managers and industry stakeholders had discrepant views on diver carrying capacity.

1. INTRODUCTION

Coral reefs provide important ecosystem services, including a tourism industry worth billions of dollars annually. High in biodiversity and aesthetic appeal, coral reefs provide the foundation of the Self Contained Underwater Breathing Apparatus (SCUBA) dive industry, which is one of the world's fastest-growing leisure activities (Ong & Musa, 2012, Schuhbauer et al., 2023). The uniqueness and abundance of marine life are important drivers of SCUBA tourism (Apps, Heagney, Ngoc, Dimmock, & Benkendorff, 2023). Recognised as a biodiverse coral hotspot, Southeast Asia has become a leading recreational SCUBA diving destination (Dimmock & Musa, 2015, Schuhbauer et al., 2023). Thus, SCUBA dive tourism is an important source of income for many regions in Southeast Asia (Tuntipisitkul & Fuchs, 2023). However, long-term sustainability of the industry depends on the effective management of healthy coral reefs.

SCUBA diving is typically considered a low-impact activity that provides an economic alternative to fishing (Tapsuwan & Asafu-Adjaye, 2008). Yet, diving can cause direct and indirect negative impacts on coral reef ecosystems by trampling, fin damage and inadvertently touching corals, causing breakage (Barker & Roberts, 2004; Sumanapala, Dimmock, & Wolf, 2023). Inexperienced divers were more likely to cause damage due to poor buoyancy control (Toyoshima & Nadaoka, 2015) and divers carrying cameras and other equipment were more likely to impact the reef than those without (Barker & Roberts, 2004; Hammerton, 2018). The amount of broken coral on reefs has been correlated with the number of divers and intense diving activities can lead to compositional changes (Au, Zhang, Chung, & Qiu, 2014) or phase shifts in coral reef communities (Giglio, Luiz, & Ferreira, 2020).

Further risk to coral reefs stem from the synergistic impacts of multiple stressors, including human activities and climate change. Ocean acidification poses a particular threat to coral reefs by reducing the concentration of carbonate ions required to build reefs (Albright et al., 2018) and increasing the risk of reef dissolution (Eyre et al., 2018). The mechanical integrity of coral reef structures is fundamentally important to coral reef ecosystem services, including the strength of the reef substrate (Madin, Dell, Madin, & Nash, 2012). Exposure to elevated CO_2-induced acidified waters can increase the skeletal porosity and reduce the bulk density of corals (Fantazzini et al., 2015), which reduces their mechanical strength and increases susceptibility to damage. Intense diving activity could drive coral reefs towards their tipping point, leading to a phase shift in community structure and potential functional collapse (Hoegh-Guldberg et al., 2007). Serious socio-economic consequences for coastal protection and regional communities that

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are dependent on coral reefs for their livelihoods, including marine tourism industries, would occur.

The combined effects of acidification and SCUBA diving on increasingly sensitive coral reefs require effective management to ensure the protection of ecological, cultural and economic values. The sustainable management of dive tourism requires stakeholder engagement to account for divers' environmental awareness and willingness to contribute to marine conservation (Apps et al., 2023; Hillmer-Pegram, 2014). Sustainable marine tourism requires consideration of social, environmental and economic factors, and therefore, a systems approach to consider the views of all stakeholder groups is preferred over narrow, linear approaches (Dimmock & Musa, 2015). Recently an online survey has been undertaken on SCUBA divers to gauge the level of awareness of threats to coral reefs from ocean acidification and diver impacts (Apps et al., 2023). Here, we build on this to gain insight into the environmental awareness of Dive Company Managers and Dive Masters working at the forefront of the SCUBA dive industry.

Southeast Asia is one of the world's leading recreational SCUBA diving destinations (Dimmock & Musa, 2015) and ocean acidification-induced damage to coral reefs will disproportionally impact developing countries that rely on marine-related economic activities (Cooley, Kite-Powell, & Doney, 2009). This study investigates knowledge of ocean acidification, awareness of the risk from diver-induced damage and other perceived threats to coral reefs from the perspective of stakeholders in the SCUBA dive industry across four areas within the Asia-Pacific region. Interview sessions were also held with staff from marine management agencies from two regions. We hope to empower stakeholders with a greater sense of environmental stewardship by providing information to support effective education and leadership with "future-oriented thinking" (Dimmock & Musa, 2015) necessary for sustainable marine tourism in a changing world.

2. METHODOLOGY

2.1. Study locations

Four locations were selected as case studies to conduct interviews with the SCUBA dive industry: (a) Solitary Islands and Cape Byron Marine Parks on the mid-north to north coast of New South Wales (NSW), Australia, (b) Nha Trang Bay Marine Protected Area, Nha Trang, Vietnam, (c) Ambon and Banda Islands, Maluku Archipelago, Indonesia, and (d) Tioman Island, East Peninsula, Malaysia. North NSW provides a case study with relatively few dive operators and high government regulation within marine parks. The reefs in this area contain a high proportion of soft coral and a high diversity of Scleractinian corals (Harriott, Smith, & Harrison, 1994), with previous reports of diver-induced damage (Hammerton & Bucher, 2015). Nha Trang Bay Marine Protected Area has rapidly grown as a popular dive spot in the last decade, with a burgeoning local and foreign tourist industry in Nha Trang and evidence of degradation of coral reefs in this area (Long & Vo, 2013). The Maluku Province has been identified as a high priority for biodiversity conservation (Asaad, Lundquist, Erdmann, & Costello, 2018) and provides a relatively untapped biodiversity hotspot for dive tourism, with an amazing diversity of coral in shallow waters (Edinger, Kolasa, & Risk, 2000). The Malaysia Islands of East Peninsula, Malaysia, are coral hotspots that have experienced rapid marine tourism growth over the last two decades. Increasing reports of diver damage and coral bleaching in the area resulted in the closure of 12 islands in 2012 (Saleh & Hasan, 2014). A Reef Check program has since been implemented in Malaysia to facilitate marine parks management and diver education (Lau et al., 2019).

2.2. Data collection

In June 2019, a preliminary survey was conducted in Nha Trang, Vietnam, using face-to-face interviews with four SCUBA Dive Company Managers and five Dive Masters. Subsequently, in November 2019, a workshop was held on the Gold Coast, Australia, involving a focus group of 13 researchers and divers across four countries to refine the questions. The final survey consisted of structured face-to-face interviews involving 15 questions delivered consecutively to Dive Masters (Supplementary Table S1). A different questionnaire was used for Dive Company Managers to obtain more information on local dive operations (Supplementary Table S2). The interviews were undertaken from 2020–2022 by researchers from the local region and translated into local language where necessary. Primary data collection included: demographics; knowledge of risks to coral reefs; familiarity with ocean acidification and diver-induced damage to coral; environmental stewardship and mechanisms for communicating impacts; and opinions on a carrying capacity for the local reefs. In tourism, 'carrying capacity' refers to the maximum number of people who can use a site without unacceptable deterioration of the physical environment or decline in the quality of the experience by the visitors (Cooper, 2016).

Marine management agencies are also important stakeholders for the ecologically sustainable use and protection of coral reefs. Therefore, additional interviews were undertaken with employees in the Nha Trang Bay Management Authority (NTBMA), Vietnam, due to rapid growth in the local dive industry and the Maluku Natural Resource Conservation Centre (MNRCC) in Ambon Indonesia, which has a relatively new tourism industry and potential for future growth (Supplementary Table S3).

2.3. Data analysis

A mixed-method approach was adopted using a combination of qualitative and quantitative techniques for both data collection and analysis. The structured interviews used a combination of binomial (yes or no), selective (multiple unranked options) and open-ended questions (reflections). Data was collated across the four countries using descriptive statistics and frequency tables. Open-ended responses were content analysed to identify themes of similar meaning, with each theme tested for reliability among two coders until a consensus was reached (McGrath, 2010). Themes were then reviewed in terms of how frequently participants mentioned them. Representative quotes from participants were included to illustrate themes, highlight particular findings and help provide transparency in the interpretation of qualitative data (Eldh, Årestedt, & Berterö, 2020).

3. RESULTS AND DISCUSSION

3.1. SCUBA Dive Master and company manager demographics

A total of 53 Dive Masters and 24 SCUBA Dive Company Managers were interviewed across the four regions (Supplementary Table S4). The majority of the Dive Masters surveyed in Vietnam (74%), and NSW (50%) had extensive experience in the dive industry, being employed for over ten years. In Tioman Island, only 32% had over ten years of experience, but 68% had over five years of experience, whereas none of the Dive Masters from Maluku had over ten years of experience, and less than 50% had over five years in the industry (Table S4b). Dive Companies have been in operation for less than one year to over 40 years across the regions, with a tendency towards more established companies in NSW and Tioman Island (Table S4b). The majority of Dive Masters were local residents and the Dive Company Managers confirmed they provide training for locals to become Dive Masters (Table S4). Findings confirm that the dive tourism industry supports local economies in these four Asia-Pacific regions, e.g. Ngoc (2019).

3.2. Stakeholder perspectives on the state of coral reefs

The majority of Dive Masters indicated they had noticed degradation or decline in local coral reefs since they commenced (Figure 1). Comments indicated the reefs are "getting worse all the time", "more bleaching, muck smothering coral", "Coral reefs are fractured, broken more and more", and in Nha Trang, they indicated that the net area of coral reefs is increasingly reduced. This is supported by recent studies in Nha Trang Bay that have confirmed the coral reefs are in a declining condition due to various anthropogenic and biotic stressors (Tkachenko, Britayev, Huan, Pereladov, &

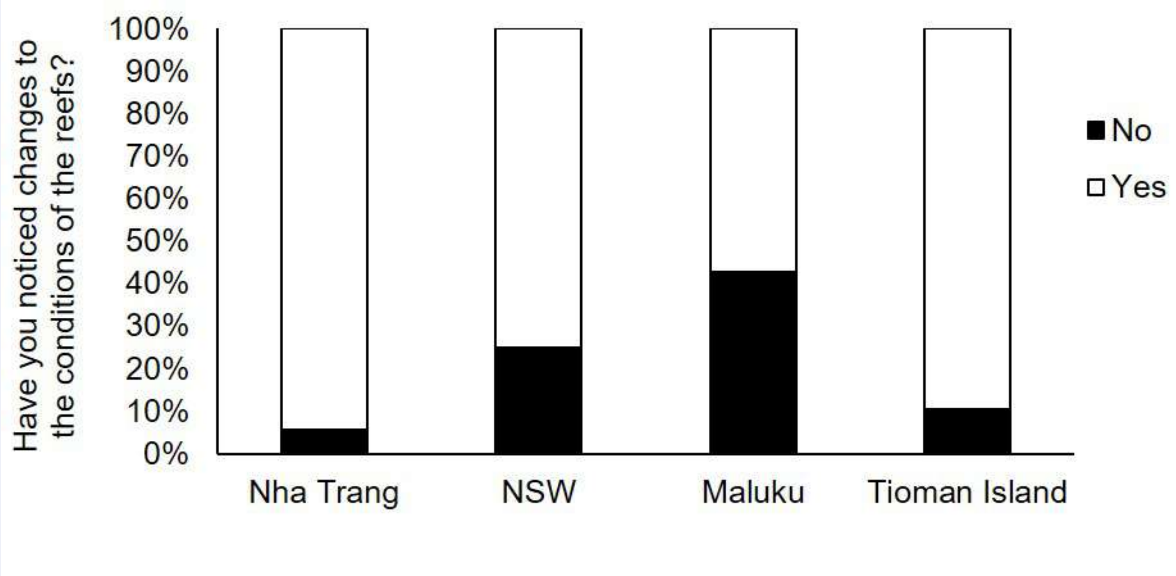

FIGURE 1. The proportion of Dive Masters that have noticed changes to the condition of local coral reefs since they have been diving.

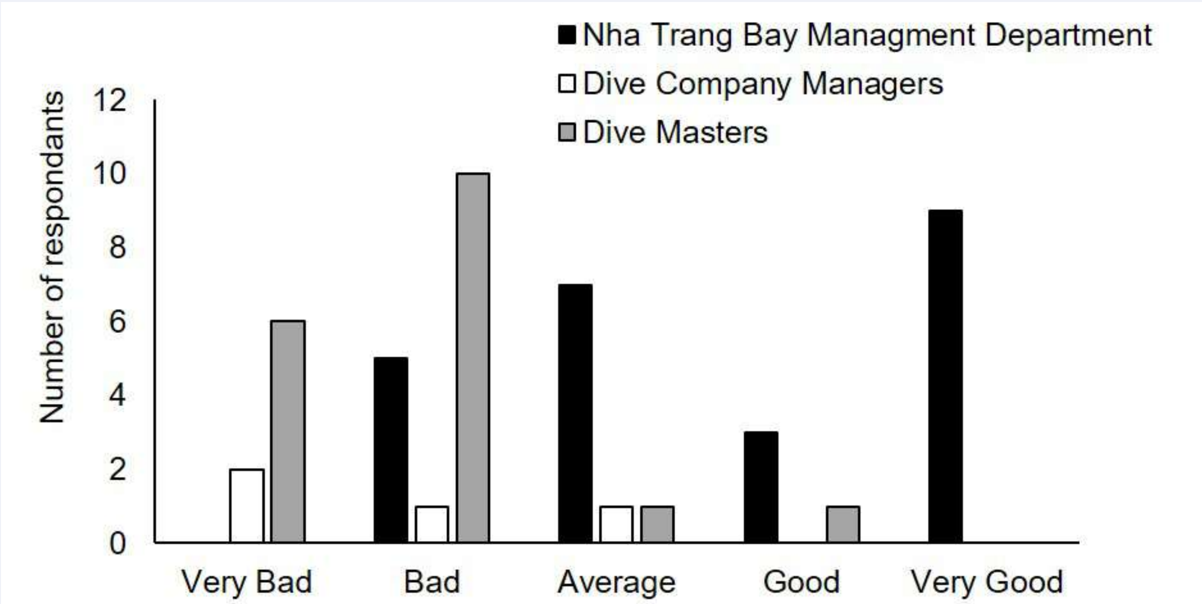

FIGURE 2. Frequency histogram comparing different stakeholders' perspectives of the condition of coral reefs in Nha Trang Bay and Hon Mun Island, Vietnam.

Latypov, 2016; Tkachenko, Huan, Thanh, & Britayev, 2021). The majority of Dive Company Managers and Dive Masters in Nha Trang rated the reefs as being in bad or very bad condition, with only one Dive Master indicating they were in good condition (Figure 2). In contrast, 47% of employees from the NTBMD thought the coral condition in Nha Trang Bay was normal or average, and 20% rated it as good, whereas only 33% indicated it was in a bad condition (Figure 2). The MNRCC considered the quality of coral reefs in Maluku province to be relatively good, but with damage in some places, which was generally consistent with the Dive Masters and Dive Company Managers from that region. In the absence of longitudinal studies documenting the actual decline of coral reefs, long-term observations from experienced divers can provide some insight into potential "shifting baselines" that could otherwise be regarded as normal.

3.3. Main anthropogenic impacts on coral reefs in the region

The predominant threats to coral reefs identified by Dive Masters were anthropogenic stressors (Table 1). Various impacts associated with fishing and boating were identified in Nha Trang, Maluku and Tioman Island, whereas these activities were not identified as major threats in mid-north NSW. In Tioman Island, one Dive Master commented on "more and more illegal fishermen", and a number of others referred to ghost nets breaking the coral. Abandoned fishing nets have been identified as a global problem causing considerable ecological and socioeconomic challenges (Do & Armstrong, 2023). Concerns regarding the use of explosives or dynamite were raised by three Dive Masters in Maluku and seven in Nha Trang, whereas one from Tioman Island highlighted both dynamite and cyanide fishing. Despite being illegal in Indonesia since 1984, dynamite fishing remains a widespread threat to coral reefs in the region (Praveena, Siraj, & Aris, 2012; Razak, Boström-Einarsson, Alisa, Vida, & Lamont, 2022). Cyanide fishing is also recognised as a most destructive technique for collecting fish from coral reefs; despite widespread laws banning the practice in most source countries, cyanide is still widely used in some Asia-Pacific regions (Calado et al., 2014). One Maluku Dive Master noted, "For coral reefs to be maintained, there must be supervision from government for fishing activities with explosives". Given that these practices are more common in socio-economically disadvantaged countries, legislation implementation approaches to deter the import of fish caught using these methods are important (Calado et al., 2014).

The major threats to coral reefs in Maluku and Nha Trang identified by the management agency employees, the NTBMD and MNRCC, included destructive fishing practices like the use of explosives and Bameti shell collecting (Table 1). The MNRCC indicated that almost all conservation areas have been degraded by human activities, and changes in the local reefs include coral death due to explosives. The steps to mitigate threats to coral reefs by the MNRCC were identified as: (a) Socialisation and community empowerment; and (b) Development of a village supporting the conservation area. When asked about ways to reduce the main threats to coral reefs in Nha Trang, 80% of the surveyed staff from the NTBMD said that all three of the following actions should be taken: (a) Socialisation and community empowerment; (b) Propagating and educating the community's awareness; (c) Increase surveillance and patrol activities at sea. All agreed there should be regulations/policies to protect coral reefs in Nha Trang. However, some Dive Masters indicated that management of NTBMD is not good or effective, complaining that there are illegal fishing activities on the coral reefs, the staff lack expertise and there is corruption. One Dive Master claimed that "night diving is not safe due to dynamite fishermen (who pay thankyou money)".

Knowledge about the scope of reef degradation caused by recreational diving and other stressors is crucial for the sustainable management of marine tourism industries (Giglio et al., 2020). The majority of Dive Masters agreed that some local dive sites had been degraded or heavily impacted by human activities (Figure 3a), except in NSW, where only one indicated there had been mild damage at one site. Diving and other tourism activities were only identified as threats by a few Dive Masters in Nha Trang, NSW and Tioman Island, but not by any participant from Maluku (Table 1). Similarly, in a previous review of threats to coral reefs in Malaysia, diving was not identified and tourism was only regarded as a minor threat in some locations (Praveena et al., 2012). In Nha Trang, one Dive Master noted "boats tying off to coral heads" and anchoring blocks being "pulled out, turned over and dragged across

Type of Impact	Threat	Nha Trang N = 24 (15)	Coffs Harbour N = 4	Maluku N = 7 (1)	Tioman Island N = 19
Anthropogenic	Human impacts broadly	5 (15)		1 (1)	1
fishing	Ghost nets / Fishing nets/ illegal nets			1	6
	Overfishing /unsustainable fishing				4
	Destructive fishing practices dynamite/cyanide, explosives	7 (15)		3 (1 main threat)	1
	Fishing line			1	1
	Bameti activities (shell hunting) that damage corals	3 (15)		1 (1)	
	Collecting coral/ornamental fish			1	1
Boating/shipping	Anchors, ships anchors, ships parked on reefs	1		3	
Tourism/diving	Other divers/lack of environmental awareness	1	2		3
	Poor diver training				1
	Tourists/island tours	2 (1)			1
Pollution	Littering/trash/rubbish/ plastic	4	1	4	1
	Oil contamination				1
	River run-off/nutrients, pesticides etc.	2 (2)	2		
	Fish feeding	1			
Habitat disturbance	Coral mining/extraction of building materials				2
	Development				2
Biotic stressors	Crown of Thorn	5 (15)		(1)	1
	Coral Bleaching	6 (15)		2 (1)	
Abiotic stressors	Climate change	1	2		1
	Global warming	1 (1)	1		1
	Ocean acidification		2		
	Intensified storms		1		1
	Weather	2			1

TABLE 1. Frequency of major threats to coral reefs identified by Dive Masters (and employees from the Nha Trang Bay Management Department and Maluku Natural Resource Conservation Centre).

reefs". Whilst not denying the economic benefits of the SCUBA diving industry, 80% of staff from the NTBMD agreed that recreational activities such as boating and diving can cause damage to coral reefs in Nha Trang. Conversely, the Maluku Natural Resource Conservation Centre indicated, "Boating

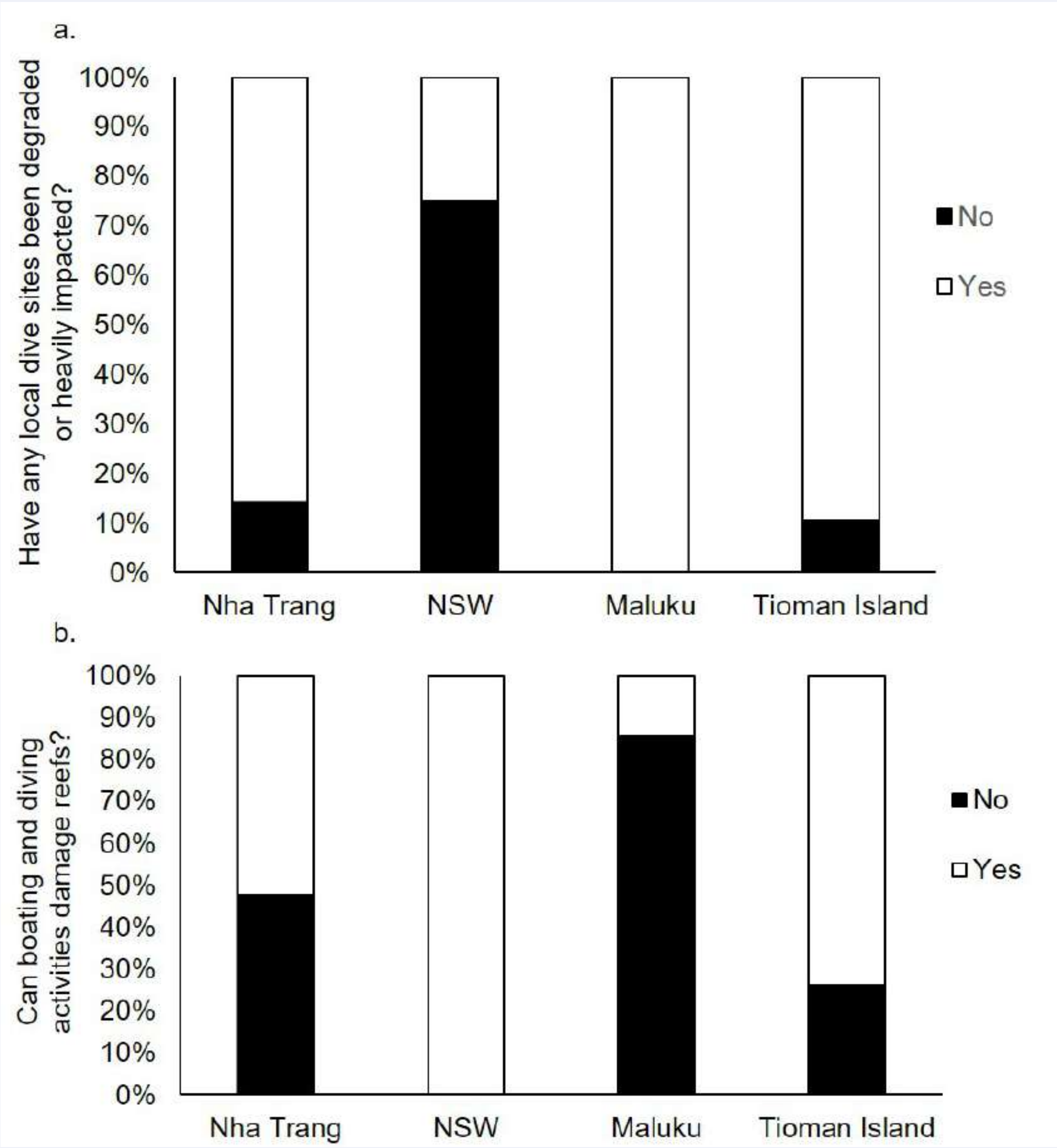

FIGURE 3. Percent of Dive Masters interviewed in four Asia-Pacific Regions who (a) have observed degradation of coral reefs, and (b) agreed that boating and diving activities can impact coral reefs.

does not damage the reef. If the diving activity involves a diving guide, it might not damage the coral reef".

The ecological impacts from diving are well documented (Giglio et al., 2020; Sumanapala et al., 2023). When asked directly whether recreational activities like diving and boating could cause damage to coral reefs, 58% of Dive Masters across the four regions agreed (Figure 3b). However, understanding of impacts from diving ranged from 100% in NSW to only 14% (1/7) in Maluku (Figure 3b). Comments from experienced Dive Masters in Nha Trang included "improper dive practices and the same dive spots regularly over-used, tea-bagging" (tethering several inexperienced divers together in a line), "many tourists stand on corals", "need to regulate bad activity, poor standard of instruction … some companies even take people who cannot swim. …others overweight to keep them on the bottom". Some dive services available in Nha Trang include "Sea Walking" and "Try Dive" for non-certified divers. Conversely, a less experienced Dive Master suggested that "Dive Masters and Instructors take care and don't allow anyone to touch or take any-thing". Dive Masters in Tioman Island noticed "uprooting", "broken corals", "coral damage (people keep touching while diving)", "assault by tourists (touching)" and "some dive sites are losing corals probably after being stepped on". One Dive Master from NSW highlighted the need to monitor for diver impacts. Previous studies on diver impacts in the Solitary Islands Marine Park have reported high levels of damage, with SCUBA tanks, cameras, divers knees and untethered equipment contributing to severe impacts (Hammerton, 2018).

Rubbish, litter and trash were identified as threats across all four regions, but more frequently in Nha Trang and Maluku (Table 1). One Dive Master from Maluku commented that they "need a government program to reduce plastic waste at sea"; another noted they need training to clean up rubbish. Some other forms of pollution identified as threats included oil contamination in Tioman Island and terrestrial run-off in NSW and Nha Trang. This is consistent with previous research on marine ecosystem impacts in these areas (Jamal, Reichelt-Brushett, & Benkendorff, 2022; Laicher et al., 2022; Tkachenko et al., 2016). Habitat disturbance from coral mining and development was identified as a threat by four Dive Masters on Tioman Island. Coral mining was previously identified as a risk to coral reefs in East Malaysia, but not on the east coast peninsular (Praveena et al., 2012), and there is no coral mining currently on Tioman Island.

3.4. Awareness of climate change and ocean acidification

Abiotic stressors associated with climate change and weather events were identified as threats in Nha Trang, NSW and Tioman Island (Figure 4), but not by Dive Masters in Maluku. These climate-related stressors were identified by 75% of NSW Dive Masters, compared to 9% in Nha Trang and 42% in Tioman Island (Table 1). Yet, coral bleaching was identified by six Dive Masters in Nha Trang and two in Maluku (Table 1). Bleaching was mentioned by 16 Dive Masters across all regions in response to the question of whether any dive sites have degraded. The susceptibility of corals to heat stress and bleaching has previously been documented for the Solitary Islands (Dalton & Carroll, 2011), Nha Trang (Tkachenko et al., 2016) and Tioman Island (Guest et al., 2012). The highest severity of coral disease and compromised health was linked to areas with greater coastal development and tourism activities on Tioman Island (Akmal & Shahbudin, 2020).

Across all regions, only two Dive Masters from NSW identified ocean acidification as a major threat to coral reefs when asked an open question (Table 1, Figure 4b). One had studied a course on Ocean Change Biology, and the other had "Heard about it and talked to a lot of people who are concerned about it". Another Dive Master from Coffs Harbour indicated they "Haven't heard of OA and want to understand it more". No Dive Masters from other locations identified ocean acidification as a specific threat, compared to 42% identifying "climate change" and global warming as threats in Nha Trang and Tioman Island (Table 1, Figure 4a). Nevertheless, when asked specifically if they had heard about ocean acidification and the problems it could cause for coral reefs, 74% and 68%, respectively, agreed they had in those two regions (Figure 4b). In Nha Trang, one Dive Master indicated they had heard of it "But what could be done about it?".

Similar to Dive Masters and Company Managers in Nha Trang, the majority of employees from the NTBMD were aware of ocean acidification (93%) but did not identify it as a specific threat to coral reefs. Conversely, MNRCC employees had never heard of ocean acidification, no Dive Masters or Company Managers from Maluku were previously aware of ocean acidification, and none identified climate change as a threat. However, 71% had observed coral bleaching as a change since they have been diving on local coral reefs (Figure 4). These findings align with findings from surveys of divers (Apps et al., 2023; Buckley et al., 2017), which found divers less aware of ocean acidification than other coral reef impacts. Given that ocean acidification is likely to make coral more fragile and, therefore, more vulnerable to diver impacts, this highlights the need to raise public

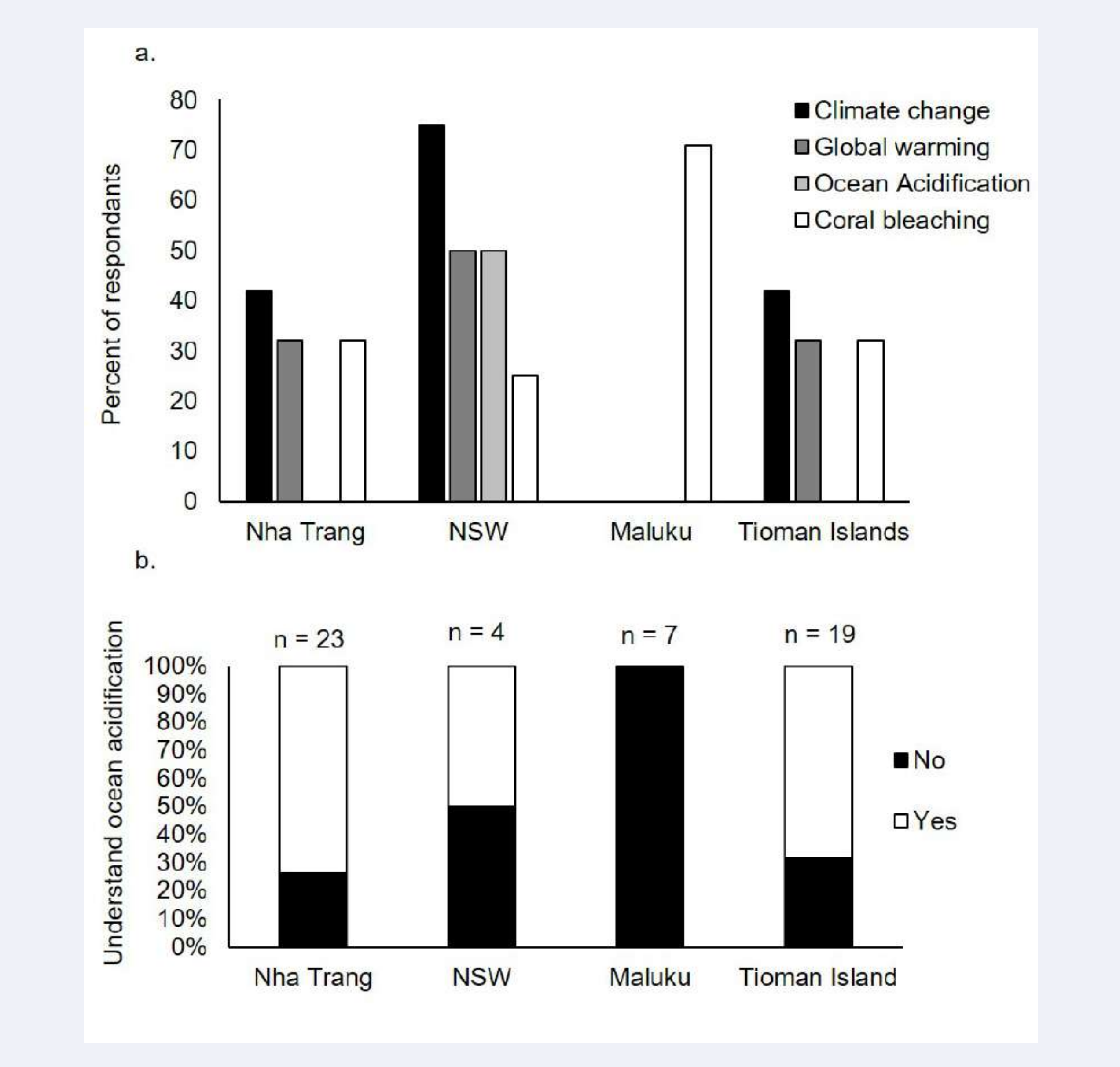

FIGURE 4. Percent of Dive Masters interviewed in four Asia-Pacific countries who (a) identified factors associated with ocean climate change as a major threat or factor associated with degradation at dive sites in the region and (b) indicated that they understand what ocean acidification is and the consequences for coral reefs.

awareness. To support the SCUBA dive industry in this endeavour, we have produced an information brochure that is available for free download and display (https://www.apn-gcr.org/publication/protect-coral-reefs-under-climate-change-how-you-can-help/).

3.5. Environmental education and stewardship in the SCUBA Dive industry

The impacts of diving on coral reefs are typically managed with non-regulatory strategies implemented by dive companies, such as education, improving dive techniques and pre-dive briefing (Sumanapala et al., 2023). Three dive companies on Tioman Island are certified members of Green Fins (https://greenfins.net/), which provides environmental guidelines to promote a sustainable diving industry. Green Fins has been implemented internationally by the Reef-World Foundation and the UN Environment Programme to provide an independent assessment system of digital or certified membership (in active countries) for sustainable marine tourism operators. The program aims to empower

Question	Nha Trang N = 23	NSW N = 4	Maluku N = 19	Tioman Island N = 7
Do you provide training to alert and educate divers (e.g. buoyancy control, fin damage, not holding coral)?	87	100	100	100
Participation in marine-based community environmental activities	61	100	71	100
Do you communicate concerns about reef health or potential diver-induced damage?	78	100	86	100
Do you have a choice of dive sites with different quality reef health where you take divers?	83	100	100	100
Are inexperienced divers taken to particular dive sites – already damaged sites vs. fragile sites?	61	100	0	84
Does local culture influence the choice of dive sites (e.g. protected areas, no diving during coral spawning)?	87	0	0	32
Do you think the capacity has been reached?	78	33	0	11

TABLE 2a. Environmental stewardship in the SCUBA dive industry (a) the percent of Dive Masters responding positively to questions relating to environmental stewardship and strategies to reduce diver impacts on coral reefs.

Dive Guides to positively influence diver behaviour and effectively manage divers to prevent them from causing damage to coral and other marine life. No other region in our study participates in this program, although several Dive Company Managers mentioned a code of practice. Furthermore, all Dive Company Managers in NSW and Tioman Island and several in Nha Trang ensure their Dive Masters provide a thorough pre-dive briefing with education around fin damage and buoyancy control (Table S1b). Consistent with this, all Dive Masters in NSW and Tioman Island, as well as Maluku, indicated they provide training to divers to limit coral reef damage, whereas a minority in Nha Trang did not (Table 2a). The majority of Dive Masters said that diving in Nha Trang is an indispensable part of Nha Trang tourism but highlighted that some diving companies operate for profit and neglect the protection of marine natural resources; they recruit amateur or unqualified divers to cope but do not have adequate knowledge of environmental protection.

Targeted interventions, including pre-dive briefing and direct underwater reinforcement at the time of first contact, were effective in significantly reducing the impact of divers (Hammerton & Bucher, 2015). While most Dive Masters provide dive briefings on site, reminding divers to stay off the bottom, maintain buoyancy, watch fins and not touch the coral, only a couple of the Company Managers from NSW indicated their Dive Masters are trained to intervene/intercept when required. One Dive Master from NSW confirmed, "If they are unsure of weights or buoyancy, I do a surface check. I have more on me to give them..". Another indicated, "If I see poor buoyancy underwater, I go up and let them know". One Dive Master in Nha Trang "Evaluates all groups to find out the weakest and strongest link…" and "Trains divers to use lungs instead of buoyancy vests…". These are all useful strategies for improving diver awareness and skills, thereby reducing likely diver contact with coral (Hammerton & Bucher, 2015).

Experienced SCUBA divers generally have good environmental ethics (agree they have a responsibility to protect the marine environment) and show a preference for operators that promote coral reef conservation (Apps et al., 2023). Involvement in diver awareness, marine education programs or marine conservation training was mentioned by three Dive Company Managers in Tioman Island, two in

Number involved in environmental activities	Nha Trang		NSW		Maluku		Tioman Island	
	DM	DCM	DM	DCM	DM	DCM	DM	DCM
Rubbish removal	4	3	4	2	4		19	9
Ghost net removal							2	3
Crown of thorns removal	2	1						3
Habitat rehabilitation			1	1			2	2
Reef Check							2	1
Other (fish recovery and turtle conservation)			1	1				1

TABLE 2b. Environmental stewardship in the SCUBA dive industry (b) the number of Dive Masters participating in different environmental activities.

Nha Trang and one from NSW. All Dive Company Managers interviewed from Nha Trang and Tioman Island indicated their companies participate in some sort of environmental programmes, along with two from NSW and one from Maluku. Consistent with this, all Dive Masters in Tioman Island and NSW and over 60% in Maluku and Nha Trang indicated they participate in marine environmental activities (Table 2a). However, not all Dive Masters or managers specified what these activities were in Maluku or Nha Trang (Table 2b). The activities primarily included rubbish collection, informally or as part of Project Aware clean-ups and crown of thorns removal (Table 2b). Other environmental programs include coral planting, ghost net removal, and turtle conservation. A survey of divers has confirmed they enjoy learning about the environment whilst on holidays and generally agreed that dive operators have a responsibility to protect the environment at their dive sites and support marine conservation and education (Apps et al., 2023).

Sharing information with government managers and their diving clients is important to improve awareness of factors contributing to coral reef degradation (Giglio et al., 2020). The majority of Dive Masters across all four regions communicated concerns about reef health and/or potential diver-induced damage (Table 2a). Nearly half of the Dive Masters in Nha Trang indicated they notified the NTBMD when they observed deterioration or reef damage. However, others have the opinion that when they announce any broken coral reefs, their company or NTBMD always opposes them and claims the coral reefs are in good condition. Conversely, 14 of 15 NTBMD employees interviewed acknowledged changes in coral reef health in Nha Trang, including reduced coral reef area and more and more broken coral. This is noteworthy because it indicates a lack of trust between the Dive industry and management agencies in the region. However, 87% of employees surveyed from NTBMD believe they have close cooperation with the SCUBA diving industry.

The Maluku Natural Resource Conservation Centre indicated they do not work closely with the SCUBA dive industry, although they ask for help from the diving community for activities like coral reef transplants. In other regions, most Dive Managers communicated concerns about coral health, but the responses focused on educating customers on dive charters. Both non-regulatory and regulatory management strategies are required to facilitate an ecologically sustainable SCUBA dive industry (Giglio et al., 2020; Sumanapala et al., 2023).

3.6. Regulatory strategies for management of coral reefs

Regulatory strategies to manage diver impacts on coral reefs can be self-imposed by the Dive Industry or Company Managers or formally regulated by the government. Spatial or temporal zoning (Giglio et al., 2020) can limit the overall number of sites accessible to divers or times of year in which diving can occur (Sumanapala et al., 2023). Temporal zoning typically occurs in response to seasonal weather patterns that influence safety. On Tioman Island, most Dive Company Managers indicated that it is a closed season, with diving restricted to 7-8 months per year. A few Dive Masters in Tioman Island and the majority in Nha Trang indicated that some protected areas are not accessible for diving (Table 2a). In NSW, SCUBA diving is not excluded from sanctuary zones in multi-use marine parks. However, NSW Dive Companies must report the number of dive charters annually to the Marine Parks Authority. Regulation can be further achieved by introducing a permit system or charges (Sumanapala et al., 2023). In Nha Trang, all Dive Charters pay a fee for each diver to access Nha Trang Bay Marine Park. However, one Dive Company Manager noted that "many cheat even though it is cheap (they claim less on board)", and they have "no idea if marine park fees are going back to the marine park for management".

Another mechanism for regulating diver impacts could involve limiting access to diving sites depending on the experience level of divers (Sumanapala et al., 2023). Many studies found no direct correlation between diver experience and damage to corals, yet introductory-level divers can have poor buoyancy control and are likely to cause damage at the start of the dive (Giglio et al., 2020). The majority of Dive Masters indicated they access a range of dive sites with different reef health. All Dive Masters in NSW and the majority on Tioman Island use different sites according to diver experience (Table 2a). This was less frequently the case in Nha Trang, although several indicated they only take more experienced divers to deeper dive sites, and many indicated inexperienced divers would be taken to specific dive sites (already damaged or less damaged). No Dive Masters in Maluku indicated that they discriminated between inexperienced and experienced divers in the choice of dive sites (Table 2a). In Tioman Island, Dive Masters indicated, "We check out divers at the shore on a sandy area to evaluate diving skills before they get on the boat. From there, we decide on the type of sites to suit them" and "I will make sure they have sufficient training or lesson on a sandy bottom area before heading to the coral area". Another commented, "It depends on the diver's technique rather than experience".

Restricting the number of divers through maximum group size, number of boats and/or establishing a reef carrying capacity are other options for regulating diving impacts (Zhang, Chung, & Qiu, 2016). The size of the dive groups varied from two up to 12 across all four regions (Figure 5). The modal group size was four in both Tioman Island and Nha Trang, where a larger number of Dive Masters participated in the survey. However, Nha Trang has a smaller frequency distribution with a maximum of five divers. One Dive Master responded, "It was based on international standards or the diving group was often divided according to the experience of the guests, but the maximum was still four people/diving group". Few Dive Company Managers mentioned restricting the dive group size. Small group size, minimal number of boats at the dive sites and high-quality coral with minimal disturbance are important features of the dive experience (Apps et al., 2023) and could be promoted by dive operators aiming to attract environmentally conscious divers, willing to pay for marine conservation (Wielgus, Balmford, Lewis, Mora, & Gerber, 2010).

Responses to the question of whether a carrying capacity for diving on local reefs had been reached were highly variable (Table 2a). In Maluku, all Dive Masters indicated the carrying capacity had not been reached and there was room for expansion. One indicated they need "support from provincial government and local communities to develop the diving industry". Consistent with this, the MNRCC agency employees indicated there is room for expansion of the SCUBA dive industry in Maluku. They are optimistic about the potential for attracting more SCUBA dive tourism due to the unique marine life and diverse coral ecosystems in the area. The MNRCC agreed there should be a carrying capacity but highlighted there had been no study on this,

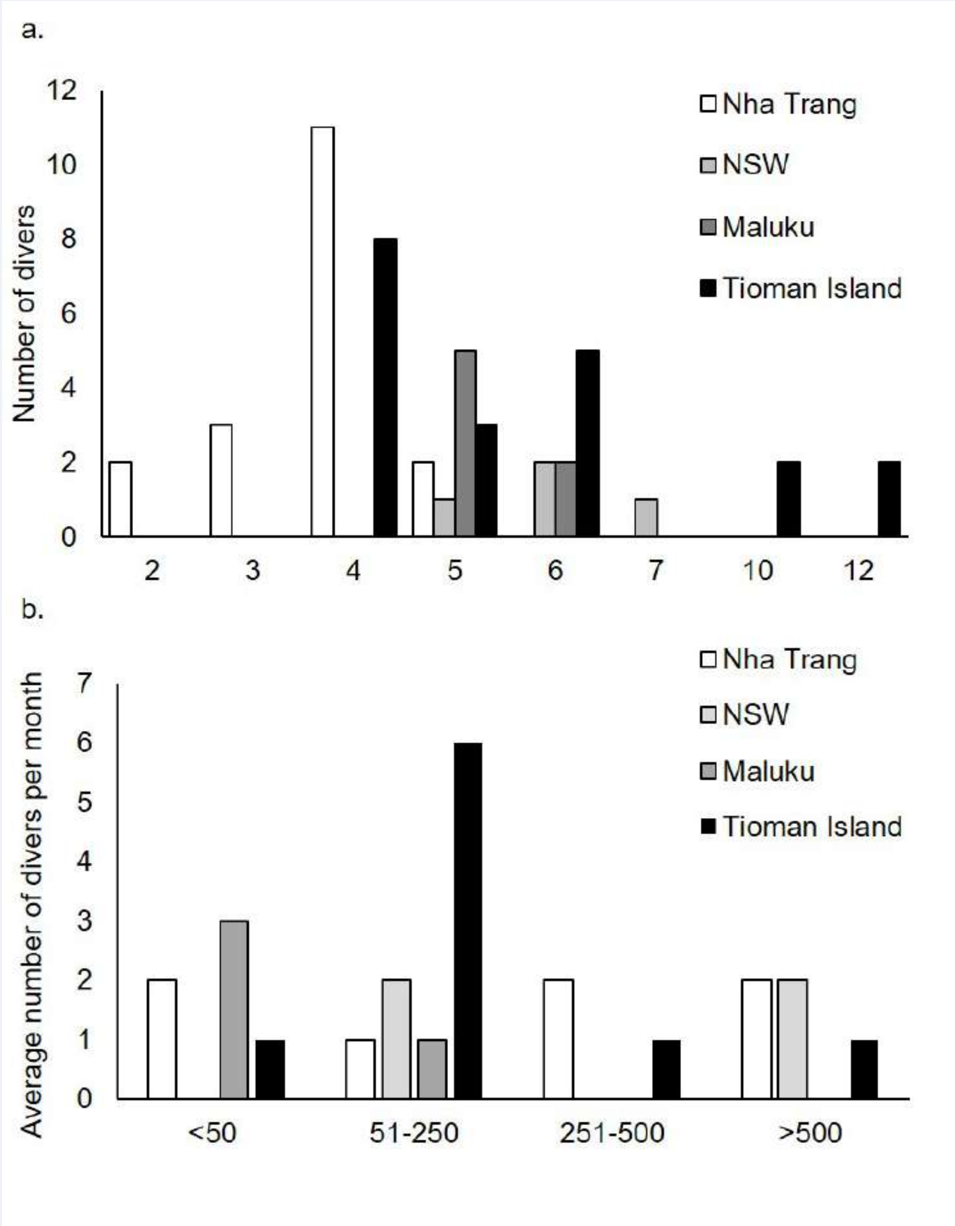

FIGURE 5. Frequency histogram of the (a) maximum size of dive groups taken out by Dive Masters and (b) average number of SCUBA clients per month for dive companies interviewed in four Asia-Pacific regions.

although they thought it had not been reached yet. In Tioman Island, the majority of Dive Masters thought there was room for expansion, although several indicated with the proviso that it is well regulated and there was an emphasis on training and environmental education. One suggested, "It's better to increase the quality of the dive/divers rather than the quantity". Several Dive Company Managers in Tioman Island indicated that the government needed to enforce a carrying capacity to limit the number of divers, and there should be stricter requirements for all SCUBA operators to enhance diver education and improve the quality of dive instructors.

In Nha Trang, responses about the carrying capacity of the local reefs were divergent, with the majority indicating the reefs were at or above capacity for diving, although several still thought there was room for expansion (Table 2a). A couple of Dive Masters indicated they were over capacity at specific sites and "need to change the mentality and prevent so many divers at one spot. "Need more moorings to spread out around the island. Boat captains all park together to drink beer and chat - need rules such as max three boats per spot". This suggests that regulatory support may be required to initiate behavioural change in some sectors of the industry to protect coral in diving hotspots. The NTBMD employees indicated they feel optimistic about the SCUBA industry in Nha Trang (93.3%), but only 53.3% of employees believe there is room for expansion, with 33.3% of employees indicating it might be possible to expand the diving area to another place, but this would not be easy. Nevertheless, 93.3% of NTBMD employees indicated the current number of divers was less than the carrying capacity of the environment and only 6.7% of employees think the number of divers is greater than the capacity. This is in contrast to the Dive Masters from Nha Trang, in which 73% think the carrying capacity has been reached (Table 2a).

4. CONCLUSION

To minimise the impact of snorkelling and diving on coral reefs, it is crucial that tourism is planned and a framework developed which is within the context of sustainable development principles. For example, the UN sustainable development goal 14: Conserve and sustainably use the oceans, seas and marine resources, recognises the need to minimise the impacts of ocean acidification and sustainably manage and protect marine ecosystems to avoid adverse impacts. It is not possible to eliminate all threats to coral reefs, including impacts of SCUBA diving. However, regulations can set controls on dive operator activity, such as establishing a carrying capacity, limiting diver numbers at one site at one time and licensing for well-qualified dive operators who are willing to take responsibility for stewardship of the environment. Non-regulatory management strategies include establishing clear guidelines for pre-dive briefings, assessing diver skills and selecting dive sites accordingly, and empowering Dive Masters to intervene on-site when they witness poor diving practice. Expansion of the active Green Fins approach into more Asia-Pacific regions could be one way to promote sustainable diving practices for the protection of coral reefs. Dive Masters and Company Managers have extensive experience of their local environment, along with a vested interest in protecting the reefs, which could provide a resource to government marine management agencies. Building stakeholder trust and collaboration should be part of the management strategies to facilitate ongoing monitoring and raise awareness of the health of coral reefs.

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6. APPENDICES

Appendices are available online at https://doi.org/10.30852/sb.2023.2346

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Case study

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Climate-smart agriculture strategies for South Asia to address the challenges of climate change: Identification of climate-resilient agriculture practices for India, Bangladesh, and Afghanistan

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ABSTRACT

In South Asia, agriculture is pivotal for food and nutritional security and the livelihood of more than 50% of the population. Food production and nutritional security pressures intensify as urbanisation decreases the agricultural land area amid population growth. Climate change complicates this scenario by introducing elevated temperatures, extreme climatic events, surging sea levels, and increased soil salinity. Identifying climate-resilient innovative technologies for farmer adoption becomes imperative to counter these adversities. An integrated approach to climate-smart agriculture, encompassing capacity building through practical training on innovative mitigation strategies, is needed. This study unites experts from Australia, India, Bangladesh, and Afghanistan in an Asia-Pacific Network for Global Change Research project, fostering mutual learning and farmer training in climate-smart practices. Insights from workshops conducted at Amity University in February 2020 and June 2022, combined with country-specific technological advances in the past 15 years gleaned from the literature, revealed key technologies to combat climate change (e.g., zero tillage, raised bed planting, direct-seeded rice, crop residue management, crop diversification, site-specific nutrient management, laser levelling, micro-irrigation, seed/fodder banks, and ICT-based weather advisories). Widespread implementation of these technologies and practices will empower farmers to navigate climate change challenges, fostering resilience and sustainability.

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KEYWORDS

Climate change, food security, climate-smart agriculture

HIGHLIGHTS

- Climate change diminishes South Asia's agricultural yields and nutritional quality.
- Climate-resilient solutions are being explored; some are in limited operation.
- Climate-smart farming strategies are classified as short-, medium-, or long-term.
- Key short-term strategies encompass zero tillage, crop diversification, and more.
- Widespread adoption of such strategies can empower farmers to tackle climate change.

1. INTRODUCTION

Food and nutrition pose significant challenges worldwide due to the expanding population, diminishing natural resource base, and farm management constraints. Food demands are increasing due to a growing global population and evolving dietary preferences. However, food production is struggling to keep pace due to declining crop yields, ocean degradation, and natural resource depletion (e.g., soil, water, and biodiversity). A 2020 report revealed that around 690 million people, accounting for 8.9% of the global population, experience hunger. Food security issues are expected to increase with the need to produce approximately 70% more food by 2050 to sustain an estimated population of 9 billion people (World Bank, 2020).

Agriculture provides avenues for sequestering carbon dioxide, but farming and allied practices and activities contribute to roughly 30% of ozone-depleting substance emissions, primarily from composts, synthetic pesticides, and animal waste. Climatic factors affect the accessibility and uptake of soil nutrients by plants, impacting the nutritional quality of food. For example, rising temperatures can affect growing season length, altering the annual and seasonal availability of nutrients.

Agricultural systems are extremely vulnerable to climate change due to their sensitivity to temperature and precipitation fluctuations and the occurrence of natural events and disasters. A recent study conducted by the World Bank across all six countries of South Asia suggested that climate change could significantly deteriorate living conditions for up to 800 million people in the region (Mani, Bandyopadhyay, Chonabayashi, Markandya, & Mosier, 2018). Furthermore, a report from the United Nations warns that advancing climate change could result in flooding, food shortages, and stagnant economic growth (Intergovernmental Panel for Climate Change [IPCC], 2014).

As of 2022, the IPCC reported that the mean global temperature had risen by 0.74 °C in the past century, with a projected further increase of 1.8–4 °C by 2100 (IPCC, 2022). Increased temperature and carbon dioxide levels adversely affect the nutritional quality of food. Elevated CO_2 levels decrease the protein content and concentration of essential elements (N, P, K, Ca, Mg, S, Zn, Mn, Fe, and Cu) in food crops. These reductions can be mitigated through increased fertiliser application, though this poses affordability challenges in South Asian nations that heavily rely on fertiliser imports, and heightened fertiliser use can undermine agricultural sustainability. Based on the estimated global CO_2 levels of 550 ppm by 2050, an estimated 175 million individuals will face zinc deficiency, and 122 million individuals will experience insufficient protein intake (Smith & Myers, 2018).

The United Nations' Food and Agriculture Organisation recommended the adoption of climate-smart agriculture as a potential solution to combat adverse climate conditions in the South Asia region (Food and Agriculture Organization [FAO], 2015). A Philippines report on climate-smart agriculture suggests that combining multilevel, multi-actor, and participatory on-farm and off-farm actions is more effective in advancing climate-smart agriculture than solely relying on technical measures (Chandra & McNamara, 2018).

Identifying climate-resilient innovative technologies for farmer adoption is crucial for maintaining or increasing agricultural productivity despite the challenges posed by climate change. In pursuit of this, experts from Australia, India, Bangladesh, and Afghanistan collaborated in an Asia-Pacific Network for Global Change Research (APN) project to share experiences and educate farmers in climate-smart practices.

Through this APN-funded project, we endeavoured to learn and implement climate-smart agriculture technologies, making them accessible to grassroots farmers in the South Asia region. We aimed to establish a strong network with regional and global organisations and scientific bodies dedicated to addressing climate change-based challenges and developing sustainable agricultural practices. This would facilitate rapid dissemination of newly developed approaches to relevant farmers within a short timeframe. In this paper, we present a concise overview of the impact of climate change on agriculture in South Asia and identify climate-resilient farming technologies and practices for India, Bangladesh, and Afghanistan, drawing from expert experiences in these countries.

Within this context, climate-smart agriculture emerges as an approach that offers guidance for transforming agricultural and food systems towards environmentally friendly and climate-resilient practices. Its objectives align with achieving the Sustainable Development Goals through three core principles: (a) increase agricultural productivity to enhance incomes, ensure food security, and promote overall development; (b) enhance adaptive capacity across multiple levels, from individual farms to national systems; (c) reduce greenhouse gas emissions and promote the establishment of carbon sinks to mitigate climate change effects.

2. METHODOLOGY

We adopted a quantitative approach that combines and compares the findings from various studies to summarise the projected outcomes presented in the literature (scientific papers and unpublished reports) and gauge consensus. The experts identified technologies and practices that enhance crop resilience to climate change while minimising environmental impacts by sharing their local experiences at two workshops organised under the APN Project at Amity University in February 2020 and June 2022. The identified technologies were predicated on reported resilience impacts and farmer experiences. Country-specific technologies and practices used in the past 15 years were also identified through literature searches (e.g., Scopus, Google Scholar, CABI) and combing websites of national institutions to enhance the analysis.

3. RESULTS AND DISCUSSION

Different regions are experiencing different climate change change-relate-related impact of agriculture viz crop loss due to floods and drought, exacerbated heat, increased aridity, and greater impoverishment, leading to a loss of agro-biodiversity, increasing the vulnerability of pastoralists and the vulnerability to insect pests and diseases and, thus, resulting in lower yields and more erratic harvests etc. Figure 1 presents the broad impacts of climate change on crop plants. Country specific impacts and intervention for climate-resilient agriculture practices are discussed in following sub-sections.

3.1. Impact of climate change on Australian agriculture

In Australia, temperatures above 34 °C from autumn to maturity have significantly impacted wheat grain quality and quantity (Asseng, Foster, & Turner, 2011). Western Australia has witnessed reduced average autumn and winter rainfall, increased

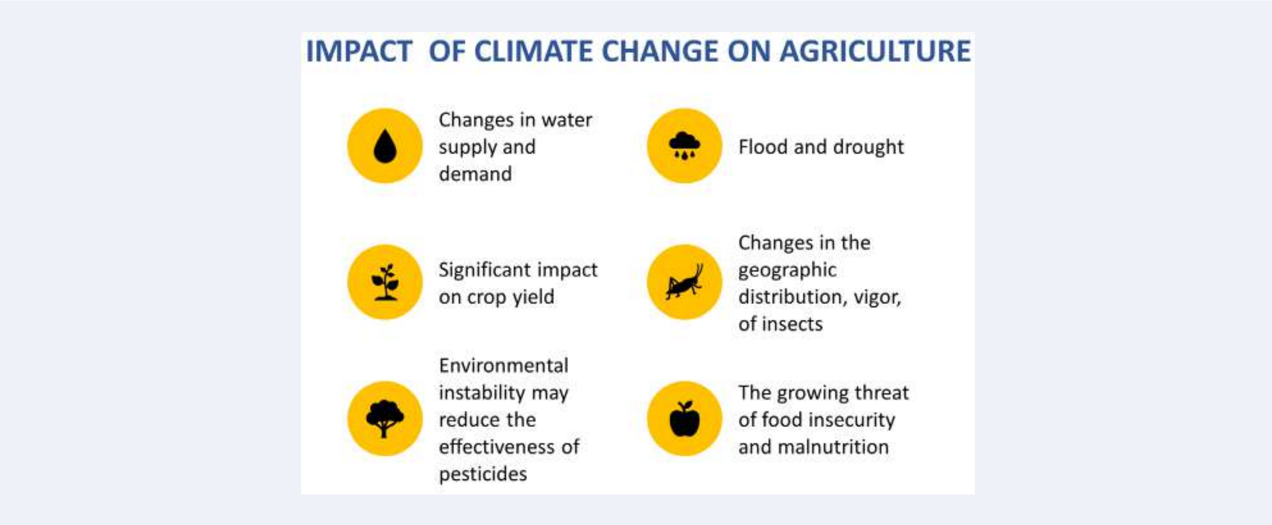

FIGURE 1. Impact of climate change on agriculture.

Period	CO_2 (PPM)	CH_4 (PPM)	N_2O (PPM)
Pre-independence (in 1750)	280	715	270
2019	411	1774	319
Increase (269 years)	@ 0.5%	@ 1%	@ 0.2%

TABLE 1. Percentage change CO_2, CH_4, and N_2O.

prolonged droughts, elevated average temperatures and evaporation rates, and increased intense tropical cyclones compared to pre-1975.

Elevated CO_2 levels favour wheat yields with temperature increases up to 2 °C but have detrimental impacts with further temperature increases (Bosco de Oliveira, 2019).

3.2. Impact of climate change on Indian agriculture

In India, a 1 °C increase in temperature will decrease annual wheat yields by 6 MT in Uttar Pradesh, Punjab, and Haryana states (Swaminathan & Kesavan, 2012). Projections indicate that the increasing temperatures could decrease the productivity of major crops by 10–40% by 2100. A 4 °C increase in developing nations could decrease their gross domestic product by 1–5%. Gas composition in India has increased by 0.5% for CO_2 and 1% for methane in the last 269 years, reflecting the pressing reality of climate change (Table 1).

While elevated CO_2 concentrations can increase crop yields, high fertiliser doses are detrimental to the environment. Elevated CO_2 levels in India decreased protein, zinc, and manganese contents by 3–17% and grain yields by 2.6–232% (Loladze, 2002).

India witnessed ten droughts between 1870 and 1939, while the subsequent next 70 years (1940–2010) saw a 1.5-fold increase (15 droughts) in drought frequency (India Meteorological Department [IMD], n.d.).

The landscape of Indian agriculture has also witnessed shifts in the prevalence of insect pests and diseases that affect major crops. Pests like the leaf miner in tomato and groundnut, early blight in groundnut, and lab blight in tomato have emerged as significant challenges. Tomato bed, phytoplasma, and leaf curl viruses in tomato are also prevalent.

3.3. Impact of climate change on Bangladesh agriculture

Bangladesh faces a multifaceted impact from the changing climate, including rising ocean levels, saltwater intrusion, increasing mean temperature, fluctuating precipitation, and intensified

Pre-production	• Soil health • Conservation agriculture • Crop planning – right crop selection • Crop calendar planning – change dates of sowing • Stress resistant variety • Dual land use
Production	• Water management • Pest management • Nutrient management • Agroforestry • Ag-met advisory
Post harvest	• Pre-processing • Packaging • Proper storage • Proper transportation • Value addition
Recycling	• Waste valorisation

TABLE 2. Building climate resilient crops.

winds (Bangladesh Bureau of Statistics, 2022). The country's south, southwest, and southeast regions are particularly susceptible to extreme hurricanes and related saltwater intrusion. Recent increases in the mean temperature in October have hampered the growth of high-yielding Aman rice. The Bangladesh Bureau of Statistics (2022) predicts decreased production of various crops by 2050, including rice (5.3%), jute (3%), oilseeds (6.3%), vegetables (5.7%), wheat (6.4%), and pulses (0.45%). The changing Bangladesh climate manifests with hotter summers, irregular monsoons, increased river flow and denudation during monsoons, and concentrated heavy rainfall, resulting in waterlogging and crop damage due to flash floods. In the last 40 years, saltwater intrusion into Bangladesh's flowing streams has notably intensified.

3.4. Impact of climate change on Afghanistan

Agriculture in Afghanistan is highly vulnerable to climate change. The ramifications are driven primarily by increasing temperatures, decreasing rainfall, water scarcity, early spring snow melts causing flooding, rapid depletion of urban underground water due to increased consumption, food and feed shortages, and rural–urban migration.

Afghanistan's geographical location heightens its vulnerability to climate change, particularly drought, with an average annual rainfall of about 250 mm. Rainfed agriculture's contribution to food security is declining due to low yields. Moreover, urban and industrial development are increasingly overtaking prime agricultural lands.

The FAO (2015) reports that the combined water storage capacity of Afghanistan's five river basins and groundwater system is about 55 billion m^3, and the current irrigated area is about 3.2 Mha. The Afghanistan Research and Evaluation [AREU] (2017) estimates this capacity is adequate for irrigating 7.7 Mha (at an average rate of 7,100 m^3/ha). Nonetheless, mismanagement of water resources impedes the irrigation potential.

3.5. Interventions for climate-resilient agriculture

Climate-resilient technologies and practices, stratified across different crop stages, can be classified broadly as pre-production, production, post-harvest, and recycling (Table 2). Various climate-

Flood hotspot	1. Flood tolerant crop cultivation 2. Cultivation of submergence-tolerate rice varieties 3. Transplanting rice seedlings thickly in flood-free land and after flood water recession 4. Transplanting in the main field and transferring old seedlings from established crop fields to land from where flood water recedes lately 5. Producing fruits and vegetables in the homestead areas 6. Adjusting cropping calendar for avoiding flood 7. Sorjan cultivation 8. Floating bed cultivation 9. Rice-duck system
Waterlogged hotspot	1. Vegetable cultivation in floating beds 2. Fruit and vegetables cultivation, following Kandi method 3. Cultivating aquatic vegetables
Salinity hotspot	1. Cultivation of salinity-tolerant rice varieties, salinity-resistant jute, peanut, sugarcane, kohlrabi, sweet potato, sesame, millet varieties, etc. 2. Water harvesting technology appropriate for farm water management 3. Practising rice-fish-vegetables cultivation in the same land 4. Crop through ditch and dyke, sorjan system and raised bed, floating beds to avoid saline water flooding
Heat stress	1. Heat-tolerant varieties
Flash flood hotspot	1. Adjusting cropping calendars for avoiding flash floods 2. Short duration early varieties
Drought hotspot	1. Fruits and vegetables production in the homestead area 2. Cultivation of low water-requiring crops like millets, maize, kaon, cowpea, etc. 3. Conservation of surface water by digging mini ponds at the corner of the crop fields 4. Using deep tillage and planting seedlings or sowing seeds at the deeper layer of the soil 5. Using mulch in fruits and vegetables cultivation 6. Relay cropping 7. Seed priming 8. Rain water harvesting 9. Watershed development

TABLE 3. Climate-smart practices for different hotspots.

resilient technologies and approaches are being trialled, with some adopted on a limited scale, such as zero tillage, raised bed planting, direct-seeded rice, relay cropping, floating bed cultivation, Sorjan, stress-tolerant varieties, crop residue management, crop diversification (e.g., horticulture, beekeeping, mushroom cultivation), site-specific nutrient management, laser levelling, micro-irrigation, seed/fodder banks, and Information Communication TechnologyICT-based weather advisories (Kakraliya et al., 2021; World Bank Group, 2015). The specifics of these strategies vary across different climate change hotspots, as summarised in Table 3. Importantly, these technologies must be documented and validated at the farm level before scaling to broader geographic areas and benefiting more farmers.

3.5.1. Stress-tolerant/resistant varieties

The prevailing practice of cultivating local or high-yielding varieties leaves farmers susceptible to climate change shocks, often leading to poor productivity or even complete failure during extreme climatic events. Various national and international research institutes have developed stress-tolerant varieties for South Asian countries (see list in Table 4), which need to be validated and extended to vulnerable regions, enabling farmers to achieve reasonably good yields in the face of climate-induced stresses.

3.5.2. Grafting plants to build stress tolerance

Climate change has exacerbated abiotic stresses in vegetable production, posing threats from flooding, drought, and extreme temperatures. Vegetable grafting has emerged as an eco-friendly, expedient, and efficient technique for producing climate-resilient plants that can withstand these abiotic pressures (Singh, Sethi, Kaushik, & Fulford, 2020).

3.5.3. Climate-resilient cultivation practices

Replacing existing crops with new climate-resilient alternatives is an emerging strategy for combating climate change. For example, in wind-prone areas of India, some farmers grow millets (e.g., pearl millet) and sorghum. They also integrate leguminous crops to enhance soil nitrogen and preserve fallow land (Satapathy, Porsche, Kunkel, Manasfi, & Kalisch, 2011). Shifting the timelines for wheat sowing and rice transplantation to 15 days earlier than conventional practices could mitigate yield losses by more than 4% (Jat et al., 2014).

3.5.4. Soil health management

The vitality of soil health in evolving environments is paramount to crop production. Notably, soil health extends beyond agriculture, with its status as an indicator of human well-being (Lal, 2022). Strategies to enhance soil health include building soil carbon, controlling soil losses due to erosion, and increasing soil water-holding capacity. Embracing practices like conservation agriculture or zero tillage, soil mulching, crop rotations involving legumes, soil microbiome management, soil nutrient management, soil-borne pest and disease management, soil moisture management, agroforestry, and integrated farming systems are pivotal in enhancing soil health and building crop resilience to climate change.

An Australian study reported that annual wheat production could increase by 1.1 to 1.2 billion AUD by improving soil conditions (Linehan, Thorpe, Andrews, & Beaini, 2012). As the largest carbon pool on Earth, soil plays a crucial role in global carbon and nutrient cycling. Enhancing soil carbon storage and sequestration is essential for improving soil quality, fortifying plant nutrition reservoirs, and increasing crop productivity amidst ongoing and upcoming climate change impacts. Furthermore, soil carbon sequestration can help mitigate adverse climatic effects, including increased surface and soil temperatures, elevated CO_2 levels, and fluctuating precipitation patterns.

The most effective strategy for accumulating and sequestering soil organic carbon lies in prudent management practices that stimulate soil carbon inputs (e.g., plant residues) rather than outputs (e.g., decomposition and leaching). Achieving a balanced and integrated use of fertilisers (organic and inorganic) presents an alternative approach to enhancing soil carbon sequestration, preserving plant nutrients, and increasing productivity.

Below are some instrumental farming practices for managing soil health.

Conservation agriculture: Significance of zero tillage

Zero tillage is becoming a cornerstone of conservation agriculture and climate-smart farming (Figure 2). Two main principles underpin zero tillage:

1. Minimum soil disturbance
2. Stubble retention in fields

Zero tillage offers numerous advantages, such as:

> Enhanced soil structure
> Improved nutrient recycling
> Increased crop yields
> Time-saving attributes

Climate Hazard	Crop	Variety	Country
Salinity and Heat	Potato	BARI Alo-22	Bangladesh
	Sweet Potato	BARI Mishti Alo-8, BARI Mishti Alo 9	
	Pulses	BARI Mug-2,3,4,5,6, BM-01, BM-08, BARI Falon-1, BARI Sola-9	
	Oil Crops	BARI Sharisha-14, BARI Sharisha 15, BARI Chinabadam-9, BINA Chinabadam-1, BINA *China badam*-2, BARI Soyabean-6, BARI Til-2,3,4	
	Sugarcane	ISWARDI-40	
	Jute	HC-2, HC 95, CVL 1	
	Rice	Kala Rata 1-24, Nona Bokra, Bhura Rata, SR 26B, Chin. 13, and 349 Jhona, CSR46, CSR49, CSR52, CSR56, CSR60 and CSR76	India[1]
	Sorghum	Raj 27, Raj 30, Raj 4, JS-2002, CSV-15, HC171	
	Barley	Ratna, Melusine, RD 2794, ND B 1173, RD 2552, NDB 1173, NarendraBarley-1 (UP), NarendraBarley-3 (UP)	
	Oats	DZ-Cr-37, JHO-815, JHO-802, JHO-816 and UPO-201	
	Wheat	KRL 1-4, KRL 19, KRL 210, KRL 213	
		Jauhar, Gold, AAS, Ujala, Galaxy, Pasban, Uqab, Sehr	Pakistan
		BARI Gom-26	Bangladesh
	Mustard	CS 52, CS 54 and CS 56	India
Drought-Tolerant	Rice	Sahabhagi Dhan, Vandana, Anjali, Satyabhama, DRR Dhan 42 (IR64 Drt 1), DRR Dhan 43, Birsa Vikas Dhan 203, Birsa Vikas Dhan 111, Rajendra Bhagwati, Jaldi Dhan 6	India
	Wheat	PBW 527, HI 1531, HI 8627, HD 2888, HPW 349, PBW 644, WH 1080, HD 3043, PBW 396, K 9465, K 8962, MP 3288, HD 4672, NIAW 1415, HD 2987	India
		Dharabi, Ihsan, FSD-08, Khirman developed in Pakistan	Pakistan
		Lalmi-2, Lalmi-1, Lalmi-3, Lalmi-4, Lalmi-15, PBW-154, Herat-99, Dehdadi-13, Zarin-13, Mirdad -19, Sharq-19, Jawahir-19, Lalmi-17, Dima-17, etc.	Afghanistan

Continued on next page

TABLE 4. Major stress-tolerant crop varieties in South Asia.

TABLE 4. *Continued.*

Climate Hazard	Crop	Variety	Country
	Maize	Pusa Hybrid Makka 1, HM 4, Pusa Hybrid Makka 5, DHM 121, Buland, MIMH1 and MIMH2, Zodrus-10, Sharq-8, Shamal-8, Maghzi-8	India
	Sorghum	CSH 19 R, CSV 18, CSH 15R	
	Pearl Millet	HHB 67 improved, GHB 757, GHB 719, Dhanshakti, HHB 234, Mandor Bajra Composite 2, HHB-226, RHB-177, Pusa Composite 443	
	Barley	RD 2660, K603	
	Chickpea	Vijay, Vikas, RSG 14, RSG 888, ICCV 10, Pusa 362, Vijay	
	Groundnut	Ajaya, Girnar 1, TAG-24, Kadiri 6, ICGV 91114	
	Soybean	NRC 7, JS 95-60	
	Sugarcane	Co 98014 (Karan-1), Co 0239, Co 0118, Co 0238, Co 06927, Co 0403, Co 86032	
	Cotton	HD 324, CICR-1, Raj DH 7, Jawahar Tapti, Pratap Kapi, Suraj, Surabhi, Veena, AK 235,	
	Jute	JBO 1 (Sudhangsu), JRO 204, JRO 524, JRC 80	
	Pulses	Bina masur-10	Afghanistan
	Chickpea	Flib-95, Flip-92, Flip-93, Rabat-13, Baghlan-13	
	Lentil	Koosk-1	
	Pistachio	Pistacia vera, UCB1,	
	Watermelon		
	Muskmelon		
Flood-Tolerant	Rice	Swarna Sub-1, Sambha Mahsuri Sub-1, Varshadhan, Gayatri, Sarla, Pooja, Prateeksha, Durga, JalaMani, CR Dhan 505, CR Dhan 502, Jalnidhi, Neerja, Jaladhi 1, Jaladhi 2, Hemavathi	India
	Maize	PMH-2, TA-5084 HM-5, Seed Tech-2324, HM-10, PMH-2	
	Sugarcane	Co 98014 (Karan-1), Co 0239, Co 0118, Co 0238, Co 0233, Co 05009	
	Jute	JRO 7835, JRO 878, JRC 321, JRC 7447, JRC 532, JRC-517, Bidhan Pat-1	

Continued on next page

TABLE 4. *Continued.*

Climate Hazard	Crop	Variety	Country
Heat	Wheat	Jauhar, Gold, AAS, Ujala, Galaxy	Pakistan
		BARI Gom-26	Bangladesh
		K1114, NIAW1994, DBW107, A-9-30-1, HD4502 (MALVIKA), GW2, GW 173, AKW 1071 (PURNA), PBN 51 (PARBHANI 51), K 9644 (ATAL), K 7903 (HALNA), WH 711, GW 322, RAJ 3777, MP 4010, K 9423 (UNNAT HALNA), UP 2565, MP 1142, DDK 1029 (dicoccum), MP 1202, RAJ 4079, K0402, DBW 107, DBW 173	India
		Lalmi-2, Lalmi-1, Lalmi-3, PBW-154, Herat-99, Dehdadi-13, Zarin-13, Mirdad-19, Sharq-19, etc.	Afghanistan
	Rice	NERICA-L-44	India
	Potato	KUFRI LIMA	
	Maize	YH-1898, KJ Surabhi, FH-793 ND-6339, NK-64017	
		BHM14, BHM15	Bangladesh
		RCRMH2, Lall-454, Zodrus-10, Sharq-8, Shamal-8, hybrid-1, hybrid-2, hybrid-3	
		Rampur Hybrid-8, Rampur Hybrid-10	
Cold and frost	Maize	HQPM-1, HHM-1, and HM-1	

[1] Source: https://icar-nrri.in/released-varieties/, www.nicra-icar.in/nicrarevised/images/publications/Climate Resilent Crop_All Pages_12-03-19_low.pdf

> Feasibility for early sowing
> Reduced soil erosion
> Reduced pollution arising from stubble burning or soil erosion
> Improved soil water-holding capacity
> Provision for grazing, if required

Data from long-term (25 years) zero-tillage experiments conducted in Australia, Mexico, Brazil, Spain, the UK, and the USA have revealed incremental yield with zero tillage over time. In Western Australia, the adoption rate of zero tillage among farmers stands at a remarkable 100% (Ward & Siddique, 2015). In India, farmers often burn crop residues for disease and weed control. However, zero-tillage systems are promoted to minimise stubble burning, and farmers can hire zero-tillage seeders for sowing. Various zero-tillage seeders are available across different countries. Recently, the Indian Agriculture Research Institute developed technology involving a consortium of microorganisms for *in-situ* stubble decomposition (Maheshwari, Mahapatra, Bharti, & Singh, 2020).

Mulching

Mulching materials (e.g., straw, gravel sand, plastics) are another effective tool for soil management, weed management, and soil water conservation.

Intercropping and relay cropping

Intercropping, the practice of cultivating multiple crops simultaneously in a field (Figure 3), offers resource optimisation and enhanced land

FIGURE 2. Conservation agriculture in Kabul, Afghanistan.

FIGURE 3. Intercropping demonstration.

productivity, increasing system productivity. For example, system productivity increased by 19% under soybean and pigeon pea (4:2 ratio), 25% under pearl millet and pigeon pea (3:3), 25% under Bt cotton and green gram (1:1), 14% under Bt cotton and black gram (1:1), and 24% under Bt cotton and

FIGURE 4. Leaf colour chart.

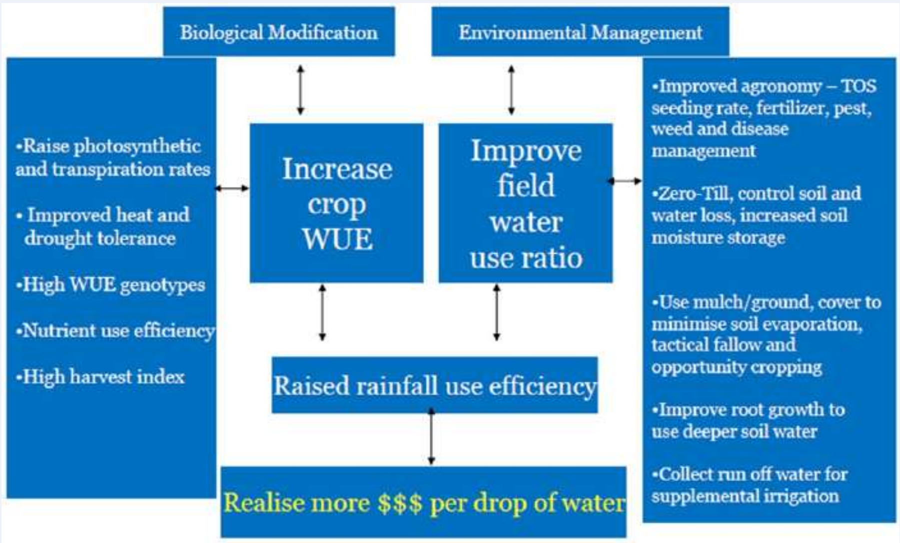

FIGURE 5. Water use efficiency.

pigeon pea (5:1) (Prasad et al., 2014). As another climate-resilient crop diversification, tree-based farming systems also benefit farmers due to the high value of horticultural products.

3.5.5. *Direct-seeded rice*

Direct-seeded rice (DSR) technology conserves water resources by up to 50% as it does not require flooding, with pregerminated rice seeds sown in puddled soil. This technique also reduces the carbon footprint of rice by reducing methane emissions. Irrigation is applied during crucial crop growth stages, such as crop emergence (first 7–15 days after sowing). DSR requires efficient weed management to prevent yield losses.

3.5.6. *Leaf-colour-based nitrogen application*

IRRI developed a leaf colour chart (LLC) for nitrogen application in rice (Figure 4; MSME MART, n.d.). Reports indicate nitrogen savings of up to 40% (Satpute, Surje, & Maity, 2014).

3.5.7. *Water management*

Water availability is a critical determinant of crop yield, with efficient water use particularly important in changing environments. For example, the water use efficiency of wheat is impacted by delayed sowing, weed proliferation, waterlogging, and nematode infection (Figure 5; French & Shultz, 1984 cited in Sadras 2020).

FIGURE 6. Floating bed cultivation.

Integrated water management, encompassing various water-saving practices and technologies, can save between 22% and 84% of water. Practices such as the system of rice intensification (SRI), DSR, relay cropping, use of waste and marginal water, laser levelling, mulching, and conservation agriculture have demonstrated water savings ranging from 22% to 43% in various crops (Jat et al., 2014). Adopting micro-irrigation systems, such as drip and sprinkler, can yield additional savings of up to 84% (Kumar, 2016).

Several water management practices conducive to adapting rice cultivation to climate change have been identified (Aryal et al., 2020):

1. Alternate wetting and drying enhances water use efficiency by 30%.
2. DSR improves water use efficiency and water stress resilience.
3. Micro-irrigation system (sprinkler and drip) saves up to 90% water.
4. Laser land levelling contributes up to 30% water savings.

Sorjan system

The Sorjan system, originating from Indonesia, features very high raised beds alternated with deep sinks, suitable for water flooding and dry systems. In the Philippines, a 1 ha Sorjan farm generated an additional Php 75,000 (1329.75 USD) in 12 months from diverse vegetables like okra, eggplant, string beans, cucumber, and tomato (Philippines Rice Research Institute [PRRI], 2017). This farming approach fosters sustainable earnings, with rice cultivation an integral component.

Floating bed cultivation

Floating bed cultivation is particularly advantageous for areas prone to extended periods of submersion (UN Climate Technology Centre and Network [UNCTCN], n.d.), as observed widely in Bangladesh. The floating beds are constructed from various substrates, such as crop residues, water hyacinth, and straw, secured with ropes atop a bamboo base (Figure 6). After harvest, the floating beds can be composted and reintroduced into the same field as a nutrient source.

Relay cropping

Relay cropping is a multiple cropping system where a subsequent crop is sown into a standing crop before it is harvested. This method addresses challenges related to resource utilisation, sowing time, fertiliser application, and soil degradation (Figure 7). Relay cropping is a sophisticated toolkit

FIGURE 7. Relay cropping.

for enhancing soil quality, increasing net returns, increasing the land equivalent ratio, and managing weed and pest infestations.

For instance, corn (grown for seed) and soybean are suitable for relay cropping as seed corn is harvested in mid-September, leaving moderate residues. Annual winter crops, such as winter wheat, could be added to the seed corn–soybean rotation to use solar energy and heat device accessible during corn harvest in September and soybean planting in May. However, winter wheat is not harvested till mid-July, much later than the prime time for soybean planting. Relay cropping in Nebraska requires middle-pivot irrigation, glyphosate-tolerant soybean, and a method of seeding soybeans into wheat at heading (approximately 30 days before wheat harvest).

The advantages of relay cropping include:

1. Decreased nitrate leaching
2. Increased carbon sequestration
3. Increased farmer income

Some examples:

1. For small grain crops as the first planting and legumes as the second, legumes can be seeded into small grain crops well before it is harvested.
2. For rice as the first planting and legumes as the second, seeding of the legume crop can be done by aerial broadcast before harvesting of rice crop so as legume crop is established and utilises residual mixture to germinate and establish before the rice crop is harvested.
3. For maize, sorghum, or millet as the first planting and soybean or legumes as the second, the second crop can be banded between rows of the first crop well before its harvesting.

3.5.8. *Protected cultivation*

Protected or greenhouse cultivation represents an advanced approach to growing crops in an optimal environment, shielded from abiotic (e.g., temperature, rain, wind, humidity) and biotic (plant pests and diseases) stressors. This method enables farmers to grow crops on demand, irrespective of the traditional growing seasons (Figures 8–11), resulting in higher yields using 90% less water and fewer nutrients.

Various types of structures are used in protected cultivation:

1. Climate-controlled greenhouses are sizeable structures incorporating transparent or translucent material, offering an ideal environment for crops to thrive under optimal conditions. Suitable for high-value crops such as vegetables and flowers.
2. Zero-energy, naturally ventilated greenhouses are simple yet effective blanketed structures

FIGURE 8. Protected cultivation.

FIGURE 9. HITECH Nursery.

with no heating or cooling devices. They rely on natural ventilation through pest-proof netting, mainly on the top and the sides. These medium-value greenhouses are supplemented with manually operated natural air flow devices. Suitable for growing cucumber, tomato, and capsicum for 8–9 months each year.

3. Shade net houses are used during critical summer months (May–September), reducing the sunlight intensity by 25–75% to decrease radiation and temperature to a certain threshold. Suited to areas where night temperatures do not drop below 15–18 °C and daytime temperatures are generally 28–30 °C.
4. Insect-proof net houses are reasonably priced, temporary or lasting structures clad with 40–50 µm mesh UV-stabilised insect-proof nylon or rust-proof metal net These structures prevent the access of dangerous insect-pest and vectors of illnesses, reducing the need for pesticides in fresh vegetable cultivation.

FIGURE 10. Low raised poly tunnel.

FIGURE 11. Climate smart plant growth monitoring system.

5. Walk-in tunnels are temporary constructs crafted from materials such as galvanized iron (GI) pipes, plastic pipes, or semi-spherical bent bamboo clad with UV-stabilised (150–200 μm) polyethylene. The central top is retained to 6–6.5 ft. and 4.0–4.5 ft wide. The tunnel length varies according to need. These tunnels are designed to be easily assembled and disassembled using nuts and bolts (no welding required). They can bear trellis loads of 15–25 kg/m^2.

3.5.9. *Zero-energy cooling chambers*

Zero-energy cooling chambers (ZECC) work on evaporative cooling principles, i.e., temperatures decrease due to liquid evaporation. Each chamber is an aboveground double-walled brick structure with a 7.5 cm wide cavity packed with river sand. The top of the structure is covered with gunny fabric filled with straw in a bamboo structure. The cool chamber is soaked with water initially and thereafter sprinkled with water in the morning and evening to preserve the specified temperature and humidity (Figures 12 and 13). These chambers can hold excessive humidity (95%) throughout the year and even reduce the chamber temperature during summer. ZECCs are best used for short-term produce storage and are particularly beneficial for marginal farmers needing short-term storage solutions (Kitinoja, Saran, Roy, & Kader, 2011; Mishra, Jha, & Ojha, 2020).

3.5.10. *Broad bed and furrow*

In the broad bed and furrow (BBF) system, a machine is used to create 90 cm wide beds and 45 cm wide furrows, maintaining a 30 cm row spacing (Figure 14). BBFs conserve rainwater *in-situ* in

FIGURE 12. Zero energy cool chamber (ZECC), constructed by Amity University at Kabul University.

FIGURE 13. Turning colour tomatoes can be kept for 29 days in ZECC, Kabul University.

furrows, allowing for excess water drainage, proper aeration, and weed control.

3.5.11. Crop pest and disease management

Crop pest and disease management are critical as many pests and diseases have shifted their geographical boundaries due to the changes in temperature and humidity, creating favourable conditions for their migration. Crop pests and diseases are projected to extend to higher altitudes. Projected global yield losses for three staple grain crops (rice, wheat, and maize) due to insect pests are 10–25%

FIGURE 14. Wheat raised bed irrigation system in Kabul, Afghanistan.

per 1 °C increase in global mean surface warming, with such losses more acute in temperate regions (Deutsch et al., 2018). Governments in South Asian countries focus on integrated pest management strategies and farmer training to handle the growing emergence of pests and diseases. Insect and disease forecasting models have been developed for their timely management. Innovative techniques, such as pheromones, push–pull, microbial seed inoculants, and resistant varieties, also aid in pest and disease control.

3.5.12. *Climate-smart future foods*

Given the impact of climate change on traditional staple crops like wheat and rice, scientists have started advocating for the cultivation of climate-resilient local grains such as millets, which can withstand most abiotic stresses and are nutritionally dense (Reay, 2019). An FAO study identified numerous Future Smart Foods (FSF) for South and South-East Asia, prioritising 39 FSFs such as sorghum, pearl millet, elephant foot yam, roselle, drumstick, Amla, lentil, jackfruit, and fenugreek (Li & Siddique, 2018).

3.6. Climate-resilient actions in India, Bangladesh, and Afghanistan

Climate-resilient practices identified for various hotspots in South Asian countries include:

1. Flood-prone areas:
   - Tomato seedling grafting on the rootstock of brinjal for flood and wind tolerance
   - Aged seedlings
   - Dense transplantation of seedlings in flood-free areas and later transferred to flooded areas after water levels recede
   - Forest nuts and pistachio trees in hilly flood-prone areas
   - Fast-growing crops, such as vegetables, millets, and maize, to avoid floods
   - Flood-resistant rice varieties
2. Waterlogged areas:
   - Float bed cultivation
   - Aquatic vegetables
   - Flood-tolerant varieties
3. Drought-prone areas:
   - Harvest rainwater using various techniques (Figure 15)
   - Sow early or late to escape drought
   - Use soil moisture by sowing seeds at depth

FIGURE 15. Rainwater harvesting using eyebrow pitting in Afghanistan.

  - Soil mulches for soil moisture conservation and to avoid weeds
  - Drought-tolerant/resistant varieties
4. Saline-prone areas:
  - Saline-tolerant crop varieties
  - Sorjan systems such as dykes/raised beds
  - Vegetables around prawn Ghers or ponds
  - Rice–duck or rice–fish–vegetable cultivation to enhance income

3.7. Initiatives in India

The Indian Government is taking proactive steps to showcase climate-resilient practices and technologies in 151 clusters located within districts highly vulnerable to adverse conditions like droughts, heatwaves, floods, salinity, high temperatures, cold waves, erratic rainfall, and cyclones.

Numerous climate-smart practices are being promoted in India:

1. Climate-resilient varieties
2. Broad bed furrow for sowing vegetables
3. Intercropping with varying row ratios
4. Conservation agriculture
5. Soil health management
6. Identifying climate-smart future foods
7. IT-based mobile app PESTPREDICT-EMS, an Android-based app developed by the Indian Government to help farmers identify pests
8. Seaweed farming, multitrophic aquaculture, and recirculatory aquaculture to combat climate change related to livelihood security issues
9. District agriculture contingency plans developed with local departments to prepare farmers to face climatic risks more efficiently

4. CONCLUSION

The undeniable reality of climate change compels us to act, using existing solutions and developing new options for the well-being of future generations. While drawing insights from a specific group of experts representing certain countries, this study acknowledges the potential exclusion of certain technologies due to its scope.

Key action points include:

1. **Forecasting extreme events**: Anticipating and preparing for extreme climatic events becomes crucial for the future, necessitating proactive strategies.
2. **Balancing yield and environmental impact**: Striking a balance between increased yields and reduced ecological footprint becomes pivotal for

preserving soil health, environmental sustainability, and socio-economic well-being.

3. **Crop rotation for soil health**: Implementing cereal–legume crop rotations will enhance soil health and mitigate the environmental impact of fertilisers.
4. **Technology transfer and farmer awareness**: Facilitate technology transfer through practical demonstrations, field visits, field training, and field days. Improve farmer awareness of the cost-benefit analysis to help drive successful adoption.
5. **Enhancing zero-tillage systems**: Successful zero-tillage systems must emphasise cultural practices, including proper sanitation (e.g., cleaning equipment to remove old seeds and weed seeds), accurate seeding depth, starter fertilisers, high-quality seeds, and seedling vigour to avoid crop competition.

By implementing climate-smart agriculture, enhancing food security becomes feasible. This involves increasing crop productivity while minimising the risk of crop failure, thereby mitigating the adverse impacts of climate change on agriculture.

As the study scope is limited, evaluating the applicability of the suggested technologies/practices across broader geographical contexts is necessary. The effectiveness of the examined technologies may also be influenced by climatic variations, underscoring the importance of local testing before wider adoption.

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Original article

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Future changes in mean and extreme precipitation over Peninsular Malaysia using CORDEX-SEA 5 km simulations

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ABSTRACT

The Coordinated Regional Climate Downscaling Experiment (CORDEX) Southeast Asia further downscaled three of its 25 km products, i.e. EC-Earth, HadGEM2-ES and MPI-ESM-MR forced regional climate simulations to a higher resolution of 5 km. A newer RegCM4.7 model was used for this exercise. For the simulations over Peninsular Malaysia, analysis shows that these simulations have much smaller precipitation biases. They can correctly predict the annual precipitation cycle over the east coast of Peninsular Malaysia compared to the 25 km simulations. The ensemble of these 5 km simulations indicates that Peninsular Malaysia is expected to experience a decrease in its seasonal mean precipitation, regardless of the RCP 4.5 or RCP 8.5 scenarios. Aside from the reduction of seasonal mean precipitation, consecutive dry and wet days are expected to increase and decrease, respectively. This indicates that Peninsular Malaysia will experience a long dry spell in the future. At the same time, it is suggested that Peninsular Malaysia will have fewer days with very heavy precipitation. Overall, the findings from this study suggest that the 5 km downscaled climate simulations improve significantly over 25 km and that the Peninsular Malaysia region can expect a drier future climate and extremes.

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KEYWORDS

CORDEX-SEA, Southeast Asia, precipitation, downscaling, CMIP5, Peninsular Malaysia

HIGHLIGHTS

- High-resolution climate data is made available for key areas in Southeast Asia.
- Further downscaling improves simulated precipitation over Peninsular Malaysia.
- Peninsular Malaysia is projected to have a drier future climate.

1. INTRODUCTION

The CORDEX (Coordinated Regional Climate Downscaling Experiment) programme under the World Climate Research Program (WRCP) plays a crucial role in advancing our understanding of climate change impacts at regional scales (Giorgi, 2019). Aiming to provide high-resolution multi-model climate projections and fulfil climate model data requirements in Southeast Asia (SEA), CORDEX-SEA was established (Tangang et al., 2022). In the first phase implementation of CORDEX-SEA, 11 General Circulation Models (GCM) from the Coupled Model Intercomparison Project phase 5 (CMIP5) were successfully downscaled using seven different regional climate models (RCMs) at a spatial resolution of 25 km (Tangang et al., 2020). The CORDEX-SEA phase 1 product is essential for policymakers, planners and scientists to make informed decisions and develop effective adaptation strategies to mitigate the effects of climate change on local communities. The CORDEX-SEA phase 1 product has contributed to many research articles, national reports and even the most recent Intergovernmental Panel on Climate Change (IPCC) sixth assessment report (AR6).

The CORDEX-SEA phase 2 programme is intended to extend the achievement of phase 1 by further downscaling the 25 km output to a finer 5 km resolution. This enabled the modelling of fine-scale climate features such as extreme events and may improve understanding of the complex interactions between climate, ecosystems and human systems (Hewitson & Crane, 2006). However, the resources needed for such a feat are unbearably high. Thus, the CORDEX-SEA phase 2 5 km downscaling exercise only focussed on four key climate change vulnerable areas in Southeast Asia (Figure 1), namely the Lower Mekong River basin (A) (Hoang-Cong et al., 2022), Mindanao Island of the Philippines (B), Peninsular Malaysia (C) and Java Island of Indonesia (D).

The 5 km downscaling conducted by the CORDEX-SEA phase 2 programme over Peninsular Malaysia enables a proper examination of the future changes in extreme precipitation in this area. Located in Southeast Asia, Peninsular Malaysia houses the capital of Malaysia, i.e. Kuala Lumpur. It also serves as a crucial gateway to the Southeast Asia region and offers easy access to international trade routes. It's diverse geography provides crucial ecological services that support various industries, such as tourism and agriculture. There is evidence of increasing trends in extreme precipitation over Asia during the last few decades (Choi et al., 2009; Donat et al., 2013; Supari, Tangang, Juneng, & Aldrian, 2017), and this trend is expected to continue as the climate continues to warm. Over Peninsular Malaysia, observational evidence indicates that rainfall extremes have also intensified in recent decades, particularly in the frequency and intensity of heavy rainfall events (Syafrina, Zalina, & Juneng, 2015). Such intensification of rainfall extremes has implications for various socio economic sectors in the country, including agriculture, water resources and infrastructure, and can lead to flooding and landslides.

Having reliable information on future changes in extreme precipitation will be imperative for local policymakers and stakeholders to draw up strate-

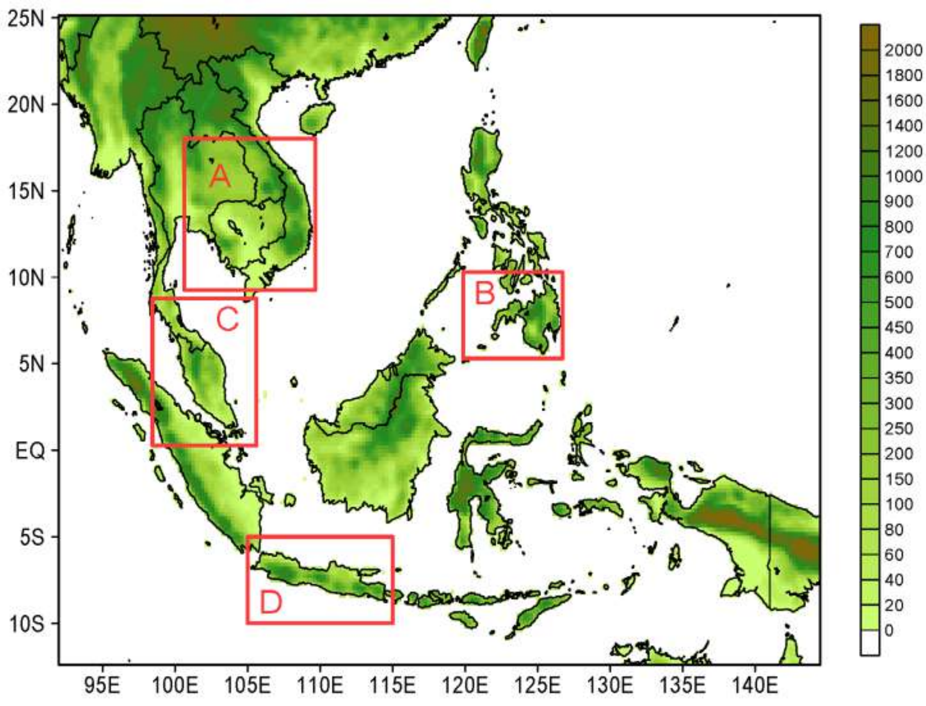

FIGURE 1. The CORDEX-SEA Phase 1 Domain. Red boxes indicate key vulnerable areas where 5 km downscaling simulations were conducted in phase 2 of the CORDEX-SEA programme. A: Lower Mekong River basin, B: Mindanao Island, C: Peninsular Malaysia, D: Java Island.

gies for adapting and mitigating the potential negative impacts of such a change. Thus, capitalising on the very high-resolution downscaling simulation carried out by the CORDEX-SEA phase 2 programme over Peninsular Malaysia, this study aims to examine the future changes in selected extreme rainfall indices over this area under the IPCC Representative Concentration Pathways Scenarios (RCP) 4.5 and 8.5.

2. METHODOLOGY

2.1. CORDEX-SEA phase 2 simulations

The 5 km × 5 km downscaling simulations over Peninsular Malaysia conducted under the CORDEX-SEA phase 2 programme (Figure 1) were carried out by downscaling the three best performing 25 km × 25 km RegCM4 downscaled simulations from the first phase of SEACLID/CORDEX-SEA programme (Tangang et al., 2020). These simulations are the runs driven by EC-Earth, HadGEM2-ES and MPI-ESM-MR.

The regional climate model (RCM) used in the 5 km downscaling simulation is the newer non-hydrostatic RegCM4.7 (RegCM4.7-NH) (Coppola et al., 2021) developed by International Centre for Theoretical Physics (ICTP). The conducted 5 km downscaling simulations cover the historical period of 1971–2005 and three future time slices, i.e., the early (EC; 2012–2039), mid (MC; 2041–2069) and late 21st century (LC; 2071–2099) considering both RCP 4.5 and RCP 8.5 future scenarios (Table 1). Initial and boundary conditions (ICBC) for the 5 km simulations were interpolated from the 6-hourly output of the first phase CORDEX-SEA 25 km simulations.

The RCM and the model physical settings used in the CORDEX SEA phase 2 simulations and their forcing 25 km CORDEX-SEA phase 1 simulation are summarised in Table 2.

2.2. Model performance and projected future precipitation extreme analysis conducted

The model performances were first analysed by comparing the simulated precipitation climatology

GCM	RCP	Simulated Period	Abbreviation
EC-Earth (EC-Earth consortium)	4.5 & 8.5	Hist: 1971–2005 EC: 2012–2039 MC: 2041–2069 LC: 2071–2099	ECE
HadGEM2-ES (Hadley Centre, UK)			Had
MPI-ESM-MR (MPI-M, Germany)			MPI

TABLE 1. List of GCMs and RCMs, including RCPs and periods of the CORDEX-SEA Phase 2 5 km simulations.

	Phase 2 (Malaysia)	Phase 1
RCM used	**RegCM4.7-NH**	**RegCM4.3**
Model dynamic core	**MM5 Non-hydrostatical core**	**MM4 hydrostatical core**
Horizontal resolution	**5 km × 5 km**	**25 km × 25 km**
Number of vertical levels	18	18
Domain simulated	**Peninsular Malaysia**	**Southeast Asia**
Cumulus parameterisation scheme	**MIT-Emanuel** (Emanuel & Živković-Rothman, 1999) **over land and Kain-Fritsch** (Kain, 2004; Kain & Fritsch, 1990) **over ocean**	**MIT-Emanuel**
Boundary layer scheme	Holtslag (Holtslag, De Bruijn, & Pan, 1990)	Holtslag
Moisture scheme	SUBEX (Pal et al., 2007)	SUBEX
Ocean flux scheme	Zeng (Zeng, Zhao, & Dickinson, 1998)	Zeng
Cloud fraction algorithm	SUBEX	SUBEX
Radiation scheme	CCSM (Kiehl et al., 1996)	CCSM
Land surface scheme	**CLM4.5** (Oleson et al., 2013)	**BATS1e** (Dickinson, 1993)

TABLE 2. Comparison between the model settings of CORDEX-SEA phase 2 and phase 1 simulations. Bold wordings indicate different settings were used.

to that of reference data to quantify the model's biases. In this assessment, the 25 km simulations will also be included to visualise the improvement the 5 km simulations would have over their respective simulation forcings. Aside from model biases, the annual precipitation cycle simulated by the 5 km simulations, the 25 km forcing simulations and observed by reference data will also be compared. The reference data of choice in this study is that of Climate Hazards Group InfraRed Precipitation with station data 2.0 at 5 km resolution (CHIRPS05) (Funk et al., 2015), which has been shown to perform reasonably well over the study area (Ayoub, Tangang, Juneng, Tan, & Chung, 2020). Another reason CHIRPS05 data was chosen as the preferred reference data is that its 5 km resolution matches that of the CORDEX-SEA phase 2 simulations.

Analysis of future projections of precipitation extremes over Peninsular Malaysia was then carried out by evaluating future changes for near, middle and end of the 21st century for each of the emission scenarios using an ensemble created from all the 5 km simulations following the approach used by Supari et al. (2020) and Tangang et al. (2020). Under

Indices	Description
CDD	The maximum length of dry spell, maximum number of consecutive days with precipitation <1 mm in a season
CWD	Maximum length of wet spell, maximum number of consecutive days with precipitation ≥1 mm in a season
R20mm	Count of days when precipitation ≥20 mm in a season
RX1day	Maximum consecutive 1-day precipitation in a season

TABLE 3. List of ETCCDI extreme indices of precipitation considered in this project.

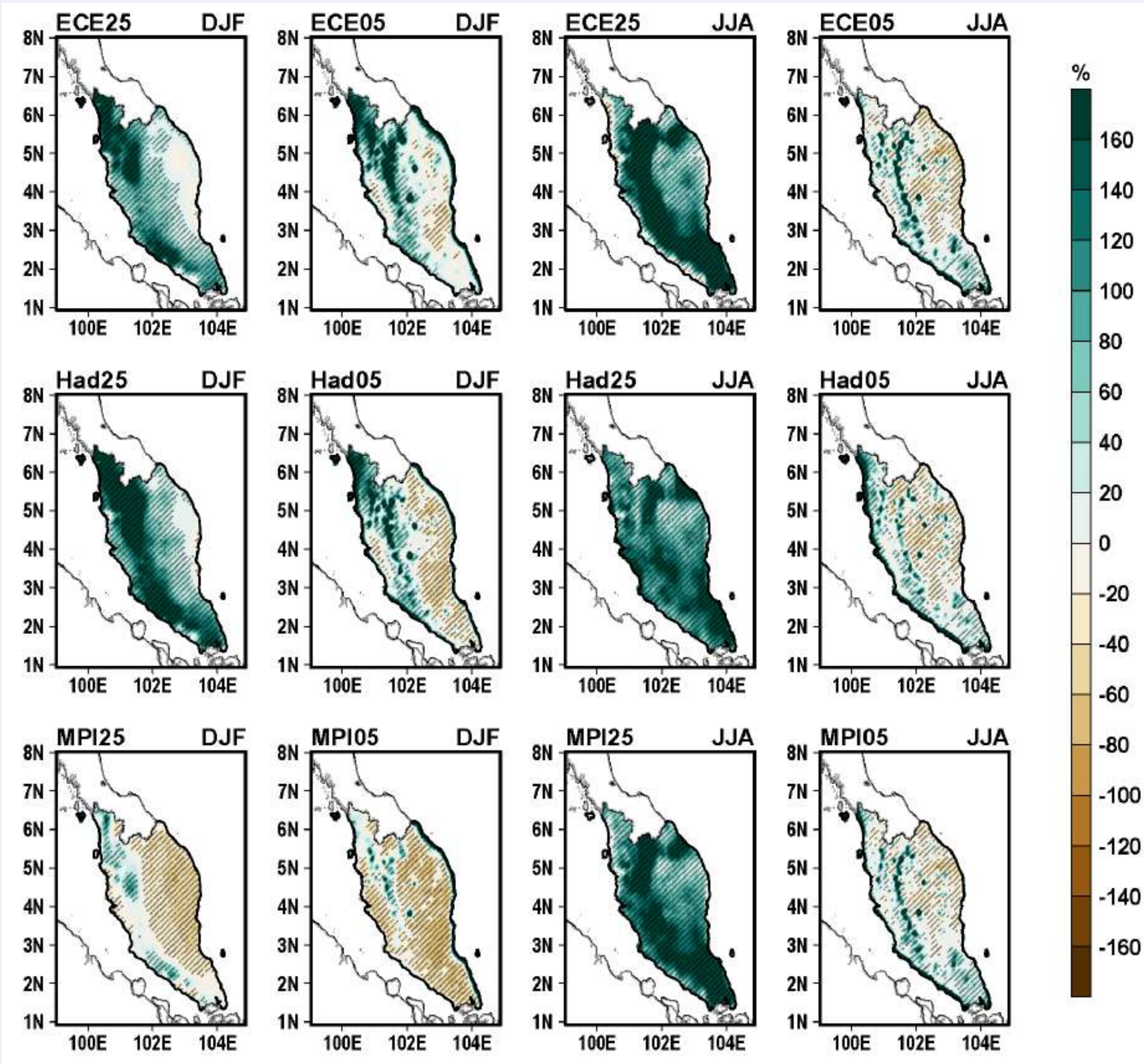

FIGURE 2. Biases of historical period seasonal mean precipitation of the 25 km (ECE25, Had25 & MPI25) and 5 km (ECE05, Had05 & MPI05) simulations for DJF and JJA relative to CHIRPS05. Forward slashes indicate that the differences between the models and CHIRPS05 are statistically significant using the Monte Carlo permutation test at a 95% confidence level.

this approach, all ensemble members will have an equal weightage in the ensemble created. This analysis used the extreme climate indices based on the Expert Team on Climate Change Detection and Indices (ETCCDI) (Zhang et al., 2011). Table 3 indicates the list of these ETCCDI indices used. Maps of projected changes in extreme precipitation relative to the historical period are made.

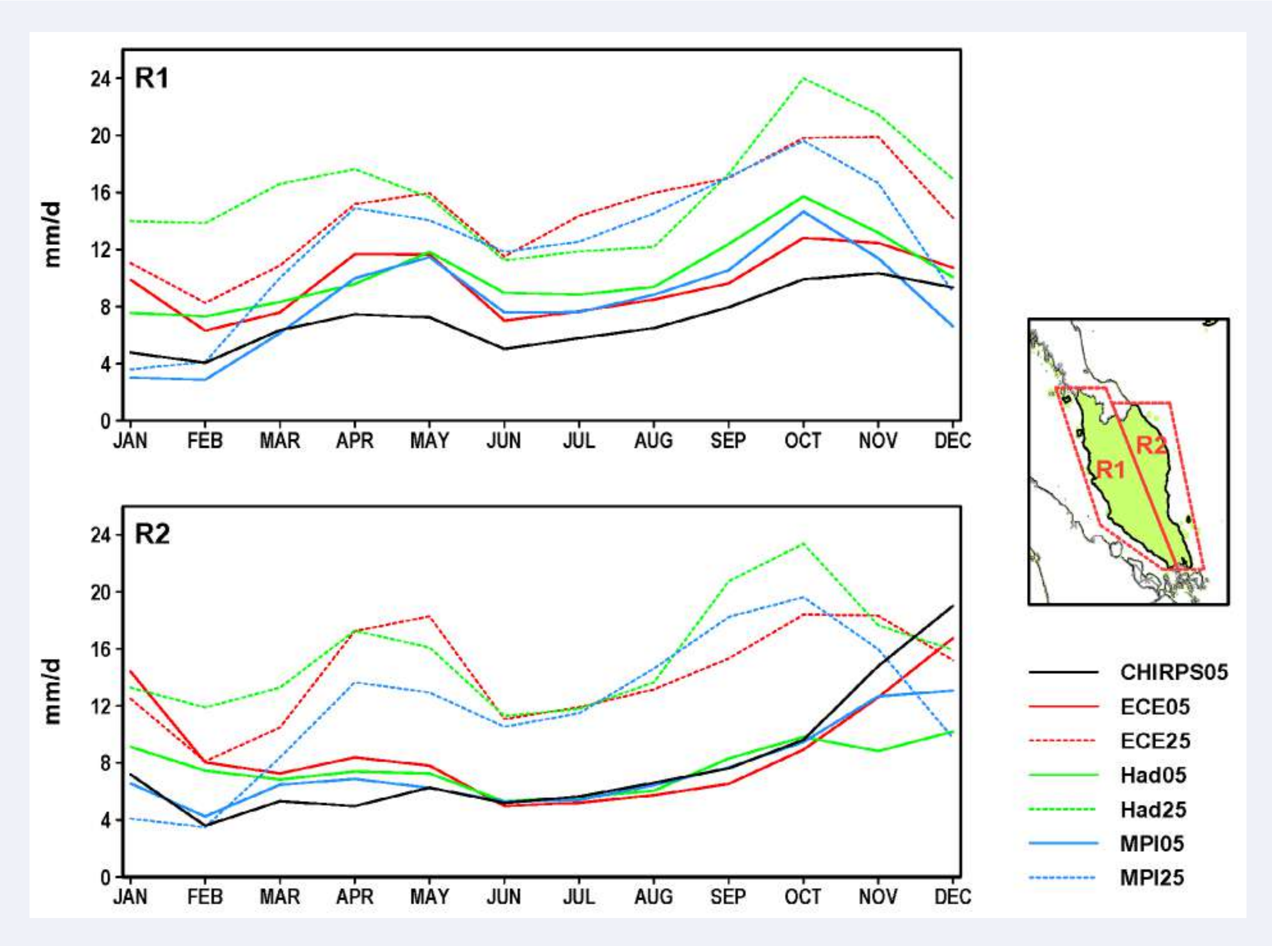

FIGURE 3. Historical period precipitation annual cycle simulated by the 25 km and 5 km simulations and observed by CHIRPS05 for sub-region R1 and R2 (indicated in map inset).

3. RESULTS AND DISCUSSION

3.1. Model evaluation and comparison between CORDEX-SEA phase 1 and 2 simulations

This section describes the performances of CORDEX-SEA phase 2 5 km simulations compared to those of CORDEX-SEA phase 1 25 km in simulating seasonal precipitation over Peninsular Malaysia. Figure 2 shows the biases of 25 km and 5 km simulations for DJF (wet season) and JJA (dry season) over Peninsular Malaysia during the historical period.

The comparison between precipitation biases in the 5 km and 25 km simulations shows that generally, for both seasons, the biases have been significantly reduced in the 5 km simulations compared to that of the 25 km. This reduction in biases in the 5 km simulations can be attributed to the newer combination of model physics schemes used: the cumulus parameterisation scheme (CPS) was changed from MIT-Emanuel to that of MIT-Emanuel over land and Kain-Fritsch over the ocean, and land surface scheme from Biosphere–Atmosphere Transfer Scheme version 1e (BATS1e) to that of Community Land Model version 4.5. The change in the model physics schemes was made because the CPS MIT-Emanuel and land surface scheme BATS1e combination used in the CORDEX-SEA phase 1 tend to cause the RegCM4 to consistently produce strong precipitation in the Southeast Asia region (Chung, Juneng, Tangang, & Jamaluddin, 2018). While general improvements have been made in the 5 km simulations after replacing the model physics schemes combination, wet biases can still be seen along the coast and the mountainous areas. These imperfections can be attributed to these in the CHIRPS05 itself.

Figure 3 depicts the observed and simulated precipitation annual cycle by CHIRPS05, 5 km and

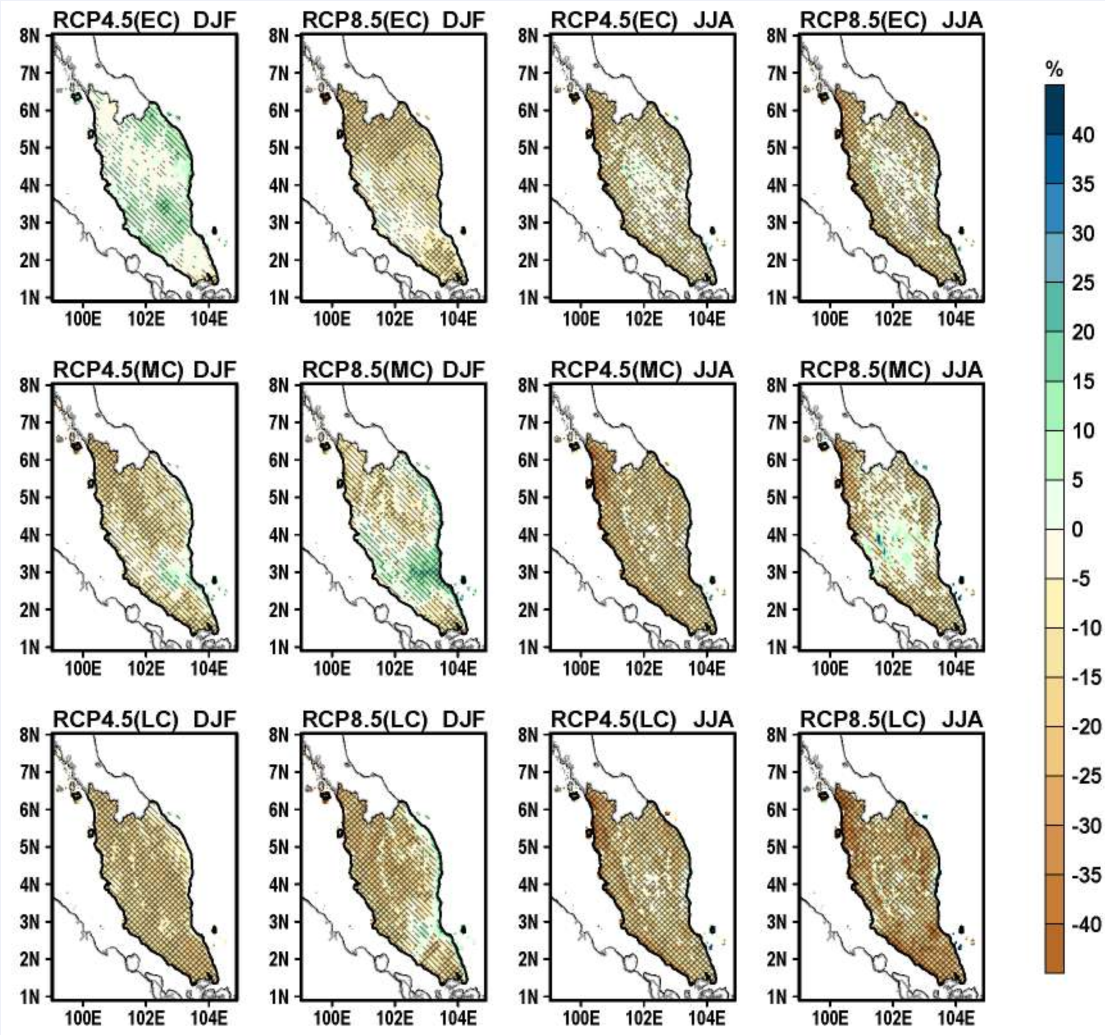

FIGURE 4. Projected mean seasonal (DJF and JJA) precipitation changes under RCP 4.5 and RCP 8.5 for the EC, MC and LC projection periods. Using the Monte Carlo permutation test, forward slashes indicate that the changes are statistically significant at a 90% confidence level. In contrast, backward slashes indicate the sign of change is agreed by 2 out of the three ensemble members.

25 km simulations over two sub-regions in Peninsular Malaysia. The two sub-regions, R1: west coast of Peninsular Malaysia, and R2: east coast of Peninsular Malaysia, were divided based on the distinct precipitation annual cycle pattern shown (Wong et al., 2016). Whereby the precipitation annual cycle pattern over R1 shows a bimodal pattern while that of R2 shows a unimodal pattern, as demonstrated by CHIRPS05 (Figure 3).

From the plots shown in Figure 3, it can be seen that both the 25 km and 5 km simulations accurately captured the bimodal precipitation annual cycle of sub-region R1. Of course, due to the 5 km simulations having much smaller precipitation biases than 25 km, the amplitude of the annual cycle simulated matches CHIRPS05 better. The most significant discrepancy between the 25 km and 5 km simulations in reproducing the annual precipitation cycle lies in the R2 sub-region. It can be seen that all the 25 km simulations could not faithfully capture the unimodal precipitation annual cycle pattern in this region, unlike that of the 5 km simulations. Thus, by increasing the model horizontal resolution from 25 km to 5 km, the originally missing east-west precipitation contrast of Peninsular Malaysia can be correctly simulated by the model. This could be due to the reason

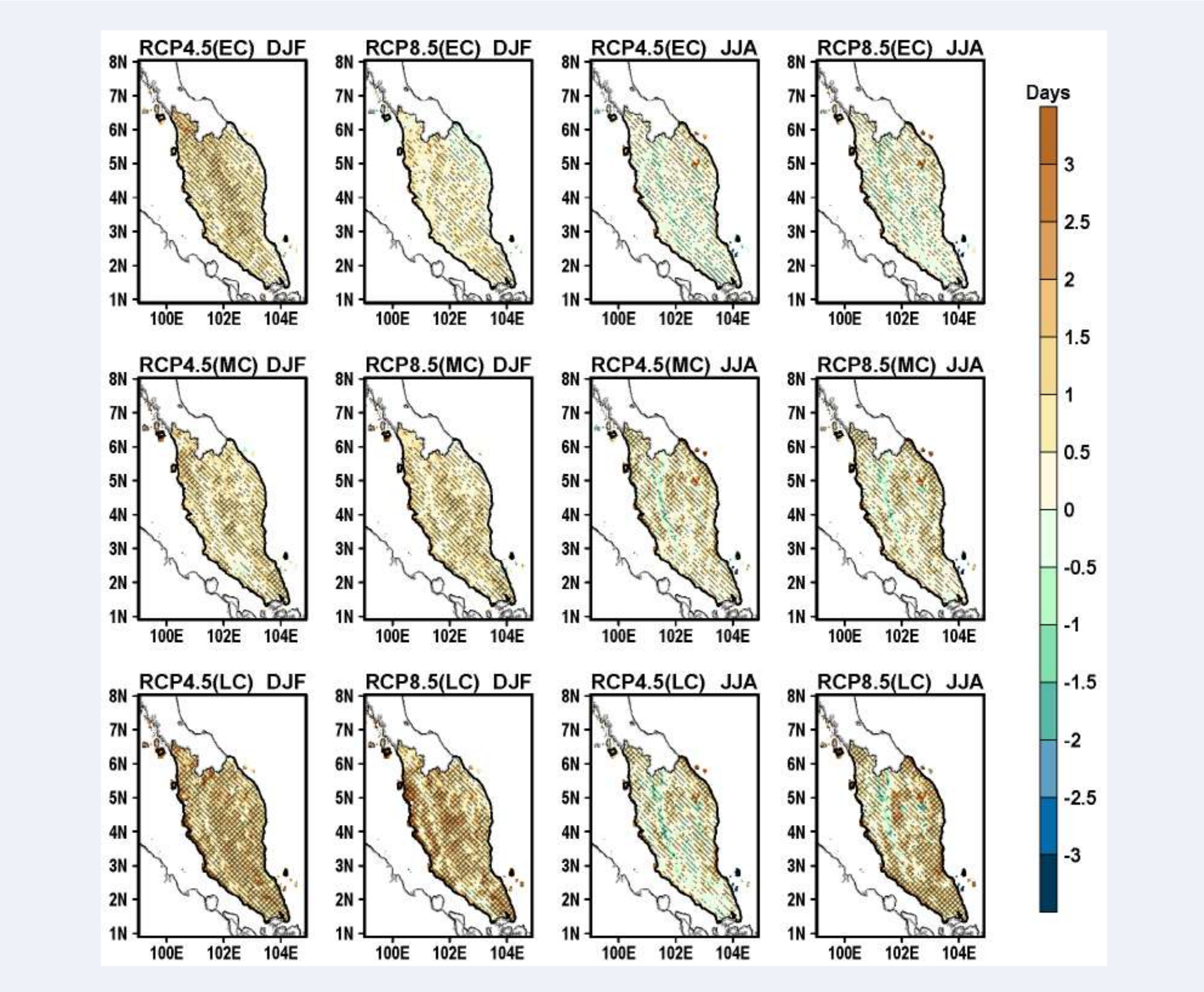

FIGURE 5. Same as Figure 4, except for consecutive dry days (CDD).

that the 5 km simulations can more faithfully represent the complex mountainous range that separates Peninsular Malaysia into east and west coasts than the 25 km simulations. Hence, the comparison suggests that increasing the horizontal resolution from 25 km to 5 km can improve the precipitation simulations, consistent with other studies (Kim, Kim, & Cha, 2022; Ngai et al., 2020; Tuju, Ferrari, Casciaro, & Mazzino, 2022).

3.2. Projected changes in mean and extreme precipitation

The changes in mean and extreme precipitation (which includes CDD, CWD, R20mm and Rx1day) over Peninsular Malaysia projected by the ensemble of ECE05, Had05 and MPI05 for each of the 21st century future periods were plotted and shown as Figures 4 to 8. Figure 4 shows the projected mean DJF and JJA precipitation changes under RCP 4.5 and RCP 8.5 for EC, MC and LC periods.

In terms of seasonal mean precipitation (both DJF and JJA), the projections show that there will be a general tendency for gradual dryness over Peninsular Malaysia in the coming future (Figure 4). This dryness tendency will occur under RCP 4.5 and RCP 8.5 futures, which is stronger under the RCP 8.5 scenario. Such results are consistent with those of Kang, Im, and Eltahir (2019) and Tangang et al. (2020). In the EC period, decreases in mean JJA rainfall can be up to 10–15%, especially under RCP 8.5. The level of dryness appears to be higher over the northwestern region of Peninsular Malaysia. During DJF, however, some areas are projected to

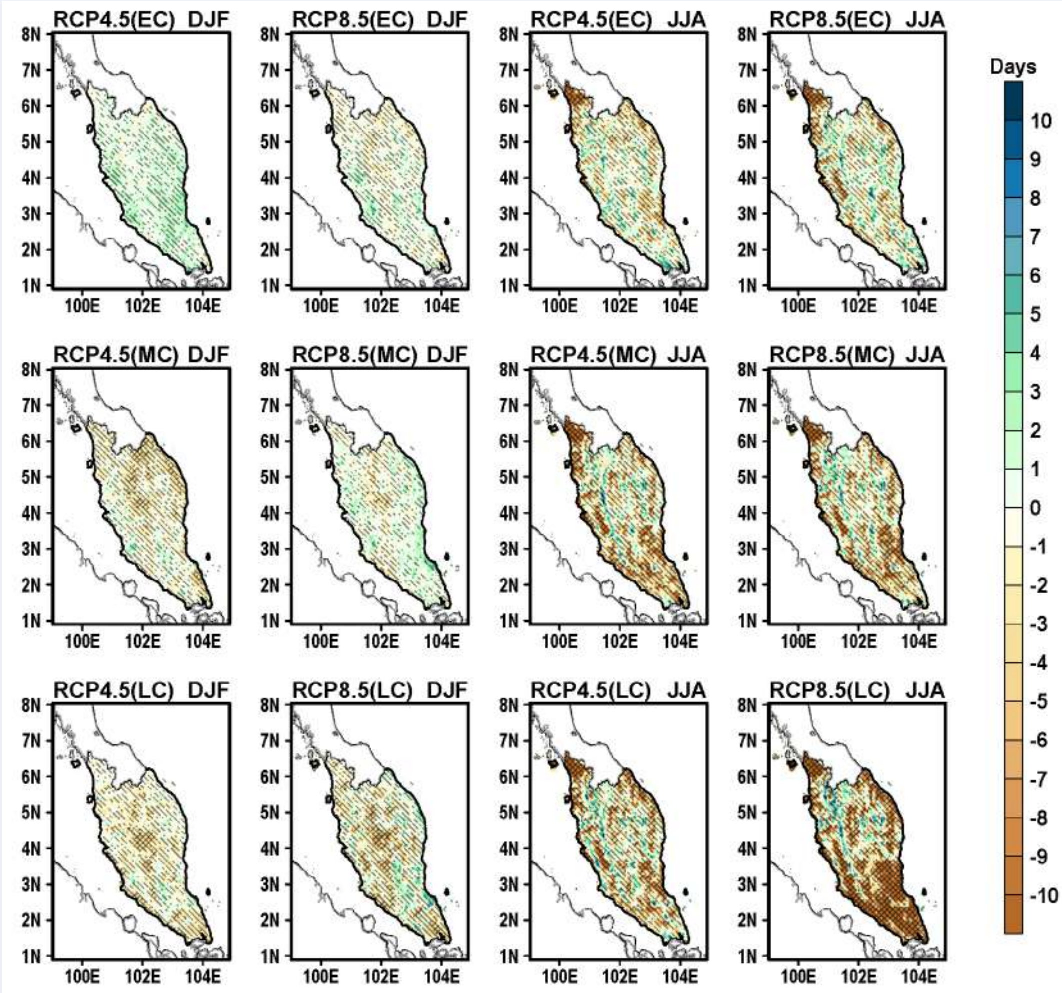

FIGURE 6. Same as Figure 4, except for consecutive wet days (CWD).

have increased rainfall for RCP 4.5. Increased mean rainfall is also projected in southern and interior parts of Peninsular Malaysia during the MC period, including RCP 8.5. By the LC period, for both RCPs, the mean rainfall is projected to show a decreasing pattern.

The drying tendency of Peninsular Malaysia in the RCP 4.5 and RCP 8.5 futures is also reflected in the precipitation extremes (Figures 5–8). Alongside the decrease in mean precipitation, an increase in the future CDD is projected (Figure 5). This indicates that the future periods will have longer dry days, especially by the 21st-century MC and LC periods. These projected CDDs are consistent with those of Supari et al. (2020). This general increase in CDD in the future matches well with the projected decrease in CWD (Figure 6). This reduction in CWD is pronounced over the southern region of Peninsular Malaysia during the JJA season in the LC period of RCP 8.5. Consequently, this increase in CDD while a decrease in CWD explains the decrease in the mean precipitation. Nevertheless, a slight increase in CWD during the EC period can also be seen for the DJF season under RCP 4.5.

Similar to CDD and CWD, the projected changes in R20mm show a general reduction in frequency in the future periods of both RCP 4.5 and RCP 8.5 futures when compared with the historical periods, particularly during MC and LC of the 21st century (Figure 7). This indicates that Peninsular Malaysia, especially the west coast, will be experiencing fewer days with very heavy precipitation.

Unlike other indices, the intensity index, Rx1day, shows mixed projected changes in future periods.

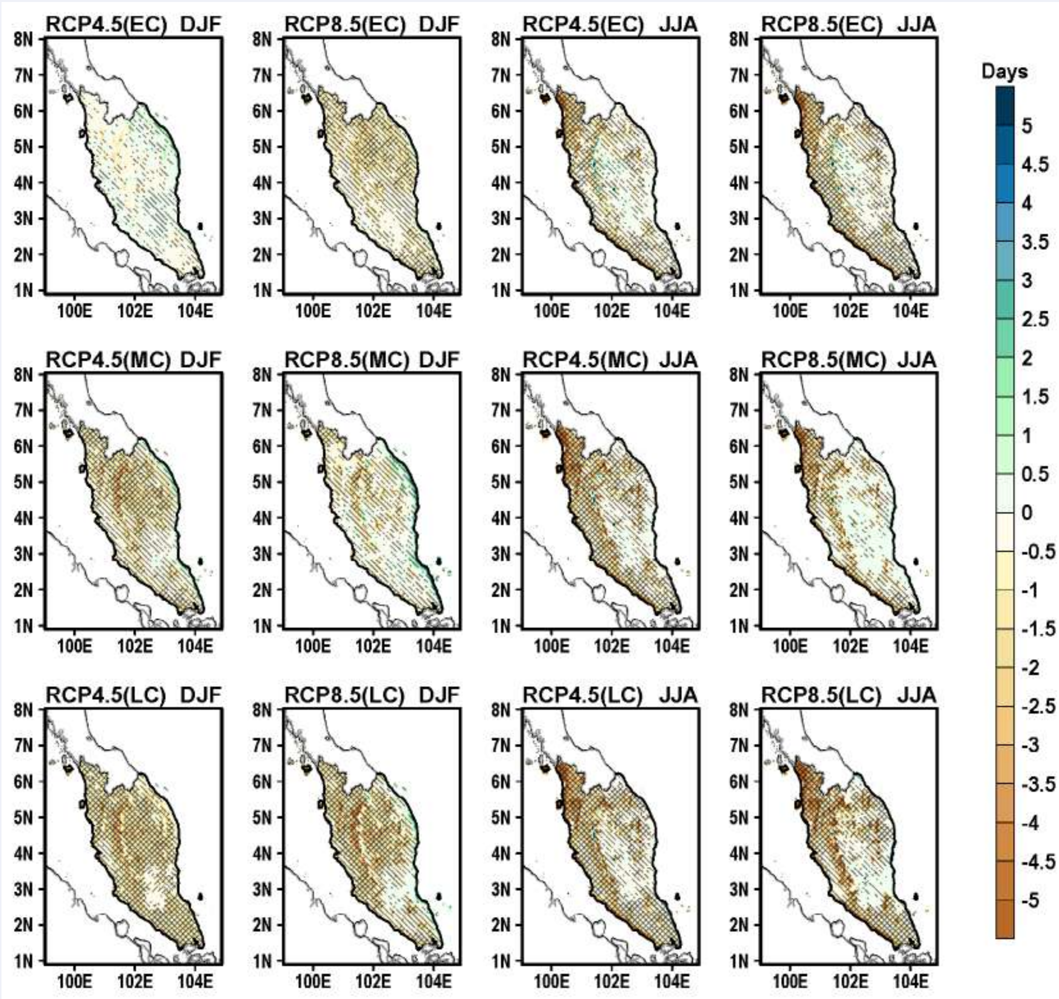

FIGURE 7. Same as Figure 4, except for R20mm.

In the EC period, increased intensity of extreme precipitation during DJF is projected under the RCP 4.5 scenario. A general increase in Rx1day can be seen throughout Peninsular Malaysia. This increase of Rx1day slowly reduced as the 21st century progressed. By the MC period, this increase of Rx1day will only be confined to the southern region of Peninsular Malaysia, and by the LC period, Rx1day generally shows a decreasing pattern. For the RCP 8.5 scenario, this increasing-decreasing tendency of Rx1day during DJF is relatively consistent through the 21st century, where a decreasing tendency will generally be found over the northern region of Peninsular Malaysia, while over the southern region of Peninsular Malaysia, the Rx1day typically showing an increasing tendency. Unlike DJF, JJA Rx1day showed a gradual decreasing tendency throughout the century, especially over the west coast of Peninsular Malaysia. This decrease in Rx1day appeared stronger under the RCP 8.5 scenario than that of RCP 4.5.

4. CONCLUSION

The CORDEX-SEA phase 2 aims to bring the achievements of CORDEX-SEA phase 1 further by providing regional climate change information at a much higher resolution over four key vulnerable areas in the Southeast Asia region. For this purpose, three CORDEX-SEA phase 1 downscaled CMIP5 GCMs (i.e., ECE, Had and MPI) were further downscaled to 5 km × 5 km resolution. The CORDEX-SEA phase 2 simulations were used to investigate changes in seasonal mean and extreme precipitation over Peninsular Malaysia.

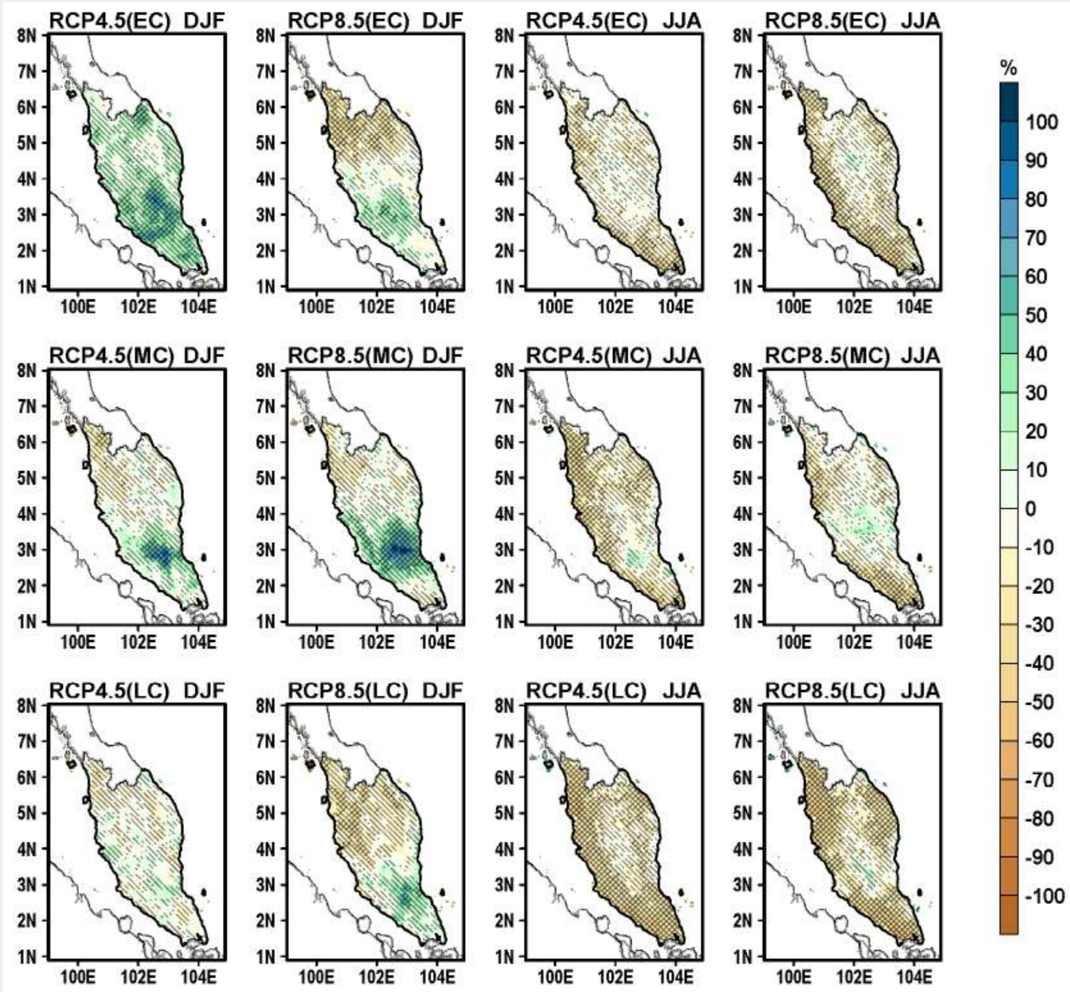

FIGURE 8. Same as Figure 4, except for Rx1day.

Model bias and annual cycle analysis show that the phase 2 simulations generally show improvement over the phase 1 simulations. The phase 2 simulations tend to have much smaller precipitation biases than phase 1. This decrease in bias can be attributed to the newer physics schemes combination used. That said, the phase 2 simulations are not entirely bias-free. Aside from the improvement in biases, these higher resolution simulations were noticeably able to correctly reproduce the annual precipitation cycle over the east coast of Peninsular Malaysia, which the 25 km simulations had failed to do. Moreover, due to the phase 2 simulations having lower precipitation bias, the simulated amplitude of annual precipitation cycles matches that of reference data (i.e., CHIRPS05) better.

An ensemble was created from the three downscaled simulations to assess the projected changes in mean and extreme precipitation over Peninsular Malaysia. Analysis suggests that Peninsular Malaysia will be experiencing a decrease in mean precipitation, especially during the MC and LC periods for both RCP 4.5 and RCP 8.5 scenarios. Aside from the decrease in mean precipitation, CDD is showing an increasing tendency, while CWD is showing a decreasing tendency, suggesting Peninsular Malaysia will be experiencing a long dry spell in the future. At the same time, the frequency of very heavy rainfall (R20mm) is projected to decrease as the 21st century progresses, regardless of the RCP 4.5 or RCP 8.5 scenarios. For Rx1day, the projected future changes show a somewhat mixed signal for DJF but generally show a decreasing trend for JJA.

The analysis results from this study imply that Peninsular Malaysia will likely become drier in the future, not limiting to its mean precipitation but the extremes as well. This raises concern because of potential severe implications on the socio-economy of Malaysia, such as in the agricultural and energy sectors, which are highly dependent on the availability of water resources.

Policy development, decision-making processes, and infrastructure planning to enhance adaptation and mitigation strategies must take into account the climate change projection information. Impact modelling communities can utilise the data to assess sector-specific vulnerabilities and the effectiveness of interventions, while planners and engineers can design resilient infrastructure systems and develop localised adaptation measures. However, it is essential to acknowledge the limitations and uncertainties associated with the projections. Future initiatives will prioritise fostering more collaborative studies with potential CORDEX-SEA data users within Southeast Asia to establish best practices in utilising the downscaled projection datasets in addressing climate change challenges.

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A case study on regional arsenic sources and its distribution in Mekong River groundwater

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ABSTRACT

Arsenic contamination in the Mekong River is a well-known environmental issue yet to be resolved due to its transboundary nature which further limits its access and data collection. Other than that, the key mechanisms that controlling the arsenic release in Mekong sub-region groundwater was heterogeneously distributed and can be varied from region to region. The main purpose of this project is to identify the regional arsenic contamination levels in the hope of helping the government integrate regional groundwater arsenic risk reduction policy in their near future planning. Sampling was conducted during May and August 2022 in Cambodia and Laos, respectively. The findings revealed that the topography of certain areas in Cambodia has exposed significantly high concentrations of arsenic in groundwater compared to those in Laos. About 33% of the sampling sites in Cambodia had shown a high arsenic contamination (>10 µg/L, World Health Organisation guidelines) with its concentration ranging from 47.7 ± 0.8 to 696.9 ± 5.6 ppb. The physicochemical properties revealed that the arsenic controlling mechanisms were totally different between both study area. More regional and site-specific arsenic contamination research related to climate change and arsenic hydrology at regional levels should be carried out to ensure the water safety plan in specific regions. Further, we believe that the findings of this study will be beneficial to policy and regional water safety plans for the Mekong River, especially in Cambodia.

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KEYWORDS

Arsenic, groundwater, Mekong River, regional pollution

HIGHLIGHTS

- The arsenic concentrations in household tube wells were investigated in Cambodia (KMH) and Lao (LAO), where the arsenic contamination (exceeding the WHO drinking water guidelines) observed in KHM is approximately 30 times higher than that in the LAO region.
- The physiochemical properties of the water samples demonstrated a more oxidising water in LAO (high nitrate with absence of ammonia), lower iron content, and lower pH than that in KHM. This suggests that the arsenic in the LAO study area could potentially be attributed to a secondary reabsorption phase. Different topographical redox conditions could control the arsenic mechanisms in the groundwater system.
- The highest arsenic concentrations were discovered in shallow wells at depths of approximately 40 m, in KHM. The concurrent presence of reducing water chemistry suggests that processes such as reductive dissolution and potentially bacterial sulphate reduction could have substantial effects on the mobility of arsenic. These mechanisms are particularly relevant due to the presence of young organic matter which serves as a carbon source and an electron donor for microorganisms. This dissolved organic carbon (DOC) is reported to rapidly recharge into the groundwater through ponds or clay windows.

1. INTRODUCTION

The amount of exploitable water resources in the world barely makes up 0.3% of its total (Kılıç, 2020). As the global population continues to expand, there is a significant increase in the demand for clean water across various sectors (Salehi, 2022). Clean water is essential not only for maintaining our health but also for supporting agriculture, energy production, navigation, recreation, and manufacturing activities (Biswas & Tortajada, 2018). Arsenic ranks as the twentieth most abundant element on the Earth is naturally ubiquitous within the ecosystems. The presence of arsenic (As) in groundwater, which is utilised as a source of drinking water, is linked to various health issues (Phan et al., 2016). These include skin abnormalities, the development of lung, liver, and kidney cancers, cardiovascular disorders, and the potential impact on the well-being of a significant global population (Abernathy et al., 1999; Barringer & Reilly, 2013; Fatoki & Badmus, 2022; Hong, Song, & Chung, 2014). Thereby, the provisional guideline established by the World Health Organisation (WHO) suggests a maximum allowable limit of 10 µg/L arsenic content in drinking water. Despite its threat to human health, it is well known that arsenic contamination in Southeast Asia is featured by contaminated sediments especially in Holocene deltaic and organic-rich surface sediments. In those areas, arsenic level in groundwater can exceeded values hundreds of times higher than the concentration recommended for drinking water (Hanh, Kim, Bang, & Hoa, 2011; Ishii, Tamura, & Ben, 2021; Luu, Sthiannopkao, & Kim, 2009; Penny, 2006).

Arsenic in groundwater can be released through (a) oxidation of aquifer arsenical pyrite and other arsenic-bearing sulphide minerals, (b) reductive dissolution of arsenic-rich Fe(III) oxyhydroxides and Al-hydroxides, and (c) exchange of adsorbed arsenic with other competitive anions, such as phosphate, bicarbonate and silicate (McCarty, Hanh, & Kim, 2011). Nevertheless, the reductive dissolutions of arsenic-rich Fe(III) oxyhydroxides and/or Al-hydroxides were widely accepted to be the main mechanism of direct arsenic mobilisation. The mechanisms responsible for its release can vary depending on the specific geological and hydrological conditions, such as redox reactions (Herath, Vithanage, Bundschuh, Maity, & Bhattacharya, 2016), microbial activity (Ko, Lee, & Kim, 2019), dissolution from minerals (Robinson et al., 2009; Welch & Stollenwerk, 2003), etc. It is important to note that the factors that regulate these mechanisms also vary depending on the characteristic of bedrock aquifer, recharges rate, flow processes, groundwater levels, etc. (Lipfert, Reeve, Sidle, & Marvinney, 2006; Peel et al., 2022). During intense and prolonged low flow, the decrease in the water table's level is anticipated to amplify the oxidation process of sulphides containing arsenic within the unsaturated zone. Furthermore, reduced groundwater flow enhances geochemically evolved arsenic-rich groundwater consequently boost the release of arsenic through reductive dissolution and alkali desorption (Bondu, Cloutier, Rosa, & Benzaazoua, 2016).

Southeast Asia has been identified as a significant "climate change hotspot," (Yusuf, 2010). The primary climatic risks affecting the countries include flooding, drought, flash flooding in the mountainous parts of the country, windstorms, and large-scale farmland erosion. Situated within latitudes of 10–15° north of the equator, both Cambodia and Lao region experiences a tropical monsoon climate or inter-annual variations in climate (annual dry and wet seasons) due to the influence of El Niño Southern Oscillation aka., monsoon season from May to mid-October, and a dry season from mid-October to April. During the wet season, flooding accompanies overflow of the Mekong River and its tributaries, which is triggered by tropical storms, intense monsoonal rainfall, and the runoff originating from the northern mountains (Kazama et al., 2012; Koem & Tantanee, 2022; Phy et al., 2022). Cambodia, predominantly impacted by floods and droughts, achieved the eighth position out of 193 nations in 2014 Maplecroft's Climate Change Vulnerability Index, a composite measure that assesses a country's sensitivity to extreme weather events (Davies et al., 2015). Climate change has the potential to increase the frequency and intensity of flooding and/or drought, both of which already cause severe hardship to communities. The impact of extreme climate recharge events on the fate of arsenic is currently a subject of debate and is greatly contingent upon the characteristics of the bedrock aquifer, which in turn influence the susceptibility of groundwater.

To date, the scarcity of data concerning the household arsenic levels in the high-risk arsenic zones further poses a significant challenge in assessing the potential evolution of the resource quality. The mechanism responsible for regulating groundwater arsenic concentrations in arsenic high-risk zone can be heterogeneous and site-specific underlying to its intricate interactions with geological formations, hydrological conditions, and chemical processes. The purpose of this study is identifying spatial arsenic in the sub-region groundwater of Mekong River area which is heavily affected by arsenic and typical of many circum-Himalayan shallow aquifers. The arsenic release mechanism is investigated through the interactions between water bodies. The study on the regional arsenic contamination levels is important for the government integrate regional groundwater arsenic risk reduction policy planning.

2. METHODOLOGY

2.1. Study area

The design of the study area was based on the location of Mekong River Basin, specifically in Lao (LAO) and Cambodia (KHM). The Sekong river were selected as the control site. After the release of COVID-19 travel restriction, sampling was conducted in households nearby the Mekong

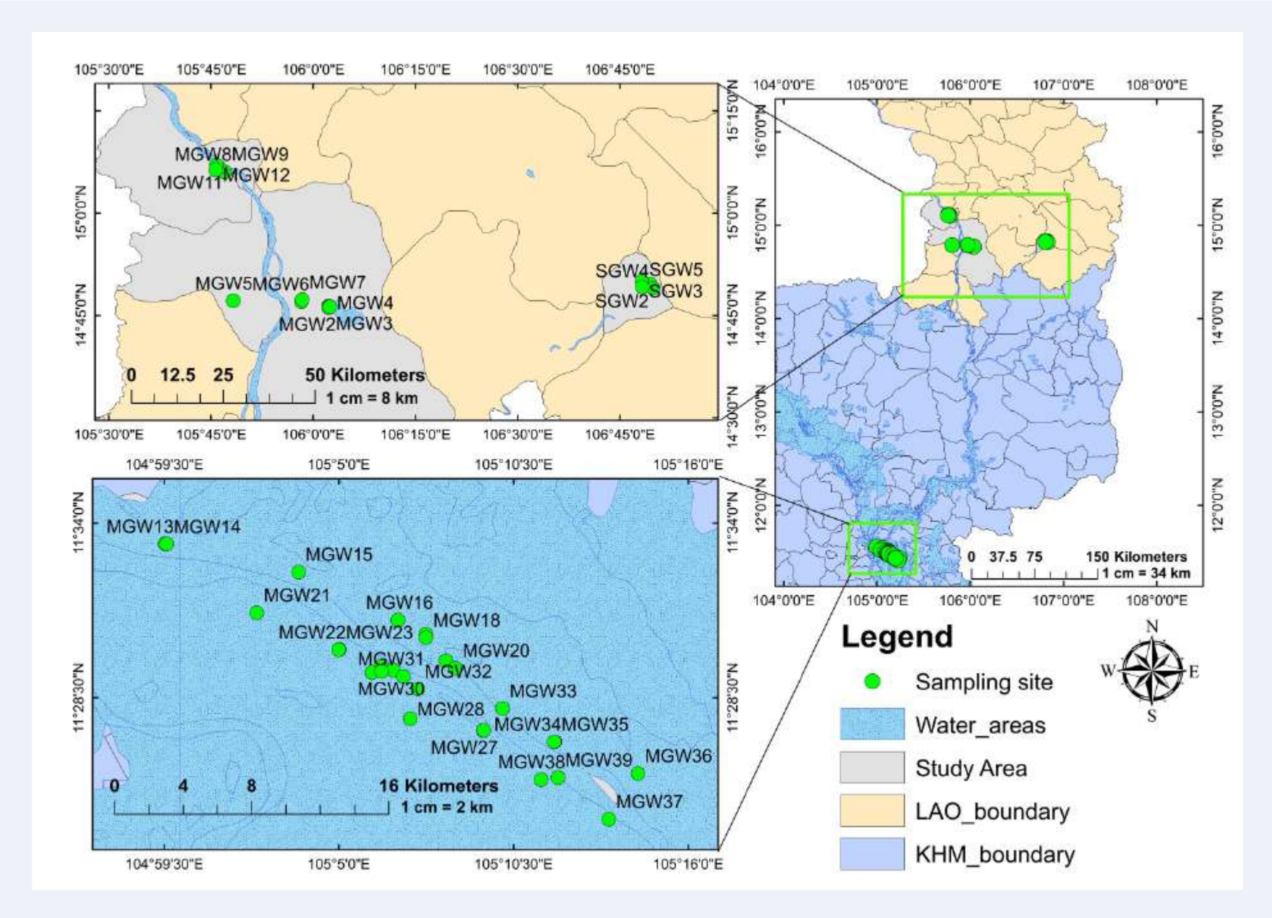

FIGURE 1. Sampling map of the tube wells located between Lao and Cambodia, where groundwater samples (n = 44) were collected in the households near the Mekong and Sekong Rivers.

River during May and August 2022. The study map is presented as in Figure 1 where groundwater samples were collected 2–3 km from the river basin. The study area was located from (14°77′ to 15°10′ N, 105°76′ to 106°83′ E) for the Lao sampling site whereas (11°24′ to 11°33′ N, 105°07′ to 105°14′ E) for KHM sampling site. A total of forty-four tube-well water samples located at Mekong River sub-region were collected from household or community tube in May and August of 2022. Laos is situated more to the north, as Figure 1 shows, in the upstream of the Mekong's passage through Lao PDR; while the Sekong river originated in the Central Highlands of Vietnam is one of the most important Mekong tributaries. It flows downstream through Laos and merge with Mekong River in Cambodia, contributing ten percent of the water flow to the Mekong River. Samples in Sekong river area were collected at Laos before its merge into Mekong River in Cambodia.

The study areas along the Mekong River located from the southern parts of Lao PDR to Cambodia are floodplain areas. In Cambodia, a significant portion of the land consists of a floodplain, with approximately 85% of the country's land located within the lower Mekong basin. Tube-well water is used by the communities for drinking, cooking, and household consumption as well as for irrigation. The depth of tube wells tested varied from 10 to 60 m. Meanwhile, the sampling area of Cambodia is located at a lower topographic gradient than in Laos. The average temperature of the study area is around 26 to 30 °C with the highest temperature recorded in May (Tsujimoto, Ohta, Aida, Tamakawa, & So Im, 2018). A study of seasonal influences on groundwater arsenic near to our sampling locations did not show much evidence of seasonal-scale recharge of the Bassac River to aquifer except one site where arsenic concentration was increased from 1.3 µg/L

Parameters	Mekong River		Sekong River		Chanpiwat et al. (2011)	
	Average	Range (min–max)	Average	Range (min–max)	Average	Range (min–max)
DO (mg/L)	LAO: 2.8 KHM: 4.7	LAO: 1.9–4.0 KHM: 3.5–5.6	5	2.9–8.6	-	-
Temp. (°C)	LAO: 28.0 KHM: 32.5	LAO: 26.8–28.8 KHM: 29.8–35.8	29.3	29.2–30.1	-	-
pH	LAO: 6.5 KHM: 7.3	LAO: 5.7–7.2 KHM: 6.8–7.8	6.9	5.8–6.9	6.58	3.54–7.37
EC (μS/cm)	LAO: 462.6 KHM: 738.6	LAO: 116.3–744 KHM: 228.7–1787	342.4	183.1–509	358.27	132–1520
TDS (ppm)	LAO: 295.8 KHM: 370.1	LAO: 74.4–476.2 KHM: 114.5–901.3	219.1	117.1–325.8	358.27	27.8–1520.0
Salinity (ppt)	LAO: 0.1 KHM: 0.2	LAO: 0–0.3 KHM: 0–0.5	0.1	0–0.2	0.31	0–0.95
Nitrate (mg/L)	LAO: 4.0 KHM: 5.9	LAO: 0–10.5 KHM: 5.1–7.5	9.6	1–17	-	-
Ammonia (mg/L)	LAO: 0.6 KHM: 4.1	LAO: 0–0.6 KHM: 0–28.1	0	0	-	-

TABLE 1. General physicochemical properties of groundwater samples.

to 8.6 μg/L due to wet season recharge processes (Tweed et al., 2020). The seasonal fluctuation was not essential, and therefore was not included in this study.

2.2. Sample collection and analysis

Groundwater samples were collected from 44 households in May and August of 2022. Ultra-clean sampling protocols were used to prevent contamination of samples. Ancillary parameters, such as dissolved oxygen, pH, temperature, salinity, total dissolved solid and conductivity were recorded in situ using a multi-parameter probe. Filtered surface water samples were collected using a syringe filter connected to disposable PTFE filter membrane (Advantec®, 0.45 μm). At each site, duplicate samples were collected in polyethylene bottles for analysis (Yu et al., 2015). The water samples then preserved with high-purity nitric acid, HNO_3 (0.1% v/v), and stored at 4 °C until they were measured with inductively coupled plasma mass spectrometry (ICP-MS) (Thermo Elemental X7) in the Gwangju Institute of Science and Technology.

2.3. Statistical analysis

All statistical analyses were performed using IBM SPSS Statistics version 20 for Windows. A principal component analysis (PCA) was applied to extract the components of the variables of parameters in groundwater (Bartlett, 1954; Cattell, 1966; Kaiser, 1960) to understand the factor on the release of arsenic in Kandal and Prey Veng groundwater, where high range of arsenic in groundwater were observed.

3. RESULTS AND DISCUSSION

3.1. Physicochemical properties

The physicochemical properties of groundwater collected were shown in Table 1. In summary, KHM groundwater showed an average dissolved oxygen (DO) up to 4.7 mg/L, electric conductivity (EC) 738.6 μS/cm, total dissolved solid (TDS) 370.1 ppm and salinity 0.2 ppt. The average temperature and pH were 32.5 °C and 7.3, respectively. As compared with the results reported on 2008, the average temperature was increased by 4.3 °C (Park et al., 2011). The results of the in-situ analysis (Table 1) showed that the acidity level of all the water samples were relatively neutral (pH = 6.8 to 7.8). The overall TDS and EC value observed in this study was slightly lower than the data collected in Kahe catchment area during wet season. Both TDS and EC have been regarded as a major contribution by increase in runoff during monsoonal precipitation (R^2 = 0.84) (Lwimbo, Komakech, & Muzuka, 2019). Nitrate in groundwaters in KHM study area is mostly below the detection, except site MGW 13, 25, and 27 where ammonia concentration was ranged from 0 to 0.7 mg/L. Other sites showed high ammonia concentration compared to nitrate. Such high ammonia concentration potentially anthropogenic sources resulting reducing water in the groundwater thus highlighted the infiltration of water from surface to groundwater.

In comparison, LAO groundwater showed lower averaged DO, EC, TDS, salinity, temperature, and pH compared to KHM groundwater. The groundwater physicochemical characteristics demonstrated the distinct in water bodies between LAO and KHM groundwater. Other reason could be due to the dilution after rainfall events which means the groundwater in LAO region could be mostly of unconfined aquifer. It is important to note that higher nitrate concentration was observed in all LAO and Sekong groundwater as compared to ammonia concentration which contrasts with that observed in the KHM groundwater. This phenomenon could be attributed to the topographic gradient effect, as Cambodia is situated at a lower topographic gradient in comparison to LAO. Other than that, the water catchment area demonstrates that the study area in KHM was predominantly covered by water, in contrast to the LAO and Sekong study areas where dry land was more prevalent (Figure 1). Though the samples were collected from similar groundwater depth range, the topographic gradient is steeper in KHM (Cambodia) than in LAO (Laos), resulting in the groundwater bodies in KHM groundwater to be more reducing compared to the LAO groundwater bodies. Variance in topographic gradient contributes to differing hydrogeological conditions and redox potentials, subsequently influence the geochemical characteristics of the respective groundwater (Lei, Wagner, & Fohrer, 2021).

3.2. Arsenic concentration in groundwater

The average total arsenic concentration was 81.36 ppb, 6.1 ppb and 7.0 ppb in KHM (n = 27), LAO (n = 12), and Sekong (n = 5), respectively. The sampling site where arsenic concentration exceeds the WHO guideline (>10 μg/L) was mainly found in the KHM study area i.e., Kdei Kandal village (MGW 13), Kvea Aem village (MGW 16, 17, 18, and 19), Khsom village (MGW 22 and 23), Stueng village (MGW 38), and Chrouy Dang village (MGW 39). The percentage of sample sites that showed high arsenic contamination was about 33% (9 out of 27 sampling sites). In LAO and Sekong, three sites out of twelve and one site out of five showed arsenic (>10 μg/L), however not exceed 20 μg/L. The range of arsenic concentration observed in KHM is approximately 30 times higher than those in LAO and Sekong area, Figure 2. High arsenic concentration observed in groundwater has been observed in countries such as Argentina, Chile, Mexico, China, and Hungary, and more recently in West Bengal (India), Bangladesh and Vietnam (Smedley & Kinniburgh, 2002).

In Cambodia, high arsenic was reported to be contributed by strongly reducing aquifers specifically from arsenic-bearing alluvium (Chanpiwat et al., 2011). The reducing aquifers were further proved through our study where high correlation was observed between ammonia and arsenic (Figure 3). In KHM, water nitrate ranged from 5.1–7.5 mg/L (n = 4) where most samples showed nitrate concentration lower than the detection limit while high ammonia (ranged from 0–28.1 mg/L) was accompanied by high arsenic (except for site MGW 17 and 18). In site MGW 17, the ammonia concentration was 28.1 and arsenic concentration was 50 ppb while for site MGW 18, 15.3 mg/L ammonia was accompanied by 90 ppb of arsenic. This suggests the potential anthropogenic sources of nitrogen infiltrating into

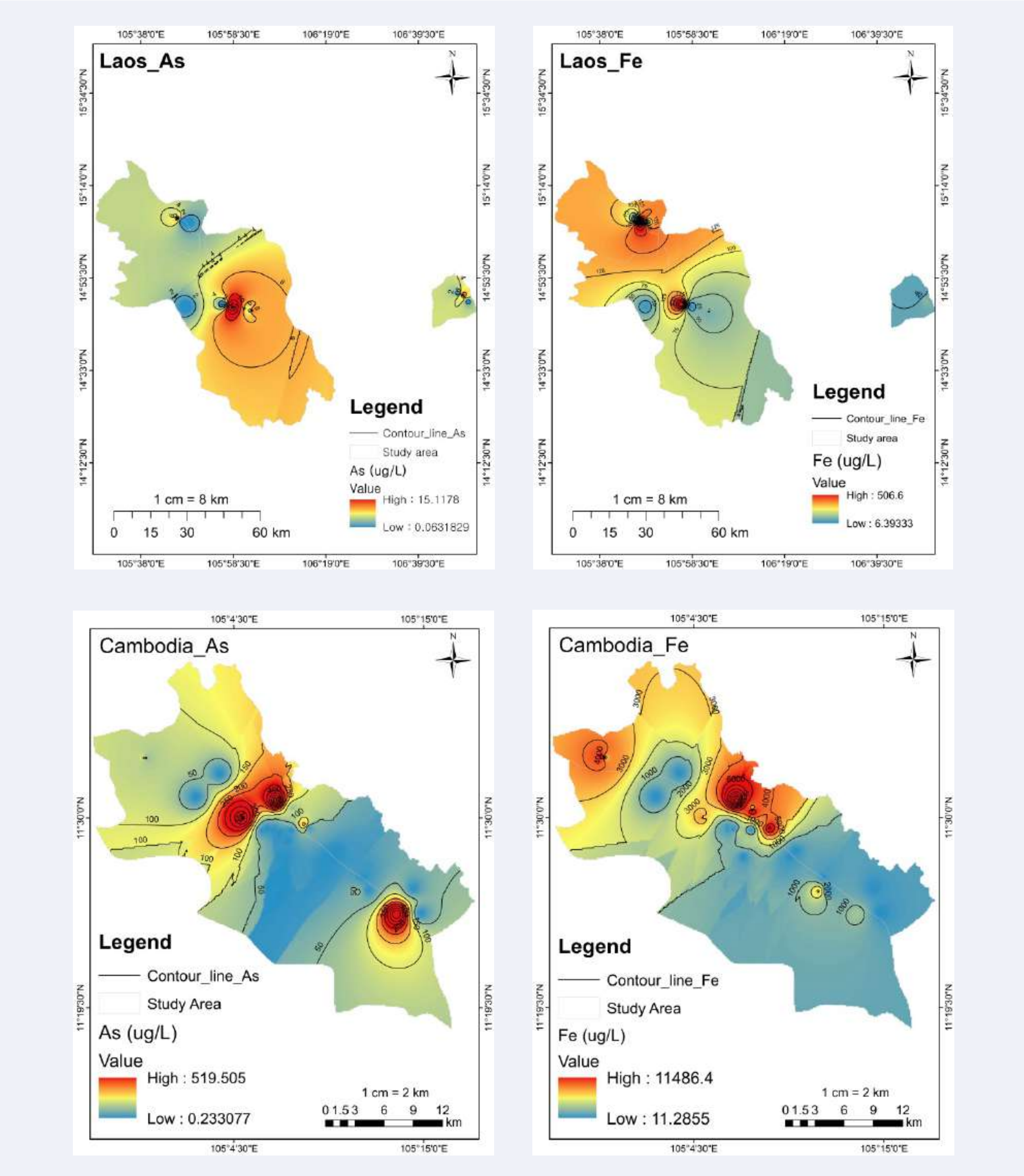

FIGURE 2. Spatial distribution of groundwater arsenic and iron concentration in (a) Lao and (b) Cambodia.

the groundwater, and it's possible that these two sites are associated with an unconfined aquifer. In contrast to KHM, the water nitrogen content is LAO is mostly in oxidised form (Table 1) where ammonia could barely detect. This proposed that the mechanism controlling the release of arsenic might be different between KHM and LAO.

Other than that, slightly lower pH was observed in LAO water bodies compared to the KHM groundwater (Table 1). Mineral surfaces tend to acquire a negative charge under alkaline conditions; therefore, a higher pH (7 to 8.5) leads to a reduction in the sorption of arsenic oxyanions, ultimately resulting in an increased likelihood of arsenic release (Raven-

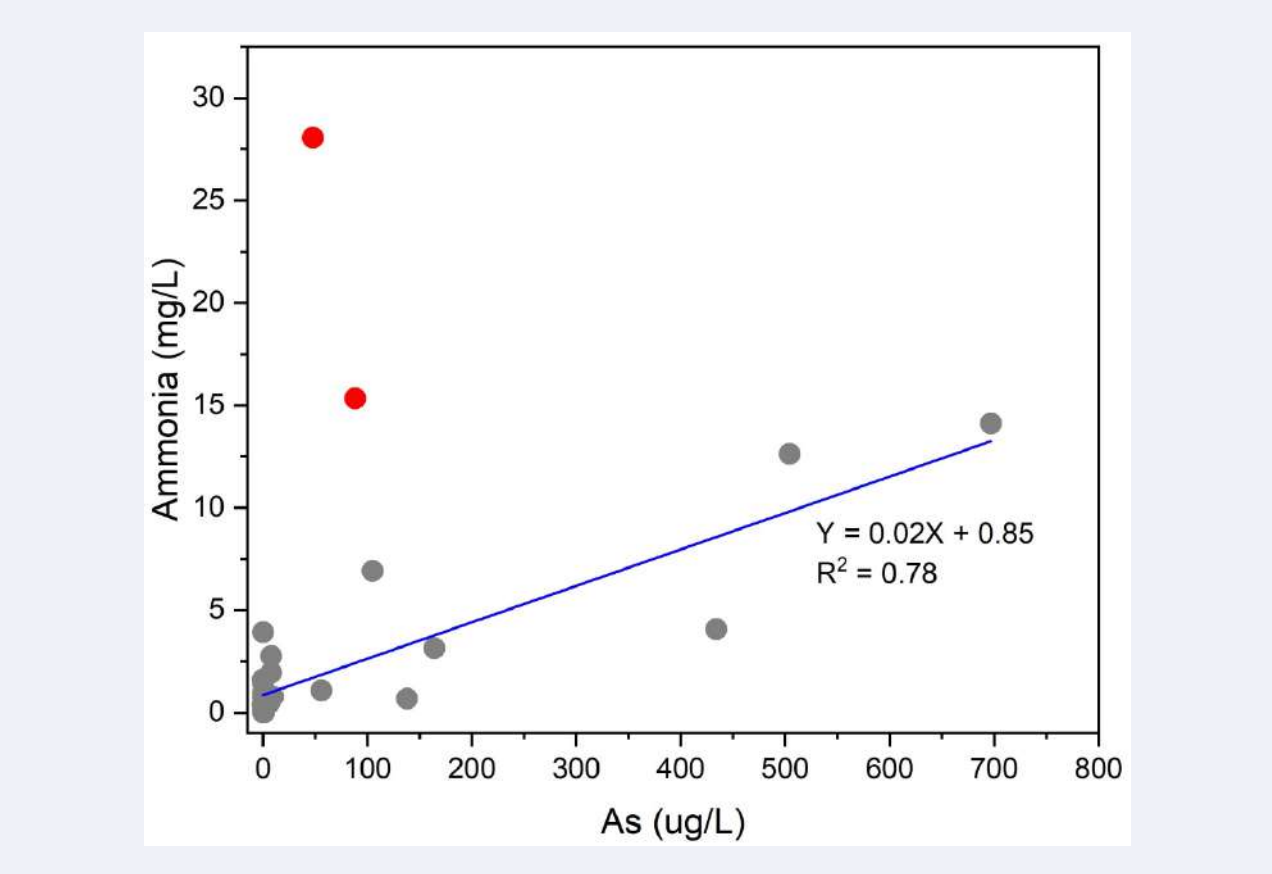

FIGURE 3. Arsenic concentration plotted against the concentration of ammonia (in mg/L) across the sampling area in Cambodia (n = 27). Red dots indicate the outliers pointing to site MGW 17 and 18.

scroft, Brammer, & Richards, 2009). This could be the main mechanism underlying in KHM study area. Under anoxic conditions, the introduction of oxygen triggers the oxidation of arsenic-containing minerals, resulting in significant alterations to water chemistry. The oxidative dissolution of these minerals releases iron, sulphur and arsenic. However, under near-neutral pH conditions, arsenic tends to precipitate with iron, adhere to iron (hydr)oxides, or integrate into secondary oxide phases. In a study (Battistel, Stolze, Muniruzzaman, & Rolle, 2021), it was found that 40% of the released arsenic through oxidative dissolution was reabsorbed into a newly formed iron-arsenate phase. This phase formed a coating on the mineral surface, which further limited the extent of dissolution reactions. The presence of a secondary reabsorption phase might explain the comparatively low levels of arsenic concentration in the LAO study area.

Sampling site that yields high arsenic was also associated with shallow groundwater zone with depth between 35–65 m (Figure 4) which agree with the finding in the study of Buschmann, Berg, Stengel, and Sampson (2007) where up to >1000 µg/L of arsenic was reported between 25 and 45 m depth. However, similar trend was not observed in either LAO or Sekong groundwater samples. Rapid weathering of arsenic-bearing rocks in the upper Himalayan catchments is transported by large rivers and deposited in the low-lying, young alluvial floodplains (Polya et al., 2005). The Mekong River conveys approximately 160 million tons of sediment annually that ultimately reaches the South China Sea (Ta, Nguyen, Tateishi, Kobayashi, & Saito, 2001). The mechanisms responsible for arsenic release was reported to be varied by the sources of organic carbon. Extensive groundwater pumping likely caused the lateral intrusion of transporting the young organic carbon to greater depth such

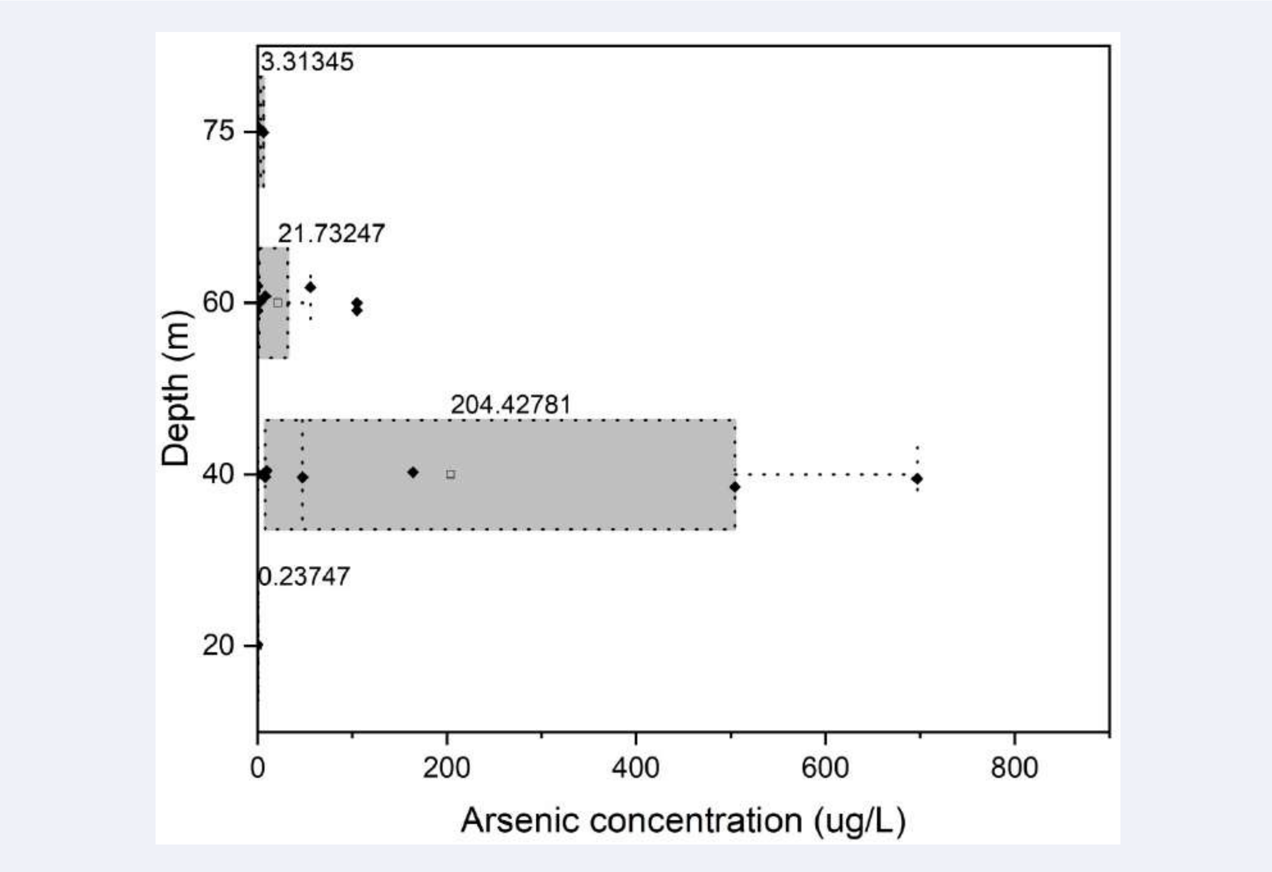

FIGURE 4. Arsenic concentration grouped by well depth across the sampling area in Cambodia (n = 27). Data are overlain by box plots where the centerline is mean, box edges are the 25th and 75th percentiles, and the bars are 10th and 90th percentiles.

as in Bengali (~80 m) and the Red river (~120 m) (van Geen et al., 2013). Study of arsenic release in shallow groundwater using tritium and radiocarbon data also demonstrated that rapid recharge through ponds or clay windows transport the young, surface derived organic matter into groundwater under natural flow conditions (without groundwater abstraction) can reach up to 44 m (Lawson, Polya, Boyce, Bryant, & Ballentine, 2016; Richards et al., 2017). Given these number of recharges, relatively young labile organic matter was reported to play an important role in (a) microbial-mediated reductive processes and (b) reduction of Fe(III) oxyhydroxides resulting in elevated concentrations of arsenic under reducing conditions that develop in young (Quaternary) Holocene alluvial aquifers in this region (Lawson et al., 2013; Polizzotto, Kocar, Benner, Sampson, & Fendorf, 2008).

3.3. Factor analysis on arsenic distribution in KHM Mekong River sub-region groundwater

To provide better insight into the mechanisms of arsenic in KHM groundwater, parameter associations were performed by principal component analysis (PCA) as shown in Figure 5. Variables with a correlation matrix (r) of less than 0.3 were eliminated from the data interpretation. The first three factors were adopted as shown in Table 2, which explain 74.4% of the variance expressed by the data matrix. After the factors were extracted, a rotation of the factorial axis was performed (varimax algorithm). The factor loadings showed that factor 1 (43.5% of the variance) has factor loadings > ±0.5 for salinity, cation, anion, TDS, EC, and Mg. This factor represents the major cations and anions resulting from water-rock interactions in the aquifer. Factor 2 (19.5% of the variance) has factor loadings > ±0.5 for Fe, Ba, As, and Ca. Obviously, this factor reveal

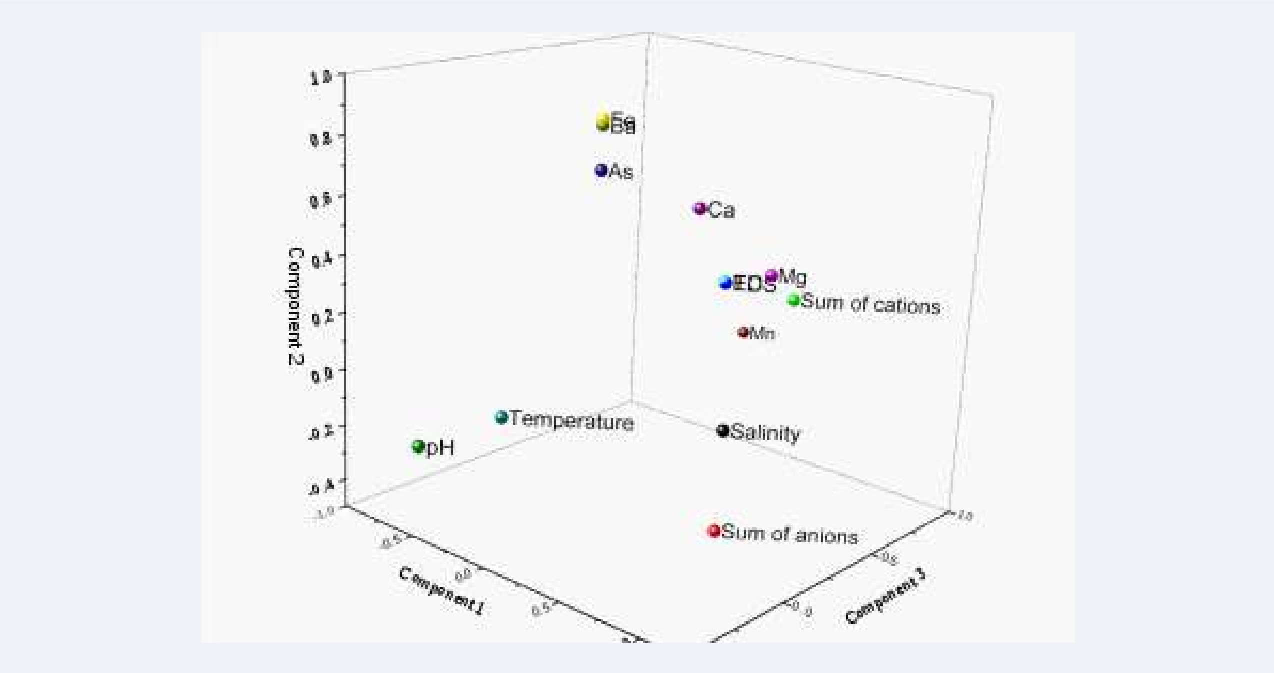

FIGURE 5. Principal component analysis (PCA) for the parameter association. A principal component analysis (PCA) was run on the parameters (n = 27). The overall Kaiser-Meyer-Olkin (KMO) measure was 0.65. PCA results revealed three components that had eigenvalues greater than one which explained 43.5, 19.5, and 11.4% of the total variance, respectively. Component loadings and communalities of the rotated solution are presented in Table 2.

that elevated As levels occurred under reducing conditions, i.e. high Fe(II). Lastly, factor 3 (11.4% of the variance) has factor loadings > ±0.5 only for Mn and pH. In this study, the concentration of Fe in LAO water bodies was about 20 times lower than those found in KHM water bodies. An increase in As was found together with high Fe (Guo et al., 2016) as proposed, where reductive dissolution of iron (III) oxyhydroxides play an important role leading to arsenic release from aquifer sediments under anoxic conditions. Yet the fundamental mechanism might begin with bacterial sulphate reduction (BSR) (Moore et al., 2023). Similar mechanisms were report by Kocar et al. (2008) whereby under reducing conditions, As-bearing Fe (hydr)oxides drives the reductive mobilisation and release As to the aquifer in the Mekong River.

4. CONCLUSION

Overall, the study highlights the physicochemical properties of groundwater, the presence of high arsenic contamination in certain KHM sampling sites, and the factors influencing arsenic distribution in the Mekong River sub-region groundwater. These findings provide valuable insights for understanding the water quality and potential risks associated with arsenic contamination in the study area. By providing a clearer understanding of the complex interactions through the results obtained, this study lays the groundwork for further research on the impact of climate change and its effects on the system. Further investigation into the seasonal fluctuations such as the influence on clay layer deposition rate utilising tritium tracers would provide a better insight on the impact of flooding on arsenic mobility especially in highly contaminated area is suggested.

Local and regional policies related to water quality and public health can vary widely depending on the specific area and its unique challenges. Water quality and risk assessment, including water quality monitoring and the evaluation of health impacts, stakeholder engagement, technology transfer, and collaboration - especially regional cooperation - can lead to more comprehensive and effective solutions for resolving the current issue. In addition to that,

Parameters	Rotated Component Coefficients			
	Component 1	Component 2	Component 3	Communalities
Salinity	**0.832**			0.263
Sum of anions	**0.819**	−0.349		0.654
Sum of cations	**0.810**	0.353	0.358	0.930
TDS	**0.791**	0.481		0.931
EC	**0.789**	0.482		0.794
Mg	0.666	0.415	0.358	0.909
Fe		**0.903**		0.736
Ba		**0.884**		0.543
As		**0.736**		0.744
Ca	0.616	**0.693**		0.816
Mn			0.833	0.793
pH			−0.785	0.697
Temperature			−0.431	0.867

TABLE 2. Rotated structure matrix for PCA with Varimax Rotation of a three component parameters association.

implementing suitable climate mitigation technology and infrastructure, such as promising treatment technologies like nanofiltration membranes, which achieve a 99.8% arsenic removal rate (Worou, Chen, & Bacharou, 2021) or low-cost hydrotalcite-like compound adsorbent (Kato et al., 2020), is recommended in regions where high arsenic concentrations have been detected. This is to minimise potential health risks within the community.

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Case study

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Impact of climate change, climate variability and adaptation in coastal area of Cambodia

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ABSTRACT

Cambodia's coastal zones are highly dependent on climate and weather, making them susceptible to climate change and causing farmers' livelihoods to be more vulnerable compared to urban residents. Since climate issues already impact the agricultural sector in Cambodia, this paper aims to assess the impact of disasters in the context of climate change, which impacts household agricultural production, and to identify the existing community's capacity to respond and adapt to climate change and climate variability in the coastal zones of Cambodia. A survey was conducted in the agricultural coastal zone provinces of Cambodia. Data was analysed using SPSS software. The survey data demonstrates that disasters and climate change, particularly drought and floods, significantly impact the economic status of the interviewed households. The proportion of households experiencing disasters and climate change impacts has increased gradually. Regarding household capacity to respond and adapt to disasters and climate change, households in the target area mainly focused on resilient farming techniques for rice crop production rather than other farming activities, and most of the practices were targeted to adaptation in the occurrence of droughts. The issue of receiving Early Warning Signs (EWS) information was addressed and 37% of the respondents reported "no source of climate information". Therefore, it is recommended to strengthen the capacity of local people in the coastal areas of Cambodia in responding to climate change.

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KEYWORDS

Climate change, coastal zone, climate variability

HIGHLIGHTS

- The coastal zones of Cambodia are vulnerable to climate change.
- Agriculture is one of the sources of income for rural livelihood in the coastal zone of Cambodia.
- Adaptive capacity seems to be low in the coastal zones of Cambodia.

1. INTRODUCTION

Global or economy-wide models are the most frequently used assessment indicating the impacts of climate change on the economy (Kikstra et al., 2021; Nordhaus, 2010, 2018). In the previous studies, these assessments were used to estimate the total impacts on poverty projected aggregate under the baseline scenario business as usual or an emission abatement path (Nordhaus, 2010, 2018; Skoufias, 2012). Although the estimation models are marginal, GDP is projected to decline to 1.5% by 2055 (Skoufias, 2012). Therefore, climate change, the environment and socioeconomics are linked together, which differ from sector to sector.

The impacts of climate change and variability on worldwide agricultural production are significantly concerning. The first concern is that human activities interfere with the ecosystem harming the Earth's climate and threatening food security (Easterling & Apps, 2005; IPCC, 2001a, 2001b). The second concern is the potential damage of climate change impacts at the national level that may arise over the coming decades as well as globally; since the damage affects national and international policies, trading patterns, resource use, regional planning, and ultimately the welfare of citizens (Easterling & Apps, 2005; Foresight, 2011; IPCC, 2012; Skoufias, 2012). Furthermore, the susceptibility of agriculture and fisheries to climate change causes either direct or indirect impacts on the economic sector (IPCC, 2012). Also, the severity of climate change depleting natural resources as the environmental and demographic pressures will increase (Anthoff & Tol, 2014). The gradual climate change and extreme weather in recent years have hampered the progress of alleviating poverty and food insecurity, negatively affecting overall development efforts (Foresight, 2011; Skoufias, 2012). Therefore, the concern in these sectors tends to increase as the years pass as a result of rising threats to current income and consumption patterns of households and individual livelihoods. In particular, the changes in climate and weather conditions that impact the livelihoods of the households involved in agriculture and fisheries or other affected groups are frequently the way to approximate the different patterns. Furthermore, Cambodia's National Adaptation Programme of Action (NAPA) 2006 report has prioritised the water resource sector in NAPA preparation, particularly since it affects agriculture and food security, which would affect Cambodia's socioeconomic development (Royal Government of Cambodia [RGC], 2006). In the last few years, Cambodia's economy is highly reliant on agriculture and fisheries, which contribute about 25% of the GDP and employ 49% of the labour force (WBG and ADB, 2021). Meanwhile, the Cambodian rural livelihood is mostly dependent on the agricultural sector, including farming, fisheries and forestry, which is directly sensitive to climate variability and change. Extreme climate change events and irregular seasonal weather patterns harm food security, infrastructure and livelihoods in rural and urban areas (Easterling & Apps, 2005). At the same time, slow onset events as a result of climate change are evident in land properties for farming and pasture, forestry, fisheries, biodiversity and ecosystems (van der Geest & van den Berg, 2021).

From a socioeconomic point of view, climate change impacts not only agricultural households in rural areas but also highly increases welfare vulnerability (Skoufias & Vinha, 2012). There are two primary ways in which environmental changes have an impact on livelihood consumption in rural areas. The first way is through their direct effect on agricultural production, which subsequently reduces income for vulnerable households. The second way is through the influence of climatic variations on the health of economically disadvantaged households. Among these households, children are particularly susceptible to these effects. This susceptibility stems from the fact that climatic changes can potentially lead to an increase in the prevalence of diseases or elevate the risk associated with exposure to significant weather fluctuations (Skoufias & Vinha, 2012).

Consequently, the impacts of climate change play out in two ways. On the one hand, they have an indirect role by influencing factors like income levels, the availability of resources, and the need for their reallocation. On the other hand, there is a direct connection between the environment and both health outcomes and consumption patterns. These combined effects ultimately determine the overall well-being of local households over any given period of time. Skoufias and Vinha (2012) indicated that an environmental shock might have an indirect impact but a direct negative impact on health. In the case of Cambodia, increasing the temperature or precipitation in different regions may show benefit or damage to crop yields, depending on the category of crops or the season that occurred (Tong, Yoshida, Maeda, & Kimijima, 2007). For that reason, changes in climate, such as temperature or precipitation, may negatively affect health conditions of households in rural areas as the higher temperature creates suitable conditions for diseases to develop (WHO, 2015).

Climate change is projected to increase the frequency of extreme events, resulting in significant alterations to Cambodia's climate patterns, including shifts in temperature, rainfall distribution, and rising sea levels. Cambodia's Second National Communication to the UNFCCC (NC2) examines the impact of climate change on various aspects of life in the country, revealing its potential to substantially affect both human well-being and economic growth, as well as the depletion of natural resources, as estimated by the GSSD in 2015.

The repercussions of these changes are particularly pronounced in coastal regions, where habitats, resources, and populations are experiencing considerable impact. The physical variables of temperature, rainfall, humidity, and winds are undergoing shifts. The coastal environment faces profound disruption due to rising sea levels, increased storminess, shifts in wave patterns, variations in coastal runoff, and changes in sediment loading. Previous reports from multiple countries, including the IPCC in 2001a and 2012 and Carmack, Winsor, and Williams in 2015, have highlighted these trends. The intricate web of biological changes, spanning from individual organisms to entire ecosystems, is transforming the coastal zone's suitability for human habitation and use. Notably, small island subsistence and commercial agriculture are especially vulnerable to climate change, with rising sea levels leading to freshwater inundation, soil salinisation, and a consequential decline in water supply (IPCC, 2012).

Across the globe, coastal communities are bracing for the impacts of climate change, particularly those countries that are already deemed vulnerable to ongoing climate variability. Among the anticipated changes, the acceleration of sea-level rise stands out due to the cascading effects it triggers, such as increased flooding, coastal erosion, saltwater intrusion and ecological disruptions. As a result of these biophysical transformations, a range of socio-economic consequences is expected to reverberate throughout coastal regions. This encompasses not only declines in economic output but also dwindling ecological, cultural, and subsistence values that are tightly interwoven with these environments.

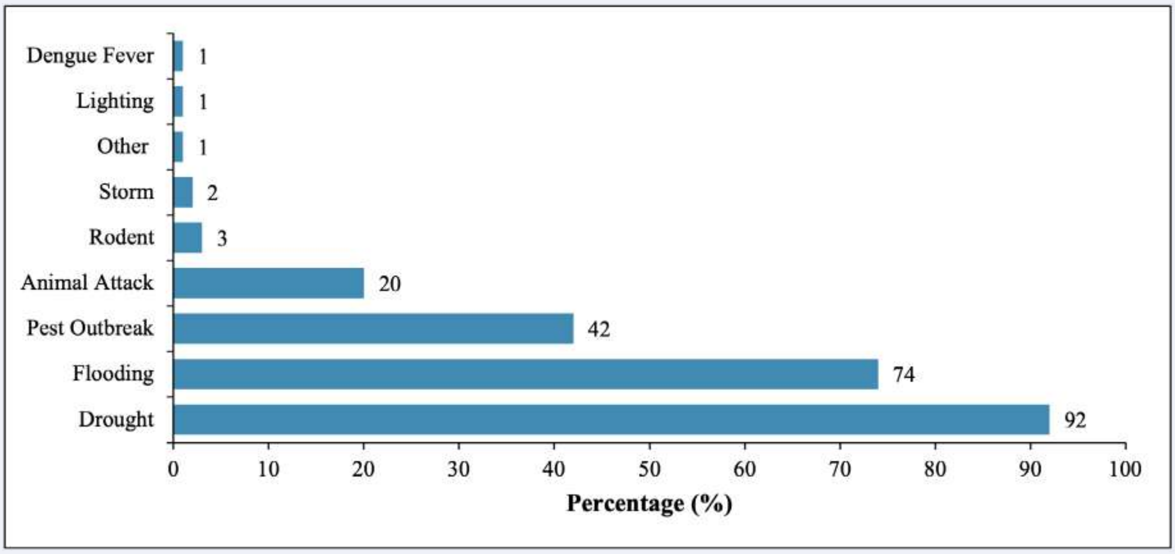

FIGURE 1. Perceived disaster occurrence in the community.

2. METHODOLOGY

The research design was divided into three phases: scoping, data collection and analysis. The sample selection, survey tool design and logistical arrangements were categorised into scoping phases. Then the training workshops on survey ethics and tools for data collectors, pre-testing of questionnaires in the field, and field surveys were categorised into the data collection phase. Finally, the performance of collected data, such as quality checking, entry, clean-up and analysis, was categorised into the data analysis phase.

Quantitative methods were used to collect the information using a structured questionnaire (tool) to survey individual households in the target areas. Thethe surveys on beneficiaries were then undertaken through face-to-face interviews. The representative samples were selected from the total samples of the target areas, indicating the whole targeted population with 95% confidence. The samples were selected from villagers living in a target area for longer than ten years using a random sampling technique with 400 sample sizes. The sites selected for the study were eight districts in the four provinces of Kep, Kampot, Preah Sihanouk and Koh Kong. The sample size was applied equally to each targeted province (100 samples/province). IBM's statistical software, SPSS version 21, was used to analyse data, mainly descriptive statistics (frequency and percentage). Microsoft Excel was used to create tables and figures.

3. RESULTS AND DISCUSSION

The target community responded that they were impacted by disasters and climate change. They reported negative impacts in areas such as food availability, agricultural production, health, education, dwellings and infrastructure. Multiple disasters and their impact on the community were reported during research in the target area, with at least three types of disasters being reported. Drought and floods were the most comment disasters that occurred in the target area and were reported by a majority of respondents (92% and 74%, respectively). Pest outbreaks were also recorded by 42% of respondents, followed by animal attacks at 20%. Very few (less than 5%) reported additional disaster types in the community, such as disease (particularly dengue fever), rodents, storms and lighting (storms). Regarding the frequency of occurrences encountered by households, the average number of incidents was reportedly 2 to 3 times for drought (ranging from 1 to 5 times) and two times for flood (ranging from 1 to 6 times) within the last ten years (Figure 1).

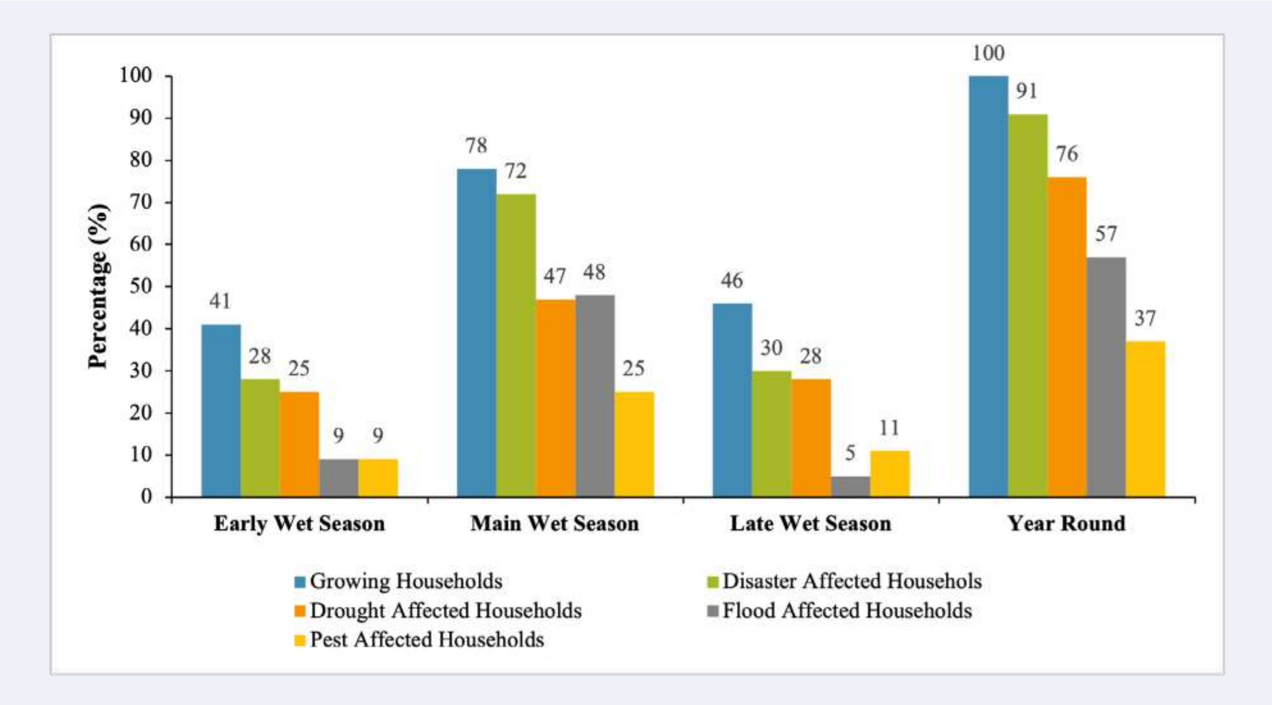

FIGURE 2. Proportion of the household encounters of different type of disasters.

To convey the impact of disasters and climate change on agriculture production, each respondent described quantities per unit of land used for different types of agricultural activities, including rice growing, cash crop growing, vegetable growing and raising livestock. The levels of impact on each activity were estimated by comparing the production obtained in normal years and those obtained in disaster years for the same unit of land. Rice production and farming activities are the main occupations of households in the target areas, and nearly all households (97%) were reportedly engaged in rice production. There were slightly different perspectives on the definition of the rice-growing season among the farmers and research team members according to geography and their understanding of the season. To avoid ambiguity, the survey teams agreed that April to July, July to October, and October to February is the Early wet season, Main wet season, and Late wet season, respectively. In Cambodia, the farmers grow three rice crops per year depending on the accessibility of irrigation systems. In target areas, nearly half of the households (45%) grew rice only one time, 40% two times, and a minority grew three times per year. The average number of rice crops per year was 1 to 2 times per year (1.65). Most households (78%) grew rice in the main wet season (Wet Season Rice), around 45% in the Early wet season and Late wet season, commonly defined as Dry Season Rice. Most of the households (90%) that grew rice crops in any season experienced at least one disaster. Main wet season crops were reported to have the highest proportion of households affected by disaster types such as pest outbreaks. Regarding the proportion of affected land, the households that encountered disaster impacts reported that all of their lands were affected by disasters, in which 60%, 54%, and 30% of total land were affected by drought, floods and pest outbreaks, respectively (Figure 2).

To predict the occurrence of disasters, the respondents from different target rural areas were asked to report various indigenous and technical early warning signs (EWS) and systems used in their communities and households. These predictions were mainly focused on flooding and drought, as these are common disasters in the targeted communities. Various indigenous EWS and systems were described during the survey, and confidence in EWS was highly associated with the education of the community members, their ages, localisation, and level of disaster occurrence and

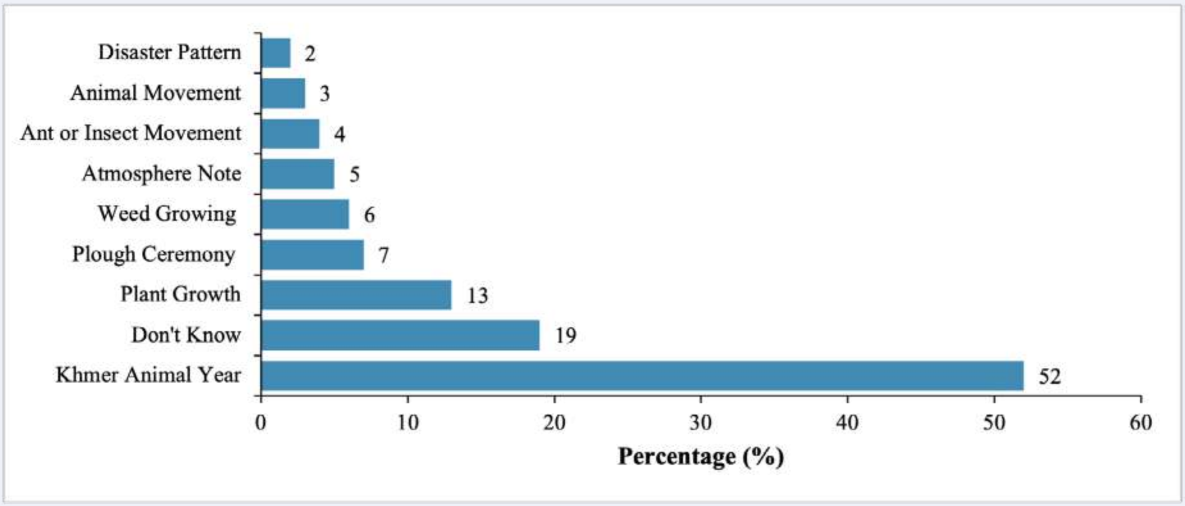

FIGURE 3. Indigenous knowledge on early warning signs and systems.

impact. Over 80% mentioned at least one type of EWS. This indigenous EWS, referred to as Khmer Animal Years, was commonly mentioned by over half of the households surveyed as a system to predict the occurrence of floods as well as drought. In this EWS, an animal represents each year in a twelve-year cycle. Belief in this system suggests that Flooding is likely to occur every 12 years, specifically in the year of Dragon, Snake or Rabbit. Belief in this EWS was most widespread among community elders. The Plant and Weed Growth EWS uses plants, known in Khmer as *troury ampel*, *khvet*, *kantrengkhet*, *ampeltek*, *trabek* and others to predict floods and drought, and was used by 13% of the households surveyed. For example, these households believed that there would be abundant rainfall when "*khvet*" produced many fruits. In other cases, if "*knantrengket*" or "*rosy*" had many flowers, that indicated little or no rainfall. The prediction made through the annual Plough Ceremony was believed by around 7% of households surveyed to indicate the occurrence of drought or floods as well as other phenomena. A minority of households mentioned the Insect Movement, including termites and ants, as an indigenous EWS used to predict flooding and rain, specifically termites for flooding and ants for rain. If termites or ants build a high hill for their colonies, it foretells the arrival of floods and heavy rain. Insects are believed to have special instincts related to the occurrence of floods. The Wild Animal EWS is used to predict occurrences of floods by very few households (3%). Various animal species, including satkrol and sathong, were utilised in this prediction process. According to the beliefs held by these households, flooding was anticipated when "*sathong*" laid their eggs atop a tree. Conversely, the occurrence of drought was predicted when specific behaviours associated with "*satkrol*," such as their crying characteristics, were observed (Figure 3).

Besides traditional EWS prediction, technical EWS was also investigated in addition to the survey. In general, flooding and drought are the main disasters that can be predicted technically, leading to early alerts. The main sources to predict are water level and rainfall level, which are recorded by the Hydrology and Water Department. Then, the information was forwarded to various channels, such as television and radio to broadcast the warning altered due to the accessibility of local television and radio channels to the target communities. Despite the fact that disaster information was disseminated through radio and television on a daily basis, the individuals within the targeted communities displayed minimal interest in weather forecasts, as reported by key informant interviews conducted within the villages, as well as observations made in the field. Most households are more interested in

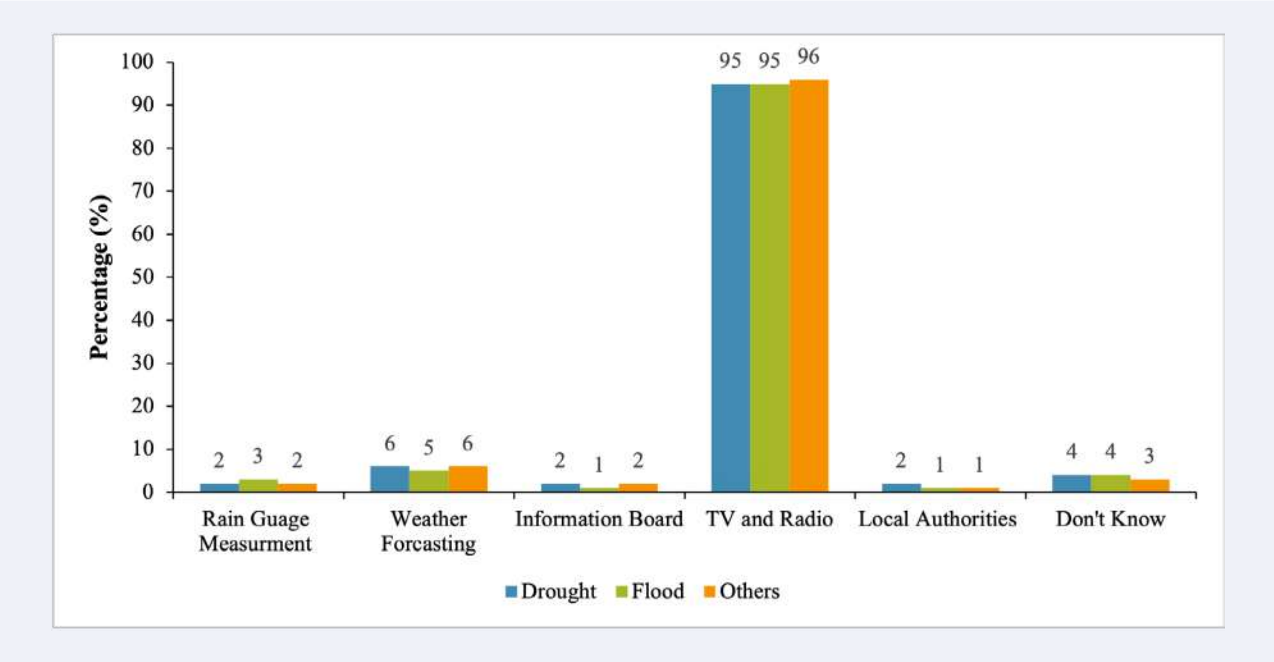

FIGURE 4. Technical early warning signs and systems.

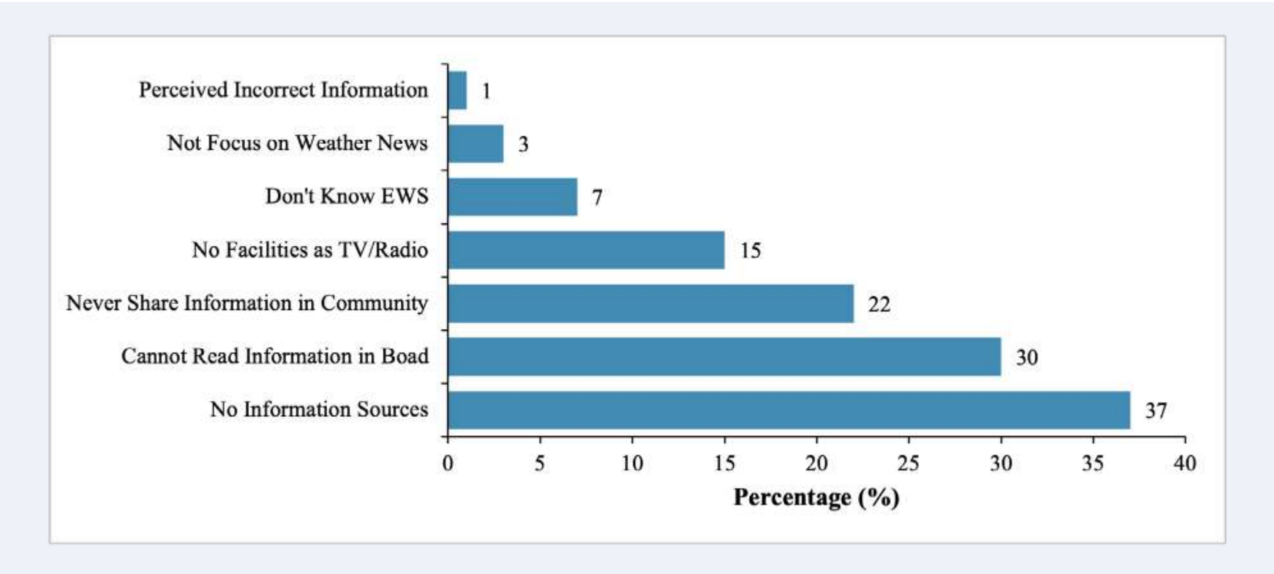

FIGURE 5. Problems on access to disaster and climate change information.

the movie (or story) than the news (or information) since they consider that disasters rarely occur in their communities. Apart from television or radio, the minority of households (less than 10%) stated that they depended on weather forecast information from various sources to predict the occurrence of disasters. A few households in the target areas also mentioned rain gauge measurements, information boards and dissemination of community information by the local authorities (Figure 4).

Regarding the issue of receiving EWS information about disasters, multiple problems were raised among the respondents during interviews. Many households claimed that they had no information sources (around 37%). Being unable to read the information on the board was also an issue raised by 30% of the respondents. A small number of respondents (15%) stated the primary issue was not having access to facilities, such as radio and television, or not being aware of EWS (7%) (Figure 5).

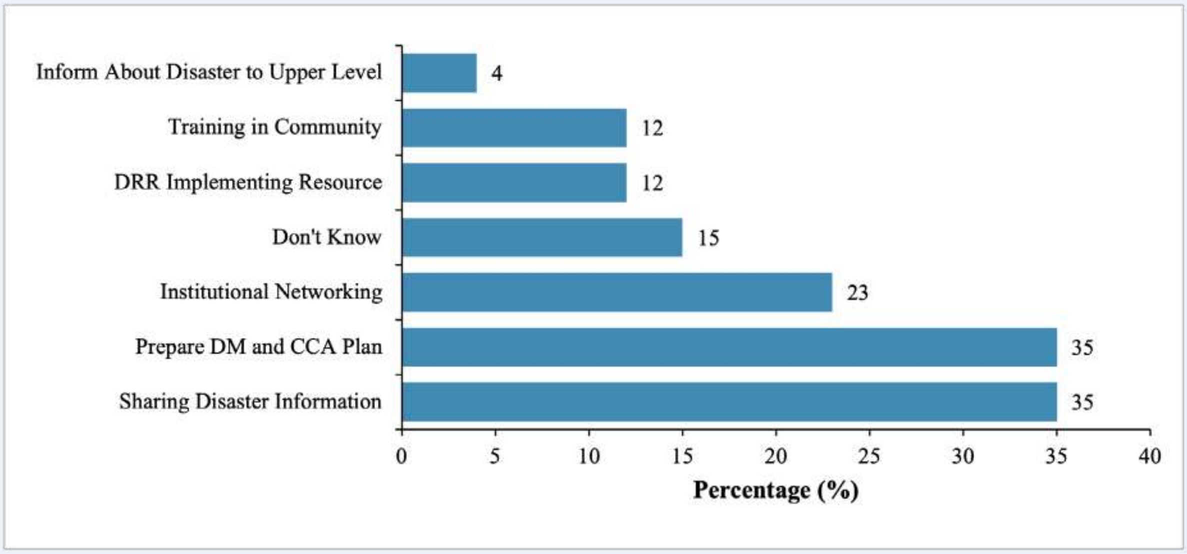

FIGURE 6. Perceived activities of committee in target village.

In order to address disaster risk reduction (DRR) issues, formal institutions were established from the national to commune levels, which signifies the most local government administration. The National Committee for Disaster Management (NCDM) leads the coordination of disaster management in the country. At the sub-national level, the Provincial Committee for Disaster Management (PCDM) coordinates and manages disaster response as well as DRR-related interventions with support from the District Committee for Disaster Management (DCDM) and the Commune Committee for Disaster Management (CCDM). CCDM and DCDM, as the lowest and most local administrative bodies, provide direct support for mitigating and responding to disasters in their locality.

The CCDM is chaired by the commune chief and has the role and responsibility for implementing policies related to Disaster Risk Management (DRM); disseminating disaster information to the local community; reporting to the DCDM and PCDM; conducting emergency rescues; acting as secretariat to DCDM; forming a supporting team and selecting volunteers and training the team; reporting emergencies to the DCDM and the PCDM; and planning and reporting budgets. To support CCDM, the Village Committee for Disaster Management (VCDM) was also established with key members, women members, and others. The VCDM works to share information on disasters and climate change with community members and provide communication between community members and upper authorities such as the CCDM, PCDM, and NCDM.

With the exception of local authorities, around 10% of all target households were highly aware of committee members in CCDM or VCDM, while over half did not know whether there was any related committee in their community. However, in cases of related activities, community members commonly targeted local authorities rather than other people. Out of the households that were aware of the committee (CCDM or VCDM), one-third reported the committee works on preparing Disaster Management (DM) and Climate Change Adaptation (CCA) plans for their village and shared disaster information with the community. Around 23% regarded the VCDM as an institutional network for their community. Regarding the work quality, 15% added that these committees were very active, while the remainder claimed not to be aware of their activities or stated that these committees were not very active (Figure 6).

4. CONCLUSION

Climate change-induced and other types of disasters, including drought, floods and pest outbreaks, were frequently encountered by the majority of households surveyed within the designated areas. These occurrences have had substantial and severe effects on these households' lives and communal undertakings. The impacts range from the devastation of crop yields and the decline of livestock production to constraints in accessing water for household needs, the destruction of property and assets, spikes in commodity costs, and limited access to social services. The frequency, intensity and severity of these phenomena have notably increased during disaster events, and this trend is anticipated to persist in the future. It is evident from the research results that drought occurrences have the greatest impact on the economic destruction of households in the target areas due to greater frequency and higher intensity of occurrences when compared to other types of disaster. In addition, serious impacts were also reported due to flooding. Rice crop production was the most seriously affected by disasters, followed by small-scale livestock production.

Agricultural production, particularly rice crop production, was reported to be the main income source of households in the target areas. However, the researchers also documented the susceptibility of agricultural production to climate change and the negative impacts of disasters because of their dependency on natural conditions and the lack of respondents' existing adaptation and coping mechanisms. The impact of natural disasters and climate change on household income in vulnerable areas is significant. These effects can be seen in the form of agricultural damage, depletion of natural resources, and increasingly frequent disasters. As a result, households are forced into chronic debt and must find alternative ways to generate income. These issues will continue if the household capacity and local institutional structures are not built or strengthened in terms of DRR and CCA.

Although the surveyed households experienced substantial effects on livestock production, they did not indicate the presence of any established mechanisms to manage or adapt to disasters or climate change concerning their animals. These outcomes may be attributed to the limitation of external interventions, poor availability of facilities or resources in the target community, lack of information, rarity of disaster occurrences, or economic constraints of the community to access facilities or resources. In conclusion, the local community's capacity for resilient agricultural techniques is notably restricted and requires substantial enhancement.

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