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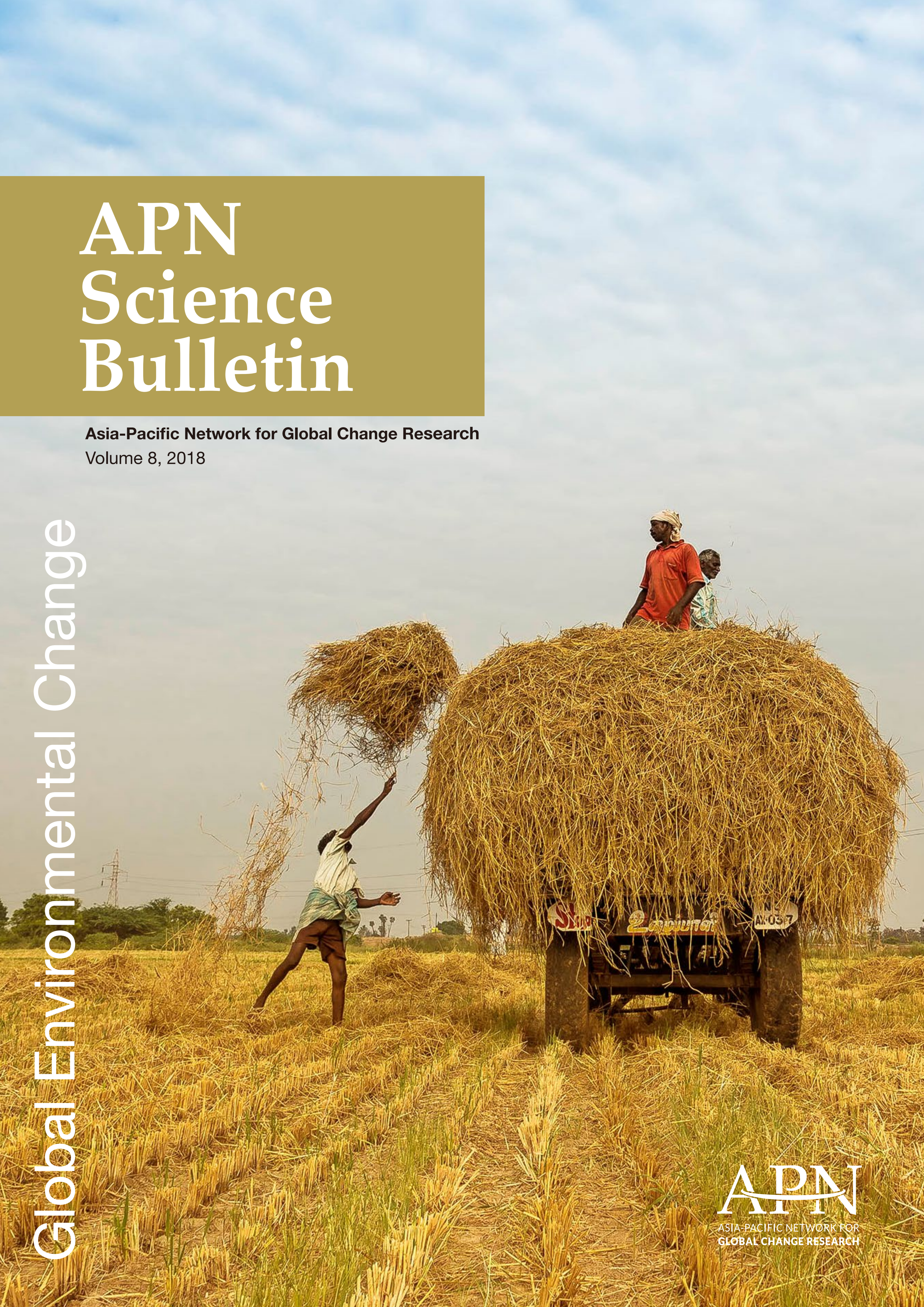

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Preface

It is my pleasure to present you with the eighth issue of the APN Science Bulletin, which features results, outcomes and findings of some recently completed projects funded by APN.

The APN Science Bulletin was first published in March 2011 as a record of recently completed projects. Since 2016, it has adopted a more rigorous peer-review process, involving external experts specialized in global change and sustainability sciences.

Eight articles are included in the 2018 issue, which covers diverse topics ranging from regional climate projections and climate impact assessments to building resilience and adaptive capacity through participatory tools. APN's emphasis on promoting multi-stakeholder, multi-country, multi-disciplinary and action-oriented research is particularly evident in this issue.

I hope that the information contained in this publication will be useful for those working in the frontline of leveraging scientific knowledge to build a safer, more resilient, and more sustain-able world for the current and future generations. I also hope that the APN Science Bulletin continues to pave the way to more and deeper collaboration among like-minded scientists and researchers to realize the vision of APN to foster an Asia-Pacific region that is successfully addressing the challenges of global change and sustainability.

Finally and very importantly, I would like to express my heartfelt gratitude to all reviewers for upholding a high-quality standard and scientific rigour, and to the authors for their hard work and cooperation throughout the publication process.

Seiji Tsutsui

Director
APN Secretariat

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Future changes in annual precipitation extremes over Southeast Asia under global warming of 2°C

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ABSTRACT

This article provides detailed information on projected changes in annual precipitation extremes over Southeast Asia under global warming of 2°C based on the multi-model simulations of the Southeast Asia Regional Climate Downscaling/Coordinated Regional Climate Downscaling Experiment Southeast Asia (SEACLID/CORDEX-SEA). Four indices of extreme precipitation are considered: annual total precipitation (PRCPTOT), consecutive dry days (CDD), frequency of rainfall exceeding 50 mm day^{-1} (R50mm), and intensity of extreme precipitation (RX1day). The ensemble mean of 10 simulations showed reasonable performance in simulating observed characteristics of extreme precipitation during the historical period of 1986–2005. The year 2041 was taken as the year when global mean temperature reaches 2°C above pre-industrial levels under unmitigated climate change scenario based on Karmalkar and Bradley (2017). Results indicate that the most prominent changes during the period of 2031–2051 were largely significant. Robust increases in CDD imply impending drier conditions over Indonesia, while increases in RX1day suggest more intense rainfall events over most of Indochina under 2°C global warming scenario. Furthermore, northern Myanmar is projected to experience increases in CDD, R50mm and RX1day, suggesting that the area may face more serious repercussions than other areas in Southeast Asia.

HIGHLIGHTS

» The models simulated the characteristics of observed precipitation extremes

» Significant and robust changes in CDD over Indonesia and in RX1day over Indochina

» Significant and robust changes in CDD, R50mm and RX1day over northern Myanmar

KEYWORDS

Precipitation Extremes, SEACLID/CORDEX-SEA, multi-model ensemble, future changes, Southeast Asia

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1. INTRODUCTION

Southeast Asia is a region highly exposed and vulnerable to the impacts of climate change. It is a problem compounded by the low resilience and adaptive capacity of the mostly developing and least developed countries in the region (Hijioka et al., 2014). The Fifth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC AR5) has indicated that Southeast Asia has already been experiencing long-term changes in climate (Christensen et al., 2013) with consequent impacts (Hijioka et al., 2014). Continued warming would likely affect the region more in the future. However, there has been no detailed study of future changes in precipitation extremes in Southeast Asia.

While the Paris Agreement provides a ray of hope for countries in the region, given its main goal to limit global warming below 2°C relative to pre-industrial level, recent studies suggested that current commitments of the agreement appear insufficient in achieving this goal (e.g., Raftery, Zimmer, Frierson, Startz, & Liu, 2017; Rogelj et al., 2016). In fact, Rogelj et al. (2016) estimated that with the current commitments in the Paris Agreement, there is a 10% likelihood that mean global temperature will exceed 3.9°C with a median range of 3.5–4.2°C. Raftery Zimmer, Frierson, Startz, and Liu (2017) also indicated only a 5% (1%) likelihood of warming below 2°C (1.5°C) by the end of the 21st century.

This study provides detailed information of future changes in precipitation extremes in Southeast Asia under global warming of 2°C, which is policy-relevant for countries in the region.

2. METHODOLOGY

The analysis in this paper was based on the output of multi-model simulations of the Southeast Asia Regional Climate Downscaling / Coordinated Regional Climate Downscaling Experiment (SEACLID/CORDEX–SEA) (Cruz et al., 2017; Juneng et al., 2016; Ngo-Duc et al., 2017; http://www.ukm.edu.my/seaclid-cordex). In SEACLID/CORDEX–SEA, many general circulation models (GCMs) have been dynamically downscaled to a 25 km resolution, except for the 50 km coupled global ocean-regional atmosphere model (ROM) (Sein et al., 2013). The models have been integrated over a domain of 85.5°E–146.5°E, 15°S–27°N, using multiple regional climate models (RCMs). Table 1 lists the 10 ensemble members used in the analysis. Most simulations started earlier than the 1970s and continued until 2100, depending on the model. The reference period in this study is 1986–2005. The year 2041 was determined as the time when global mean temperature reaches 2°C above pre-industrial level for the RCP8.5 scenario based on Karmalkar and Bradley (2017), which used the ensemble average global mean temperature from 35 GCMs of the Coupled Model Intercomparison Project Phase 5 (CMIP5). The RCP8.5 scenario, which represents a very high baseline emission scenario (van Vuuren et al., 2011), was chosen to mimic the pathway of unmitigated climate change.

Figure 1 shows the ensemble mean temperature anomalies with the range of maximum and minimum values over Southeast Asia from the SEACLID/CORDEX–SEA simulations following RCP8.5 scenario. Interestingly, the ensemble mean warming over Southeast Asia is projected to reach the 2°C threshold by 2047, which suggests that temperature in SEA region is slightly lower than the global average. To derive the climatology of precipitation extremes around the year 2041, we consider 2031–2051 as the averaging period. Many studies have indicated that a window of 20 years is sufficient for calculating a stable climatology of extremes (e.g., Lelieveld et al., 2016). Four extremes indices were selected from the set of indices described by the Joint CCI/CLIVAR/JCOMM Expert Team on Climate Change Detection and Indices (ETCCDI) (see http://etccdi.pacificclimate.org/list_27_indices.shtml) (Table 2). These indices were used to examine the characteristics of precipitation extremes on an annual scale.

The ensemble model mean of each index was evaluated using daily gridded precipitation data of the Climate Hazards Group InfraRed Precipitation with Station data (CHIRPS) (http://chg.geog.ucsb.edu/data/chirps/) from the historical period. Annual anomalies of the indices were first derived relative to respective climatological means. Then the probability density function (PDF) of the anomaly of each index was computed from both modelled and observed

Ensemble member	*GCM*	*RCM*
1	CNRM-CM5 (CNRM, France)	RegCM4 (ICTP, Italy)
2	HadGEM2-AO (Hadley Centre, UK)	RegCM4 (ICTP, Italy)
3	MPI-ESM-MR (MPI-M, Germany)	RegCM4 (ICTP, Italy)
4	EC-Earth (EC-Earth consortium)	RegCM4 (ICTP, Italy)
5	CSIRO MK3.6 (CSIRO, Australia)	RegCM4 (ICTP, Italy)
6	HadGEM2-AO (Hadley Centre, UK)	WRF (NCAR USA)
7	CNRM-CM5 (CNRM, France)	RCA4 (SMHI, Sweden)
8	HadGEM2-ES (Hadley Centre, UK)	RCA4 (SMHI, Sweden)
9	HadGEM2-ES (Hadley Centre, UK)	PRECIS (Hadley Centre, UK)
10	MPI-ESM-LR (MPI-M, Germany)	ROM (GERICS-AWI, Germany)

TABLE 1. List of GCMs and RCMs considered in this study.

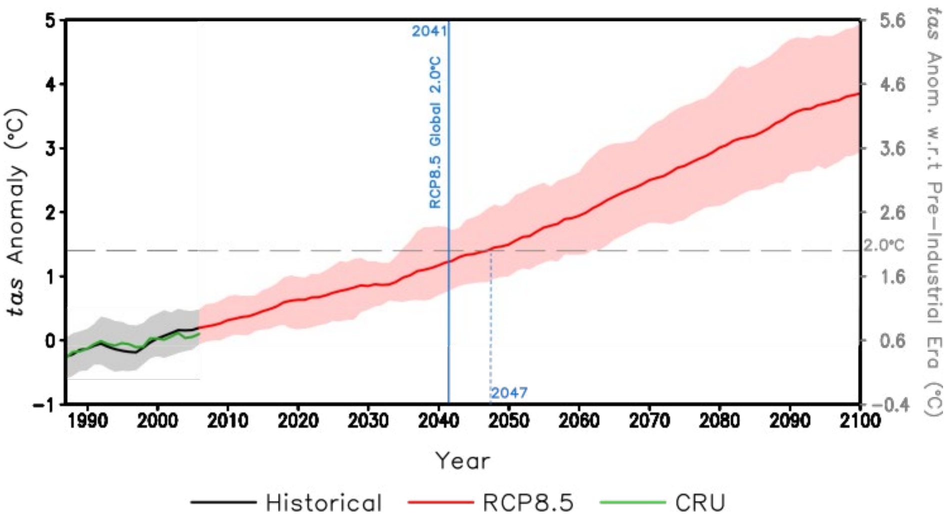

FIGURE 1. Ensemble mean annual temperature anomalies (solid line) and its spread (shaded) averaged over Southeast Asia following the RCP8.5 scenario. The scale on the left y-axis indicates the change relative to the average over the historical period (1986–2005), while the scale on the right y-axis shows the change relative to pre-industrial level. In the historical period, the ensemble mean (black) is compared with observed temperature anomalies from the Climatic Research Unit (CRU) (green). The vertical lines indicate the years when global warming (solid line) and the warming over Southeast Asia (dashed line) reach 2°C (relative to pre-industrial level).

Index	*Abbreviation*	*Description*	*Units*
Total Precipitation	PRCPTOT	Annual total precipitation in wet days	mm
Consecutive Dry Days	CDD	Annual maximum number of consecutive days when daily precipitation < 1 mm	days
Number of extremely heavy precipitation days	R50mm	Annual count of days when daily precipitation ≥ 50 mm	days
Maximum 1-day precipitation amount	RX1day	Annual maximum 1-day precipitation	mm

TABLE 2: List of precipitation extreme indices used in this study.

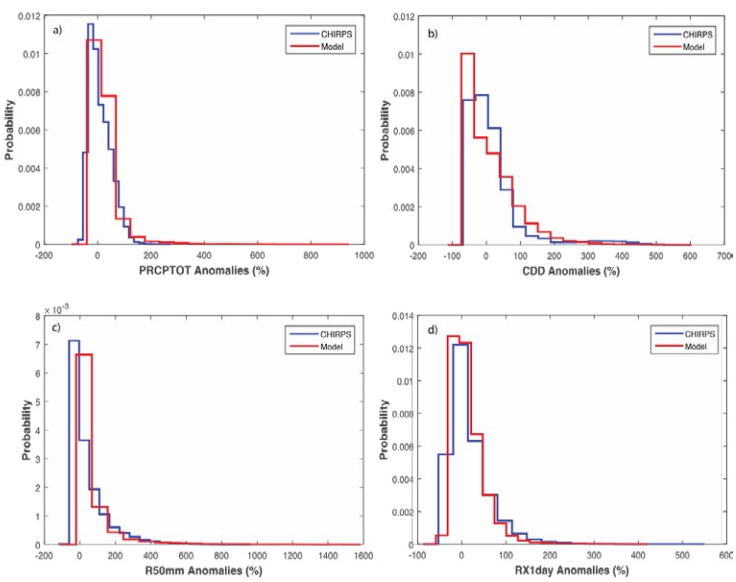

FIGURE 2. PDF of the anomalies in observed (blue) and modelled (red) indices for the historical period: (a) PRCPTOT, (b) CDD, (c) R50mm and (d) RX1day.

data (e.g., King, Karoly, & Henley, 2017). Future changes in precipitation over the 2031–2051 period when global warming reaches 2.0°C are expressed as percentage of change relative to the climatological mean. Hatching is used in the spatial maps of changes in each index to indicate areas where the climate change signal is stronger than interannual variability at a 95% significance level. The significance was determined using a Monte Carlo technique (Baez & Tweed, 2013). The robustness of the projected changes at 95% level is indicated by red dots if at least 7 models agreed in the sign of change out of the total 10 ensemble members. The number 7 was determined using a binomial probability distribution (Vautard et al., 2014).

3. RESULTS AND DISCUSSION

3.1 Validation of modelled precipitation extremes

Figure 2 shows the PDFs of the anomalies in PRCPTOT, CDD, R50mm and RX1day for both the observed CHIRPS dataset and model output. Similarities in the observed and modelled PDFs show that the regional climate simulations reasonably captured the characteristics of the observed extreme precipitation anomalies over Southeast Asia. The models have not only reasonably simulated the PRCPTOT anomalies but also the CDD, R50mm, and RX1day. Nevertheless, there are some minor differences between observed and modelled PDFs for CDD and R50mm, which could be due to the shortcomings in the model or CHIRPS data itself.

3.2 Projected changes in precipitation extremes

Understanding the changes in precipitation extremes is crucial since these changes will drive

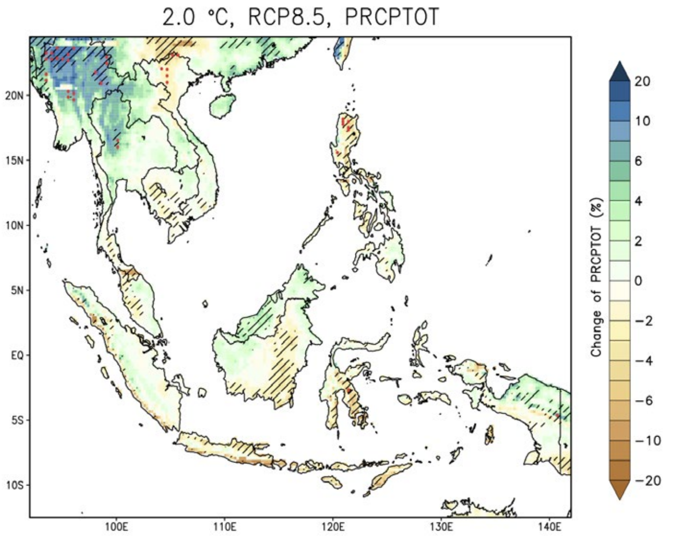

FIGURE 3. The projected annual PRCPTOT changes relative to the historical period (1986–2005) when global warming reaches 2°C (relative to pre-industrial level). Hatched areas indicate significant changes at the 95% level, while red dots show the robustness of the changes.

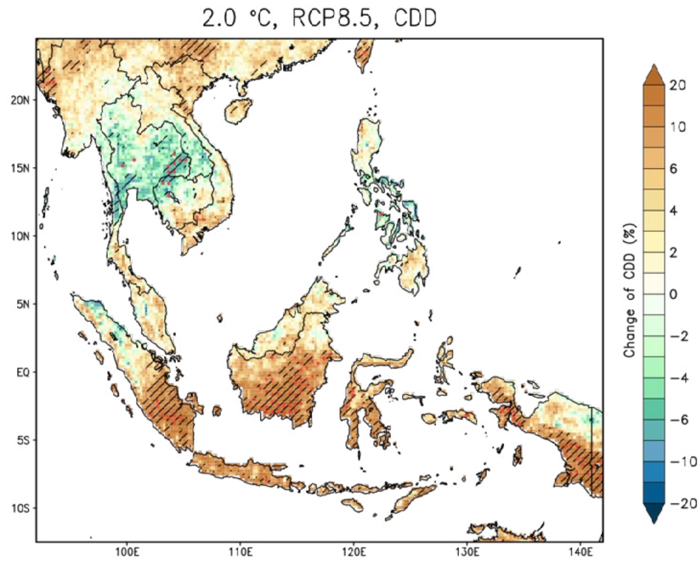

FIGURE 4. As in Figure 3, but for the projected annual CDD changes.

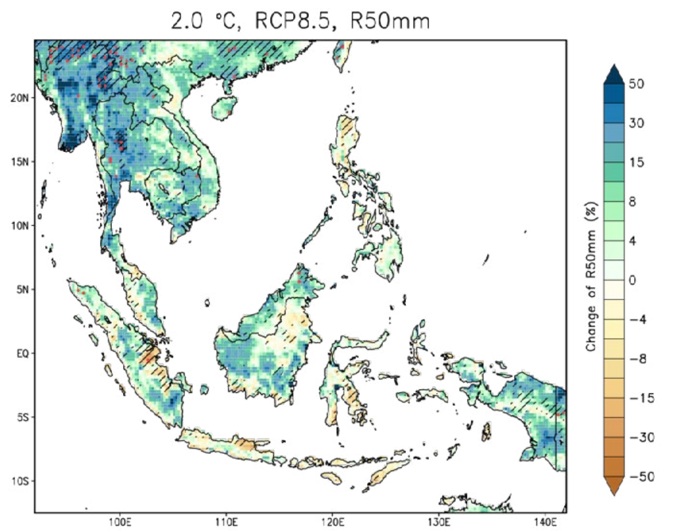

FIGURE 5. As in Figure 3, but for the projected annual R50mm changes.

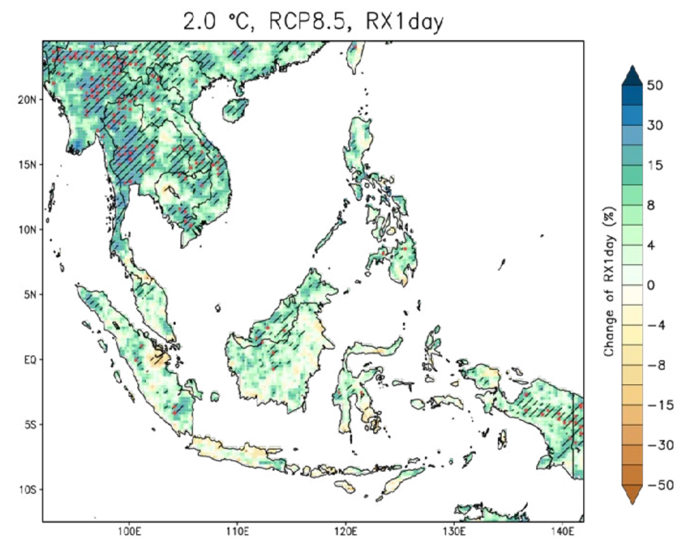

FIGURE 6. As in Figure 3, but for the projected annual RX1day changes.

the results from any impact assessment. Since there has been no previous study assessing changes in precipitation extremes under 2°C global warming over Southeast Asia, it is not possible to compare the consistency of the results with other studies. However, there is good confidence in these results given the use of the multi-model approach with 10 ensemble members. In addition, the resolution of 25 km should be high enough to resolve regional processes. Many studies have indicated "added values" of RCM compared with GCM in simulating extremes (e.g., Kanamitsu & DeHann, 2011). However, investigating the added values of RCM is outside the scope of this study.

The projected changes in PRCPTOT when the global mean temperature reaches 2°C above pre-industrial level are shown in Figure 3. Noticeably some areas indicate increases, others decreases, but the percentage of change is generally relatively small. The largest increase can be seen over northern Myanmar where the projected increase is 10-15%, which is both significant and robust. Other regions are projected to experience significant decreases and increases but these changes are not robust.

Generally, annual CDD is projected to increase over Indonesia (Figure 4). The changes are most significant and robust over southern Sumatra, Kalimantan, Sulawesi and Papua. The north-western region of Myanmar is also anticipated to have a longer duration of dry conditions. Furthermore, CDD is projected to increase over northern Vietnam and Java, and to decrease in central-eastern Thailand but these changes are mostly not significant, except in eastern Thailand.

Despite the tendency to have prolonged dry days in the future, not all regions are projected to experience significant reduction in total rainfall (Figure 3). For example, despite the increase in CDD in southern Sumatra, there is no significant decrease in total rainfall over the area (Figure 3). The decrease in rainfall due to the increase in CDD could be offset by the increase in either frequency or intensity of extreme rainfall or both. Indeed, both the frequency (R50mm; Figure 5) and the intensity (RX1day; Figure 6) of extreme precipitation events largely show increased changes albeit not significant over Sumatra. Interestingly, over northern Myanmar, changes in CDD, R50mm and RX1day are largely significant and robust (Figures 4, 5 and 6). In most areas the projected changes in R50mm are largely not significant and not robust. However, projected changes in RX1day in many areas in Indochina are generally significant and robust, which suggests the occurrence of more intense rainfall events in this region.

4. CONCLUSION

This study evaluates the changes in annual precipitation extremes when global mean temperature reaches 2°C above pre-industrial level (ca. 2041) under the unmitigated climate change scenario (RCP8.5) based on the multi-model simulation outputs of SEACLID/CORDEX–SEA. The results are likely to be policy-relevant for countries in this region, especially in light of the lingering doubt in achieving the target of capping global warming below 2°C under the Paris Agreement. The most notable changes are the significant and robust increase in CDD over most of Indonesia, and increase in RX1day over many areas in Indochina. Most likely, even larger changes are projected if the seasonal timescale is considered. Hence, this result may have some implications on water resources and food security if global warming continues above 2°C. Northern Myanmar is projected to experience largely significant and robust changes in CDD, R50mm and RX1day. This implies an increased likelihood not only for droughts to occur in the area, but also more frequent and intense extreme precipitation events in the future.

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Mapping of dengue vulnerability in the Mekong Delta region of Viet Nam using a water-associated disease index and remote sensing approach

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ABSTRACT

For the last two decades, dengue fever has continuously been a disease burden in Viet Nam, particularly in the Mekong River Delta (MRD) region, which is one of the regions most vulnerable to climate change. This study focuses on mapping vulnerability to dengue over the MRD region of Viet Nam by applying the Water-Associated Disease Index approach developed by Dickin, Schuster-Wallace and Elliott (2013) and using geospatial data. The data includes annual land cover and monthly temperature extracted from MODIS (Moderate Resolution Imaging Spectroradiometer) and monthly precipitation from GSMaP (Global Satellite Mapping of Precipitation). The maps, produced for the period 2001-2016, helped in analyzing temporal and spatial patterns of vulnerability to dengue in the region. The results show clear seasonal variation in vulnerability over the whole region following the variability in the climate factor. Pearson's correlation was used to evaluate the association between dengue rates and vulnerability aggregated at the provincial level. Significant linear associations, with a correlation coefficient greater than 0.5, were found in half of the provinces mapped. Mapping vulnerability to dengue using geospatial technology seems to be an effective means for supporting public health authorities in disease control and intervention not only for the MRD region but also for the whole country of Viet Nam.

KEYWORDS

Dengue, Vulnerability mapping, Remote sensing data

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HIGHLIGHTS

- » Mapping vulnerability to dengue in Viet Nam by exposure and susceptibility components
- » Extensive use of remote sensing data for vulnerability mapping

1. INTRODUCTION

Under the impact of global climate change on human health, there is an increasing number of infectious disease cases (Patz, Campbell-Lendrum, Holloway, & Foley, 2005), including mosquito-borne diseases such as dengue, one of the most climate-sensitive diseases. Climate factors, in addition to multiple human, biological and ecological determinants, influence the emergence and re-emergence of infectious diseases (Patz & Balbus, 1996). In Southeast Asia, a study by Sia Su (2008) has shown that there was a significant correlation between rainfall and dengue incidence in metropolitan Manila, the Philippines, from 1996 to 2005. Promprou, Jaroensutasinee and Jaroensutasinee (2005) also found a correlation between temperature, rainfall and dengue incidence in southern Thailand using multiple regression analysis. Dom, Hassan, Latif and Ismail (2013b) generated a temporal model using climate variables for the prediction of dengue in Malaysia and showed that climate variables affect dengue incidence in multiple ways. On a regional scale, a review of the impacts of climate change on human health by Patz, Campbell-Lendrum, Holloway and Foley (2005) provided more evidence of the burden of climate change-attributable diseases and emphasized the uncertainty in attributing diseases to climate change, owing to a lack of long-term and high-quality data.

However, climate change is certainly not the only factor. The land cover of the area might also have an impact on dengue fever. Cheong, Leitão and Lakes (2014) showed an important correlation between the number of dengue cases and land cover, with human settlements and water body types having higher probabilities of infection than other land types. Besides land cover, dengue incidence occurred higher in the residential area, followed by commercial and industrial area (Dom, Ahmad, Latif, Ismail, & Pradhan, 2013a).

Analysis of vulnerability has popularly been applied to assess health hazards related to climate change (Patz & Balbus 1996; Dickin, Schuster-Wallace, & Elliott, 2013). Mapping health vulnerability to climate change with three components of exposure, sensitivity and adaptive capacity is a popular assessment approach, which includes 3 phases: problem formulation, analysis, and integration (Kovats et al., 2003). Patz and Balbus (1996) proposed a framework for the assessment of health vulnerability due to climate change. Dickin, Schuster-Wallace and Elliott (2013) developed the Water-Associated Disease Index (WADI) approach to provide a "practical tool" and vulnerability map in support of dengue prevention and control in Southeast Asia and South America and on a global scale. Khormi and Kumar (2011) reviewed and highlighted the advantages of geospatial data and techniques in the issue of mapping mosquito-borne diseases where satellite images provide good data with high temporal and spatial resolution to estimate various parameters (rainfall, temperature, soil moisture, land cover type, etc.) to identify mosquito habitats. Geographic information systems (GIS) will merge such information with socio-economic factors and disease incidence, applying spatial statistical analysis to map and model diseases with high accuracy. Recent application of GIS and spatial union analysis in Malaysia was successful in visualizing and predicting dengue hotspot and dissemination pattern (Dom, Ahmad, Latif, & Ismail, 2013c, 2017). The flexibility of the WADI framework allows the ability to adapt multi-dimensional data at different temporal and spatial scales, which can be applied with geospatial data (Louis et al., 2014).

This study focuses on the mapping of dengue vulnerability to the above-mentioned factors for the MRD of Viet Nam. The extensive use of remote sensing data for presenting climate variables in the WADI framework is described in the data and methodology section. GIS-based analyses are applied for processing the outputs, and mapping correlation, temporal and spatial variations are presented in the results and discussion section, followed by the conclusion section.

2. DATA AND METHODOLOGY

2.1 Study site

The study was conducted in the lower MRD in southern Viet Nam, the area most affected by dengue fever, with up to 65% of cases recorded during 1998-2015. Moreover, dengue fever has been reported as the second most frequent cause of hospital admissions among communicable diseases in this region (Phung, Talukder, Rutherford, & Chu, 2016). The MRD is a flat and low-lying area with a very complex network of rivers, channels and floodplains, supporting agriculture fields (Figure 1). The climate is tropical monsoon with a wet season from May to October and a dry season from November to April, and the average air temperature in the coldest months is approximately 18-20°C.

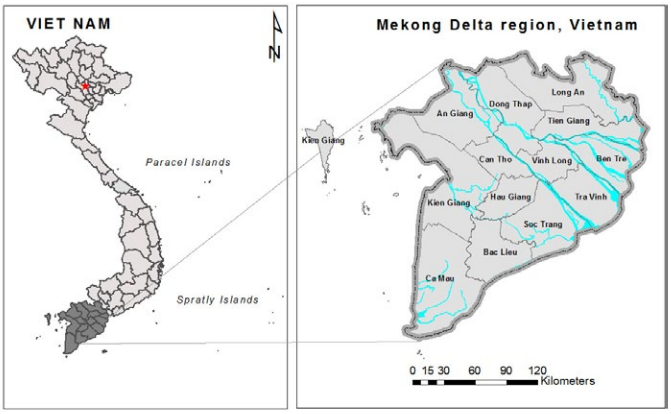

FIGURE 1. Map of the Mekong Delta region of Viet Nam

2.2 Mapping method - WADI application

This study applies the WADI conceptual framework developed by Dickin, Schuster-Wallace and Elliott (2013), which is described in Figure 2. In this framework, the vulnerability index is composed of only the exposure and susceptibility indicators, where the exposure describes conditions that are conducive to the survival and transmission of dengue in the environment. Susceptibility describes the existing sensitivity of a population to dengue. The susceptibility indicator also includes conditions that impact resilience, a concept described as the capacity to prevent, respond to and cope with disease.

We use two components of climate and human environment for the exposure indicator, while the susceptibility indicator comprises components indicating age, poverty, and healthcare access. The climate factor includes the two important variables of temperature and rainfall, and human environment consists of land cover and population density. Exposure and susceptibility scores were scaled between 0 and 1, representing a range from low to high exposure or susceptibility and

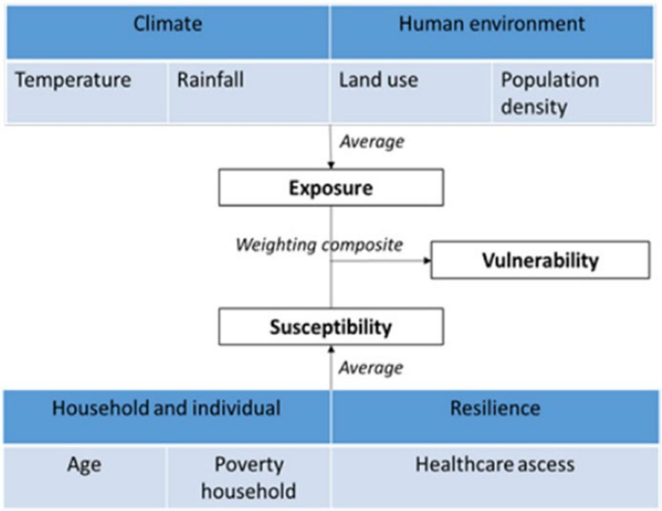

FIGURE 2. The WADI framework following Dickin, Schuster-Wallace and Elliott (2013)

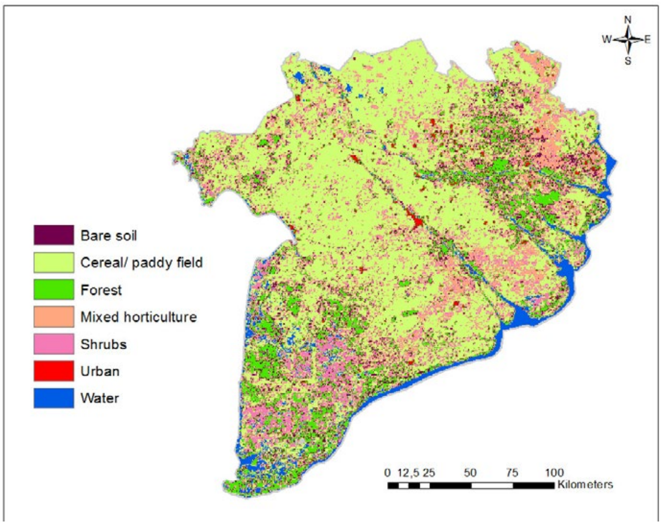

FIGURE 3. Modified land cover map from MODIS data (MCD12Q1) for the MRD in 2013

were based on the proposed threshold of Dickin, Schuster-Wallace and Elliott (2013), with modification by Cheong, Leitão and Lakes (2014) for land use.

Dickin, Schuster-Wallace and Elliott (2013) proposed 5 components, including population age, housing quality, water and sanitation, health care access, and female education level. Based on the availability of collected data, we were able to use 3 of these factors, as listed in Table 1. Louis et al. (2014) reviewed the 26 published papers on mapping dengue risk and found that age and income are two of the most commonly used factors for predicting dengue risk.

2.3 Remote sensing data

In this study, land cover data were extracted from a satellite-based secondary product, MODIS Land Cover Type yearly L3 global (MCD12Q1) product (Friedl et al., 2010; Friedl & Sulla-Menashe, 2015), and mapped with areas of standard Land Use Map of year 2010, with the scale of 1:100.000, provided by the Ministry of Natural Resources & Environment (MONRE), as in Figure 3.

In an attempt to extensively use remote sensing data, with the advantages of spatial coverage with high resolution and temporal availability, we used GSMaP data as an alternative for surface rainfall measurement. The daily GSMaP/MVK (version 6) data with a spatial resolution of 0.1 x 0.1 degrees (Ushio et al., 2009), were extracted for the MRD and accumulated to calculate the monthly amount. We used monthly Land Surface Temperature data from MODIS LST (MOD11A2) with a 1 km x 1 km resolution (Wan, 2007) as a proxy for air temperature.

3. RESULTS AND DISCUSSION

3.1 The vulnerability maps

Monthly maps of overall vulnerability were produced by combining raster layers of susceptibility and exposure indicators. The selection of weighting schemes for each indicator to the total vulnerability index was based on an approach in which different weightings were tested to find the best correlation coefficient of the WADI index with monthly dengue rates from 2002 to 2014 for each province. In fact, the vulnerability is more sensitive to exposure than the susceptibility indicator because the climate components clearly show monthly variations, while the others change at a yearly scale. Based on correlation results, we decided to use weightings of 1 for the susceptibility and 3 for the exposure indicator, so that the final vulnerability index was weighted more heavily on the exposure indicator. In addition, monthly data for temperature and rainfall were used in a time-lagged

Component	*Data sources*	*Threshold*
Age under 15 years	The General Statistics Office of Vietnam (2009 census dataset)	% population under 15 years by province
Health care access	Actual data from the General Statistics Office of Vietnam	Density health facilities per square km area
Poverty	Annual data from the General Statistics Office of Vietnam	% poverty household per province

TABLE 1. Summary of the susceptibility components used for calculation

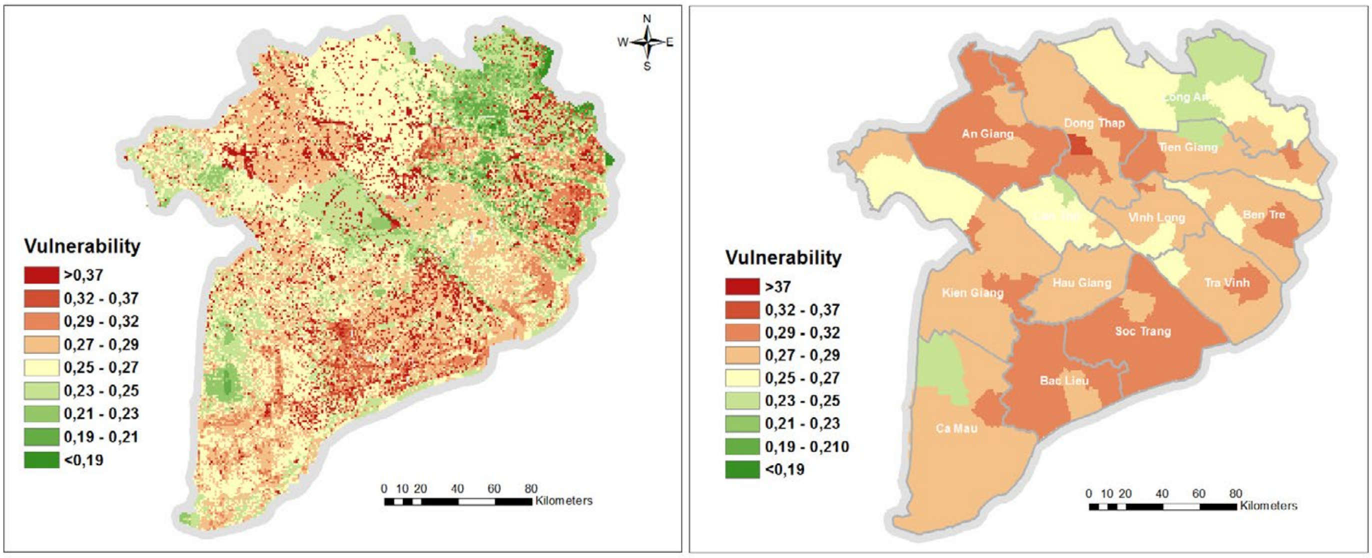

FIGURE 4. a) Yearly average vulnerability to dengue in grid map; b) that aggregated to administrative boundaries

manner based on their best correlation with monthly dengue incidences for each province. This approach is similar to the approach used by Vu, Okumura, Hashizume, Tran and Yamamoto (2014), where weather components strongly affected dengue transmission at a lag time of 0 to 3 months, with considerable variation in their influence among different areas in Viet Nam due to the delay between the onset of weather conditions and the impact on mosquito populations. Yearly vulnerability maps were produced by averaging monthly maps and aggregated to maps by district and provincial administrative boundaries by using GIS software as shown in Figure 4 (a & b).

The results suggest that vulnerability to dengue over the Mekong Delta region of Viet Nam varies greatly across spatial and temporal dimensions. The highest vulnerability is clearly observed in the scattered areas of urban and mixed horticulture land use while the lowest vulnerability is observed in the remote and sparse populations covered by forest and bare soil land types. Overall, this finding agrees well with the weighting of land use for calculating the exposure indicator (Table 1). We found that aggregated vulnerability concentrated higher in the provinces of An Giang, Dong Thap, Tien Giang, Ben Tre, and Soc Trang, corresponding to a high-risk cluster of dengue in the Mekong Delta area (Phung et al., 2016).

At a temporal scale, the monthly average data in Figure 5 clearly shows the seasonal variation of vulnerability with the lowest values in February-March, increasing towards the highest values in August-November. Obviously, this seasonal cycle is mainly affected by the seasonal variation in climate in this region, as other factors remained unchanged throughout the year. Generally, increased temperature and rainfall are associated with increased dengue transmission (Johansson, Dominici, & Glass, 2009); therefore, higher vulnerability is related to the rainy season during May-November. This trend was widely reported in many regions in Southeast Asia in tropical environments (Wai et al., 2012). This seasonal cycle also varies at a spatial scale, shown in Figure 5, which shows that higher vulnerability occurred in Bac Lieu, Soc Trang, and Ben Tre provinces in September, while it occurred in An Giang and Dong Thap provinces in October. Apparently, exposure to dengue heavily varies throughout the year, depending on the changes in climate conditions over the region.

3.2 Assessing the correlation of vulnerability with dengue incidence

We evaluate an association between monthly vulnerability indicators and dengue incidence by calculating Pearson's correlation for both the training data period of 2001-2014 and the last two years of 2015-2016 data. To avoid variance in dengue counts, the data was stabilized by log transformation to the same scale as vulnerability score. The regressions of vulnerability and dengue for the 2001-2014 training data are presented in Figure 6 for provinces with highly correlated cases. Again, we found that better regressions were associated with provinces with a high dengue rate.

The correlation varies significantly from 0.26 to 0.63 (with $p<0.05$) for different provinces, and a high correlation was only found in provinces with a high dengue rate. The most seasonal factor in this region that contributes to the exposure of vulnerability is rainfall; therefore, we also evaluated the association between monthly rainfall amount and dengue incidence for each province with Pearson's correlation. We compared two

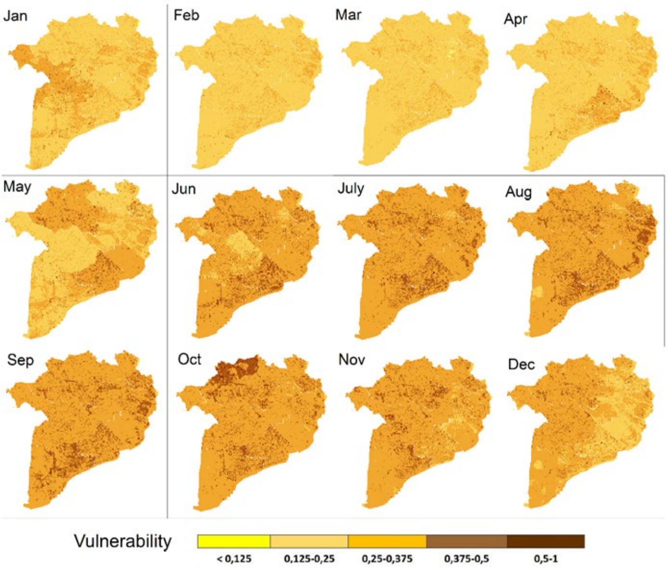

FIGURE 5. Monthly average vulnerability to dengue

correlations, as in Figure 7a, which show a similar trend in their variations: the higher correlation of dengue with rain and the better correlation of dengue with estimated vulnerability. This finding indicates that seasonal trends in exposure are highly sensitive to climate variables, as mentioned in the review of climate change and dengue with the modelling approach by Naish et al. (2014). Validation result for the 2015-2016 years of data also presented correlation above 0.5 in provinces of high-risk cluster of dengue towards the north-eastern part of the region (Figure 7b).

3.3 Discussion

With the extensive use of satellite remote sensing data for eco-environmental factors of rainfall, temperature, and land use, we have limited the inconsistency of data sources over the whole region for index calculating. As mentioned before, the vulnerability was weighted more heavily on the exposure indicator; therefore, changes in exposure resulted in greater changes in vulnerability. Because all index approaches are restrained by the weighting selection (Dickin & Schuster-Wallace, 2014), different weighting schemes were tested in this study, and the weight was assigned based on the best correlation of dengue incidence and vulnerability for the training data (2001-2014). Nevertheless, the result of validation showed the different performance of the WADI over the region; a high correlation of vulnerability with dengue incidence was found in provinces with high dengue risk. We anticipate a better correlation of dengue incidence with rain as one possible reason. However, as mentioned by Fekete (2009) dengue vulnerability includes conditions of exposure and susceptibility that can occur without virus transmission. Therefore, the high potential transmission areas or habitat are generally the areas with the densest human and vector population (Hasnan, Dom, Latif, & Madzlan, 2017).

The vulnerability maps could be constructed in raster grids with a high spatial resolution of environment variables but still be limited in social variables at the provincial and district scale levels. These data had been rasterized into grids comparable to environment variables for the input to WADI calculation. However, the availability of dengue cases at the provincial level limits the validation to that level, providing results in vulnerability relating to large-scale patterns but not processes occurring at smaller scales. Undoubtedly, a combination of socio-environmental factors affects the transmission of dengue disease at different scales: larger scale factors, such as climate, are responsible for the influence of dengue transmission over the region, while local factors relate to community activities to prevent human

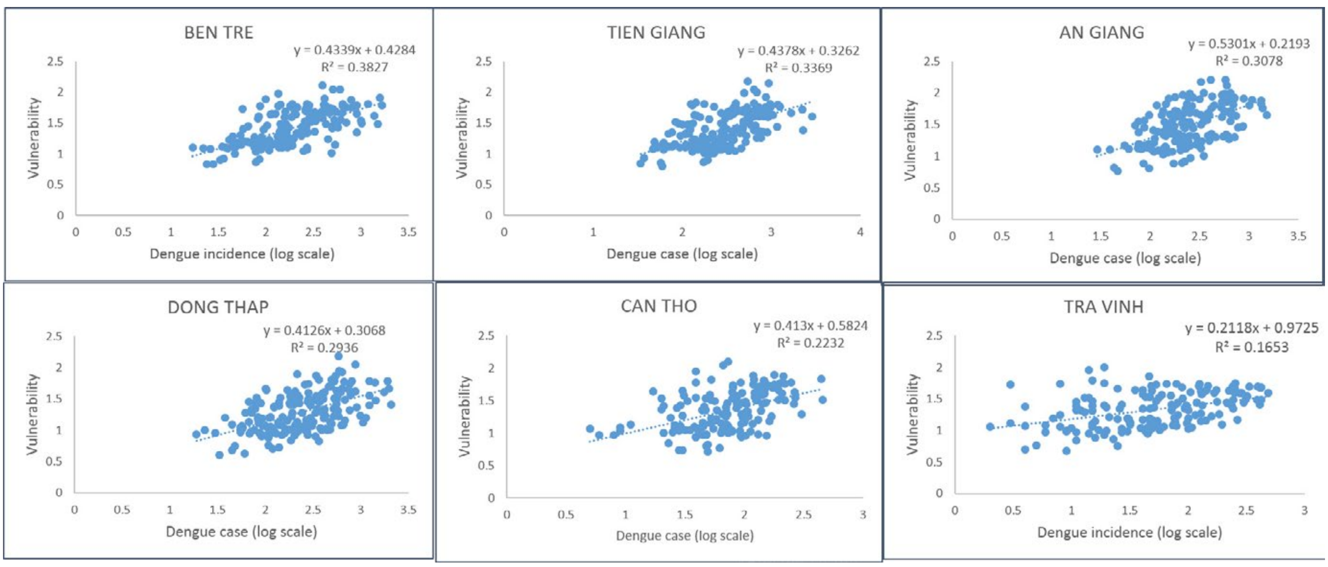

FIGURE 6. Regression between monthly vulnerability and monthly dengue for higher correlated cases of provinces

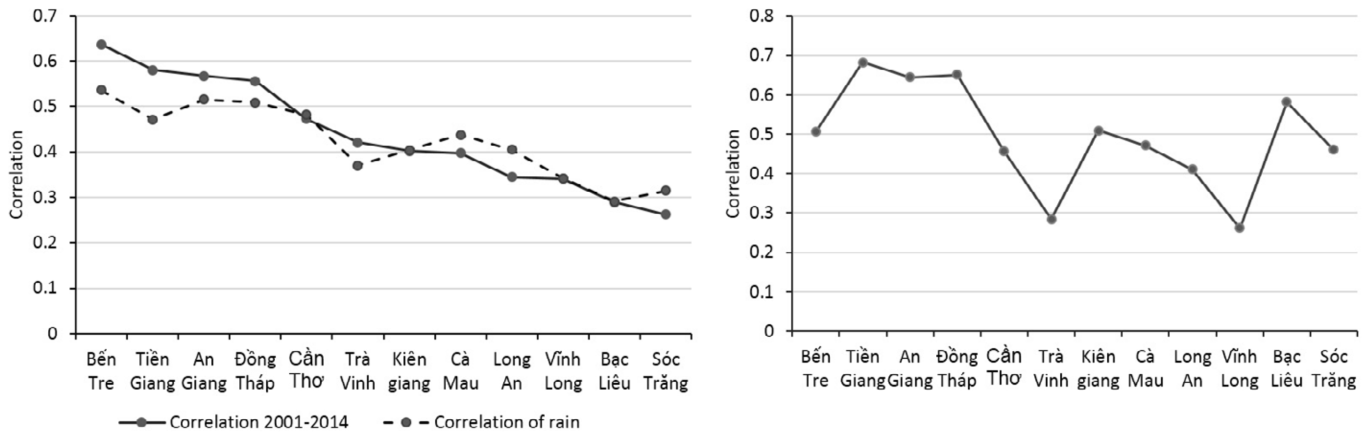

FIGURE 7. a) Comparison of the correlation of dengue with vulnerability and rain; b) Correlation of dengue with vulnerability for the validation data from the period of 2015-2016

infection (Thai et al., 2010). Dickin & Schuster-Wallace (2014) considered that a stronger weighting for exposure is attributable to larger scale factors, while susceptibility plays a role at the local level. Therefore, detailed data on social information and dengue reports at community levels are important for studying the combined effects of exposure and susceptibility at regional and local levels.

4. CONCLUSION

This study focused on presenting socio-environmental influences and climate factors on the vulnerability to dengue fever in the MRD, which has the highest dengue rate in Viet Nam. This research is the first application of the WADI approach to dengue in Viet Nam to enhance the understanding of dengue burden by exposure and susceptibility components rather than the mathematical modelling of epidemic transmission used in previous studies. Monthly and yearly maps of vulnerability to dengue in the MDR were produced by using extensive remote sensing data for climate and environment variables at high spatial resolution. The results showed that provinces along the Mekong River with higher population density are more vulnerable to dengue. There is a clear seasonal variation in the vulnerability over the whole region following variability of the climate factor, such that there is the lower vulnerability during the dry season from January to May and higher vulnerability during the rainy season from June to December. The correlation between the estimated vulnerability with dengue incidence significantly varies among MRD provinces, depending on their local condition of climate variables and land cover as well as population distribution. The validation results revealed that the WADI performed better in provinces with a high-risk cluster of dengue, where dengue has a greater correlation with rain.

The remote sensing data provides detailed information on climate and environment variables for vulnerability mapping that are advantageous over standard surface observation. However, the challenge of existing approaches in mapping dengue risk is to improve the accuracy in describing the spatially localized dengue distribution influenced by human activities. In addition, the validation of the mapping was limited to the provincial level due to the lack of dengue data at the community level in this study. Influences of combined exposure and susceptibility at regional and local scales is subject for further research in other regions of Viet Nam. Finally, all monthly and yearly vulnerability maps, as the outcome of this study, can be accessed at the GIS-based website http://www.apn-climateandhealth.com.

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Using a participatory-based toolkit to build resilience and adaptive capacity to climate change impacts in rural India: A new paradigm shift for rural communities in the Himalaya

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ABSTRACT

The Himalaya-Tibetan Plateau, also known as the Water Tower of Asia, has the highest mountains and glaciers in the world. Meltwater from this huge reserve feeds some of Asia's major river basins. Changing monsoon patterns, more extreme weather events and continued melting of glaciers have long-term implications for the region's water, energy and food security. This project utilized the ICLEI/Asian Cities Climate Change Resilience Network (ACCCRN) toolkit, referred to as IAP, to assist local governments to assess their climate risks and vulnerabilities, and to make adaptive response plans accordingly. Although specifically designed for cities, the IAP Toolkit was applied to the rural watershed of Ramgad in Uttarakhand, India. Over 40 resilience interventions were developed for vulnerable communities in Ramgad. The results of this work revealed that adaptive capacity and resilience in this rural jurisdiction were much lower compared to those of urban settings. Rural regions typically have less resources available to measure threats, disruptions and impacts compared to their city counterparts. The application of the IAP to this rural enclave has shown that a new paradigm shift is needed for the refinement of decision support tools to measure climate impacts and to build resilience and adaptive capacity in rural Himalaya.

HIGHLIGHTS

- Five fragile systems were identified for the watershed of Ramgad
- Over 40 resilience interventions were developed and assessed for their feasibility and long-term impact
- Some of the intervention strategies are cost-effective and could be implemented immediately
- The sensitivity of the IAP Toolkit scoring system could be improved to truly reflect the rural environment
- Climate and hydrological data analysis could be improved by using the appropriate software

KEYWORDS

Adaptive Capacity, Climate change, Himalaya, IAP Toolkit, Resilience

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1. INTRODUCTION

The Himalaya-Tibetan Plateau, also known as the Water Tower of Asia or the Third Pole, is home to the highest mountains and glaciers in the world. The melt-water from this huge reserve supports the wellbeing of some of the poorest people and most densely populated regions on the planet through the provision of water for drinking, irrigation and hydro-power generation (Heath et al., 2014). In addition, biomass-based subsistence agriculture is the main form of rural livelihood and food supply in the Himalaya (Tiwari & Joshi, 2012a; Tiwari & Joshi, 2012b).

The Himalayan region has seen an increase in the annual mean temperature and has borne the full brunt of climate change. An ever-increasing demand for the region's natural resources has exacerbated the impacts of climate change as evidenced by the severe water scarcity issues faced in the Midhills of Nepal (Chapagain et al., 2017). Among the numerous complex outcomes, we can expect to see the increasing consequences of climate change for river flows, groundwater recharge, food and energy security, migration, ecosystem services and human livelihood. These have inextricable implications for the many and varied rural communities that call the Himalayas home, and has emphasised the need to strengthen resilience and adaptive capacity for some of the World's most vulnerable people. Building resilience to future climatic disruptions calls for a broad framework centred on system resilience and adaptive capacity and transformative adaptive capacity.

From a policy perspective, mainstreaming adaptation into development and management strategies requires a proactive, holistic and systematic approach that does not regard adaptation measures as something distinct or excluded from other policies. Local ownership of the adaptive process is critical in ensuring adoption and buy-in and, ultimately, its sustainability and effectiveness (Nunn, 2009). Therefore, the role of participatory approaches in field based assessments to help communities derive the maximum benefit from the adaptation process is widely used and acknowledged (Fazey et al., 2010; Van Aalst et al., 2008). The role of Governments and other actors is also important in the adaptation process (Hay, 2009; IFRCS, 2007).

Significant advances in seasonal weather forecasting and climate modelling have been made over the last decade, leading to significant improvements in early warning systems and longer-term adaptation planning. This has also emphasized the importance of taking a pro-active (anticipatory) rather than reactive management approach to addressing climate change impacts (Hay, 2011). To help communities and governments navigate these processes and prioritize their responses, several "off the shelf" climate change adaptation toolkits are available to help communities adapt to the long-term impacts of climate change.

This activity utilized the ICLEI/Asian Cities Climate Change Resilience Network (ACCCRN) toolkit, referred to as the ICLEI ACCCRN Process (or IAP) (ICLEI, 2014). The IAP uses a participatory based approach, or Shared Learning Dialogue (SLD), to identify these risks and vulnerabilities and to formulate adaptive response plans accordingly. Although the IAP Toolkit is specifically designed for cities, the methodology was applied to the rural watershed of Ramgad in Uttarakhand, India. This is the first rural jurisdiction in India to use the IAP Toolkit without any modification to the methodology. This research also investigates whether a city based toolkit is appropriate for a rural system.

2. METHODOLOGY

2.1. Synopsis of ICLEI ACCRN Process (IAP)

The methodological framework was developed by the International Council for Local Environmental Initiatives (ICLEI) under the Asian Cities Climate Change Resilience Network (ACCCRN) known as ICLEI ACCCRN Process (IAP) or IAP Toolkit. The IAP has a total of six phases containing a set of sixteen tools to enable local governments to evaluate the climate risks of various systems in the context of vulnerability, and to formulate a series of resilience interventions in response to the fragile systems identified. The six phases are:

Phase 1—Engagement: This first phase focuses on acquiring political support or "buy-in" from the relevant watershed authorities and community groups. It also allows for the formation of a Climate Core Team and Stakeholder Group.

Phase 2—Climate Research and Impact Assessment: This phase involves a Shared Learning Dialogue (SLD) with the Climate Core Team and the Stakeholder Group. This interaction aims to have a mutual learning and sharing of experiences. An assessment of past climate trends and future climate projections is undertaken using climate research data which is then validated through analysis of regional climate data as well as local perceptions from rural stakeholders.

Phase 3—Vulnerabilities Assessment: This phase identifies the key vulnerabilities of each fragile rural system. It determines the spatial vulnerability for each fragile system. It also identifies the vulnerable population and the potential supporting "Actors" for each system.

Phase 4—Resilience Strategy: The relevant resilience interventions for the watershed are then identified from the results obtained from the previous phases. Resilience interventions are then prioritized according to a set of resilience indicators, their feasibility and applicability to the watershed.

Phases 5 and 6—Implementation and Monitoring & Review: Following the identification of potential resilience interventions for the watershed, project implementation plans are then prepared and options for financing these projects are then explored.

Four villages were selected for the baseline questionnaire; they represent diverse socio-economic parameters suitable for the application of the IAP procedure. These villages included Naikana, Bohrakote, Satbunga and Nathuakhan. A series of meetings and workshops were also organized in each of the 4 villages in the presence of a range of stakeholders including officials from local government departments, representatives from private sectors, civil society organizations, non-governmental organizations as well as village and forest panchayats.

The IAP Toolkit Workbook is available online free of charge at http://resiliencetools.org/node/101

3. RESULTS AND DISCUSSION

3.1. Rural Profile

3.1.1. Location and watershed characteristics

Ramgad watershed is situated in the Lesser Himalayan ranges in the district Nainital in the newly carved Himalayan State of Uttarakhand (Figure 1). The watershed is between 29°24' to 29°29' N latitudes and 79°29' to 79°39'E longitudes and encompasses a geographical area of nearly 75.8 km2 and is between 1025 and 2346 m in altitude. Ramgad is one of the principal tributaries of River Kosi and is characterized by several geological formations evidenced by rock displacement, slope failure and multi-cyclic river terraces.

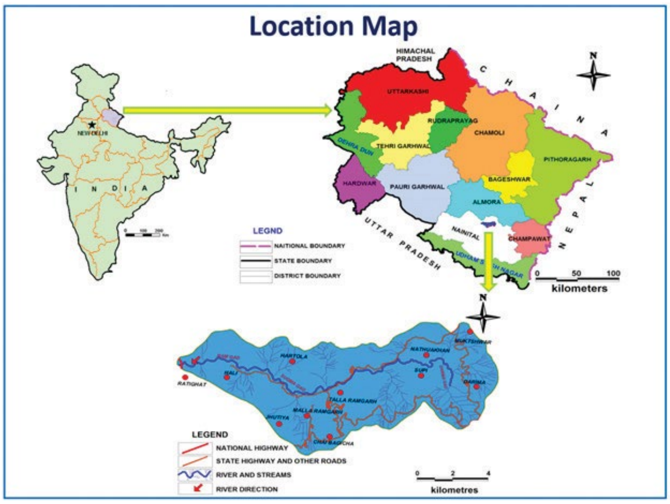

FIGURE 1. Ramgad Watershed situated in the lesser Himalayan ranges in the State of Uttarakhand.

3.2. Past Hazards and Climatic Events

The state of Uttarakhand is highly prone to natural disasters ranging from seasonal events such as forest fires, cloud bursts and flash flooding to unpredictable disasters such as earthquakes.

The Lesser Himalaya is vulnerable to landslides and the Ramgad region falls in Zone IV of the earthquake zoning map of India (Government of Uttarakhand, 2011). Zone IV is categorized as "severe to very severe". The Ramgad is also subject to landslides caused by excessive rainfall and runoff. During the summer months the watershed also experiences wild forest fires.

A timeline of hazards and extreme weather events was constructed based on historical records and perceptions. Figure 2 is the resulting timeline of events and their associated impacts.

3.3. Climate Trends and Scenarios in the Ramgad Watershed

3.3.1. Past climate trends

An analysis of over 30 years of rainfall data from the Mukteshwar weather station has revealed an increase in rainfall since 1979 for the month of August, which represents the height of the monsoon season. The results suggest the monsoon season has increased in intensity, perhaps due to higher evaporation and greater inertia in the Asia Monsoon climate system.

However, during the drier months of December, January and February there has been a sharp decline in the amount of rainfall, which is consistent with the overall trend experienced across the Himalaya.

3.3.2 Climate Change Projections and Climate Scenario Statements

Climate change scenarios for the Nainital/Ramgad region were sourced from the CORDEX South Asia domain (50 km resolution). The climate projections were based on the Intergovernmental Panel on Climate Change (IPCC) A1B emission scenarios for the time period 2041 – 2060 compared to the baseline period (1981-2000).

Based on the climate change scenarios for the Ramgad region, there will be a decrease in the maximum temperature by 1°C during the summer monsoon season (June, July and August) and a decrease in the minimum temperature by 0.39°C for the same period. Temperatures during the winter months (December, January and February) are expected to increase. The maximum temperature will increase by 1.53°C in December, January and

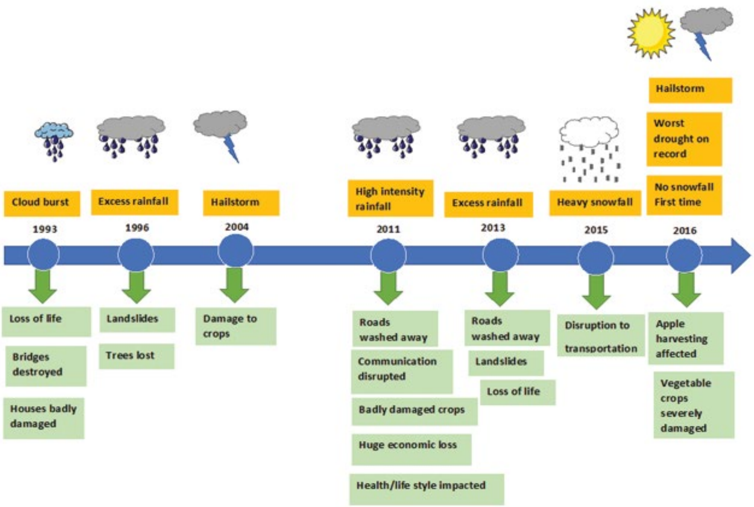

FIGURE 2. Timeline of hazards and extreme weather events and their impact on the community of Ramgad.

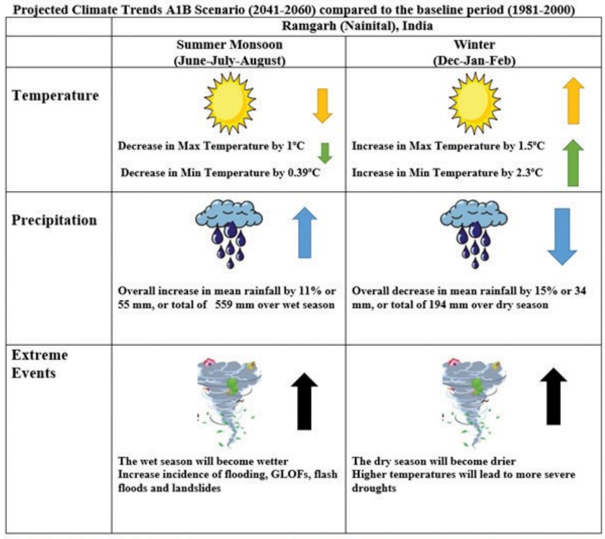

FIGURE 3. A diagrammatic representation of the projected climate change trend under the A1B Scenario (2041-2060) compared to the baseline period (1981-2000).

Rural system	*Fragility statement*	*Climate fragility statement*			
Availability and Supply of Water for Drinking and Irrigation	The system is fragile because the water sources are sensitive to small changes in the environment, population growth and ecological stress (i.e. emerging dominance of pine trees). This in turn impacts on drinking water supply, human health and agricultural production.	A decrease in winter rainfall and an increase in temperature during winter will increase the gap in the demand and supply of water.	An increase in rainfall and a decrease in summer temperatures will lead to high intensity rainfall and a change in groundwater dynamics (high intensity rainfall may lead to greater runoff and less infiltration).	Incidences of high intensity rainfall will disrupt and damage water infrastructure and distribution system.	Water sources may become dry due to prolonged droughts affecting water availability.
Road Connectivity	Road infrastructure is fragile due to the lack of resilience and preparedness planning. Therefore, road connectivity is adversely affected if the road system is disrupted thus impacting on the rural economy and livelihoods.	Incidences of high intensity rainfall will disrupt roads and bridges, which will in turn affect the rural economy, livelihood and community health.			
Community Human Health and Wellbeing	Health facilities and human health resources are unable to respond to poor water sanitation, supply and hygiene resulting from unexpected shocks to the system.	Reduced availability of water will impact the rural food system, hygiene, sanitation and community health.			
Rural Livelihoods and Economy	On-going economic hardship, droughts, extreme weather events, and the lack of a reliable water resource, have led to an increase in out-migration, food insecurity, and a loss of purchasing power.	A decrease in rainfall, frequent droughts and increasing incidences of high intensity rainfall will affect crop-rotation, agricultural productivity, livelihood, tourism and the rural economy.			
Forest Resources	The traditional forest based subsistence farming constitutes the main type of rural livelihood, which is under threat from a growing population and the subsequent increase in the demand for food, fodder, fuel wood and other natural resources.	Increase in temperature and a decrease in rainfall will increase the incidence of forest fire, loss of biodiversity, depletion of medicinal plants and a reduction in the availability of fuel-wood and fodder.			

TABLE 1. Climate Impacts on Fragile Systems (Fragility Statement & Climate Fragility Statement)

Rural System	*Climate Risks (Climate Fragility Statements)*	*Risk Status*
Availability and Supply of Water for Drinking and Irrigation	A decrease in winter rainfall and an increase in temperature during winter will increase the gap in the demand and supply of water.	Extreme
	An increase in rainfall and a decrease in summer temperatures will lead to high intensity rainfall and a change in groundwater dynamics (high intensity rainfall may lead to greater runoff and less infiltration).	High
	Incidences of high intensity rainfall will disrupt and damage water infrastructure and distribution system.	High
	Water sources may become dry due to prolonged droughts affecting water availability.	Extreme
Road Connectivity	Incidences of high intensity rainfall will disrupt roads and bridges, which will in turn affect the rural economy, livelihood and community health.	High
Community Human Health and Wellbeing	Reduced availability of water will impact the rural food system, hygiene, sanitation and community health.	Extreme
Rural Livelihoods and Economy	A decrease in rainfall, frequent droughts and increasing incidences of high intensity rainfall will affect crop-rotation, agricultural productivity, livelihood, tourism and the rural economy.	Extreme
Forest Resources	Increase in temperature and a decrease in rainfall will increase the incidence of forest fire, loss of biodiversity, depletion of medicinal plants and a reduction in the availability of fuel-wood and fodder.	Extreme

TABLE 2. Risk Assessment of Climate Fragility Statements.

February and the minimum temperature will increase by 2.26°C for the same period (i.e. winter months).

For precipitation, climate change projections indicate that there will be an overall increase in mean precipitation by as much as 10% during the summer monsoon period (June, July and August) but a decrease in rainfall during the winter months by as much as 15%. Figure 3 is a synopsis of the expected change in climate and their corresponding climate change scenario statements. The climate risks likely to affect Ramgad are therefore:

Climate Risk 1: Increase in temperature overall and a decrease in rainfall overall.

Climate Risk 2: The wet season will become wetter with an increased incidence of extreme weather events resulting in more flash flooding and landslides.

Climate Risk 3: The dry season will become drier with more severe droughts.

A major problem is the lack of available climate data. Typically, mountainous regions of the Himalaya lack weather stations. Many areas are simply too difficult to access. This is the case for the Ramgad watershed in which there is only one weather station available at Mukteshwar. Therefore, the Ramgad watershed can be defined as a hydro-meteorological data deficit region.

3.4 Climate Impact Assessment

Based on a series of active discussions in the SLDs, five fragile systems were identified for the watershed of Ramgad that require immediate attention to help improve overall resilience to the impacts of climate change. These systems are: 1) Availability and Supply of Water for Drinking and Irrigation; 2) Road Connectivity; 3) Community Human Health and Wellbeing; 4) Rural Livelihoods and Economy; and 5) Forest Resources.

The impacts from the climate scenarios (increased temperature, decreased precipitation and an increase in extreme events), were then superimposed on each fragile urban system to produce a series of climate fragility statements. The fragility statement and climate fragility statements for each rural system are summarised in Table 1.

3.4.1 Rural Systems Analysis and Risk Assessment

By using the participatory based risk assessment methodology outlined in the IAP Toolkit Workbook, the climate fragility statements were prioritized in order of their degree of risk that each expected climate impact poses for the identified fragile system(s) (Figure 4).

The participatory risk assessment exercise yielded alarming results for the all climate fragility statements (Table 2). For the rural system: Availability and Supply of Water for Drinking and Irrigation, two out of the four climate fragility statements yielded an extreme climate risk status. Likewise, the climate fragility statements for the rural systems: Community Human Health and Wellbeing, Rural Livelihoods and Economy and Forest Resources also yielded an extreme climate risk status. The remaining climate fragility statements all scored a high-risk status.

3.5 Vulnerability Assessment

The IPCC defines vulnerability as the degree to which a system is susceptible to, or unable to cope with, adverse effects of climate change (IPCC, 2001). Vulnerability is a function of a system's level of exposure, its sensitivity, and its adaptive capacity. A vulnerability assessment of

FIGURE 4. A risk assessment exercise was conducted in the Ramgad region with input from the Stakeholder Group.

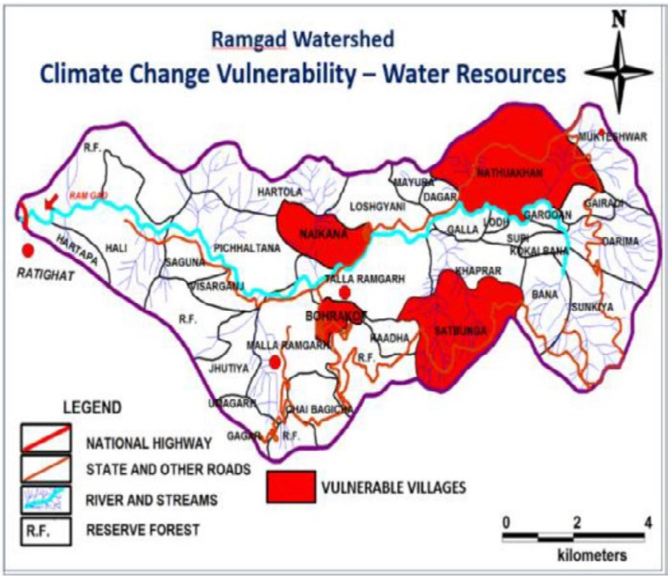

FIGURE 5. Vulnerable areas for the rural system Availability and Supply of Water for Drinking and Irrigation.

Climate Fragility Statements	*Villages*	*People and Institutions*	*Capacity to Organize & Respond*	*Resources*	*Access to Information*	*Total Score*	*Adaptive Capacity*
1) A decrease in winter rainfall and an increase in temperature during winter will increase the gap in the demand and supply of water. 2) An increase in rainfall and a decrease in summer temperatures will lead to high intensity rainfall and a change in groundwater dynamics (high intensity rainfall may lead to greater runoff and less infiltration). 3) Incidences of high intensity rainfall will disrupt and damage water infrastructure and distribution system. 4) Water sources may become dry due to prolonged droughts affecting water availability.	Satbunga	Women	1	1	1	1	Low
		Gram Panchayat	1	1	1	1	Low
		Forest Panchayat	1	1	1	1	Low
		Tourist Enterprises	1	2	1	2	Low
		Jal Sansthan	1	2	1	2	Low
		NGOs	2	2	1	4	Low
	Bohrakote	Poor Households	1	1	1	1	Low
		Women	1	1	1	1	Low
		Gram Panchayat	2	1	1	2	Low
		Forest Panchayat	2	1	1	2	Low
		Tourist Enterprises	1	2	1	2	Low
		Jal Sansthan	1	2	1	2	Low
		NGOs	2	2	1	4	Low
	Naikana	Poor Households	1	1	1	1	Low
		Women	1	1	1	1	Low
		Gram Panchayat	2	1	1	1	Low
		Jal Sansthan	1	2	1	1	Low
	Nathuwakhan	Poor Households	1	1	1	1	Low
		Women	1	1	1	1	Low
		Gram Panchayat	1	1	1	1	Low
		Forest Panchayat	2	1	1	1	Low
		Tourist Enterprises	2	2	1	4	Low
		Jal Sansthan	1	2	1	2	Low

TABLE 3. Analysis of the adaptive capacities of local actors identified for the rural system Availability and Supply of Water for Drinking and Irrigation.

Fragile Rural System	*Vulnerable Villages*	*Rural Actors*		*Adaptive Capacity of the System*		
		Vulnerable Communities	*Actors*	*Low*	*Medium*	*High*
Availability and Supply of Water for Drinking and Irrigation Road Connectivity Community Human Health and Wellbeing Rural Livelihoods and Economy Forest Resources	Satbunga Bohrakote Naikana Nathuakhan	Poor Households Women Tourist Enterprises Vegetable Grower Fruit Producers	Block Development Office	Economic Technology	Governance Societal	–
			Jal Sansthan	Economic	Technology	–
			Public Works Department	Governance Societal Ecosystem Services	Economic	Technology
			Agriculture Department	Economic Governance Societal	Technology Ecosystem	–
			Forest Department	Economic	Technology Governance Societal	Ecosystem Services
			Horticulture Department	Economic	Technology Governance Societal	Ecosystem Services
			Irrigation Department	Economic Ecosystem Services	Technology Governance Societal	–
			Gram Panchayat	Economic Ecosystem Services Technology	Societal Governance	–
			Forest Panchayat	Economic Technology	Societal	Ecosystem Services Governance
			NGOs	–	Economic Technology	Ecosystem Societal Governance

TABLE 4. Adaptive Capacity of Rural Systems assessed against the five parameters of Economy, Technology, Governance, Societal and Ecosystem Services.

the Ramgad watershed was carried out and those villages identified as highly vulnerable, based on the IAP vulnerability scale, were mapped. The results of this assessment showed that the villages Satbunga, Bohrakote, Naikana and Nathuwakhan, surveyed as part of the IAP, exhibited a high level of vulnerability to climate change for all rural systems except for the rural system Forest Resources. The village of Satbunga was the only village that showed a high level of vulnerability to climate change for this system. Figure 5 shows the highly vulnerable areas for the rural system Availability and Supply of Water for Drinking and Irrigation.

3.5.1 Actor Analysis

An Actor Analysis involves the establishment of a structured list of individuals, government agencies and organizations with differing views, priorities and opinions. These individuals, organizations and agencies are referred to as "Actors". Their skills and capabilities to assist the most vulnerable during times of threat or disruption can vary significantly. The identification of "Actors" (i.e. different parties and individuals) and their capacity to organize and respond to threat or disruption was also undertaken. In the context of the IAP actor analysis, all actors received a "Low" score overall in terms of their adaptive capacity (Table 3). No Actor received a "Medium" or "High" score in terms of their adaptive capacity. In contrast, for the city of Nainital, four actors received a "High" score and five actors received a "Medium" score (Unpublished data).

Through the SLD workshops, participants discovered that the sensitivity relating to the IAP scoring system could be improved to truly reflect the rural environment. Therefore, the IAP scoring system may not be suitable for assessing the adaptive capacity of Actors to respond to shocks and disruptions. An alternative or more "sensitive" ranking scale is probably required to reflect a more realistic level of adaptive capacity for each Actor.

3.5.2 Adaptive Capacity of Fragile Rural Systems

There was a low adaptive capacity with respect to the "economic" parameter for nearly all potential supporting actors, suggesting a limited inherent economic ability to adapt to impacts (Table 4) (e.g. probably having no legal authority to raise funds and/or no strong tax base to call upon).

Ecosystem services also ranked "low" for the Public Works Department, Irrigation Department and Gram Pamchayat. On the other hand, the Forest Department and Horticulture Department, Forest Panchayat and NGOs had scored a "high" level of adaptive capacity for the parameter "ecosystems services". The Public Works Department also had a "high" level of adaptive capacity in terms of their technological knowledge and resources. However, this department and the Agricultural Department appeared to have limited governance structures in place to adapt to impacts, perhaps due to a lack of interagency collaboration or support from higher levels. Interestingly, the NGOs scored a "high" level of adaptive capacity for three out of the five parameters, namely ecosystem services, societal and governance.

3.5.3 Gap Analysis

The gap analysis revealed serious data deficiencies around stream discharge and water demand, and supply requirements. Information is also deficient in agriculture and food systems analysis. In addition, there has been little work done on determining the extent of biodiversity loss within the Ramgad watershed.

3.6 RESILIENCE INTERVENTIONS

A series of intervention strategies were developed for each rural system and these were prioritized according to their redundancy, flexibility, responsiveness, access to information and overall impact. Over 40 potential resilience interventions were identified across the five rural systems and these have been summarized in Table 5. Some of the intervention strategies are cost effective and could be implemented immediately. Greater awareness of water conservation, as well as the revival of some traditional water management strategies, were viewed as a way of ameliorating some of the negative impacts on the availability and supply of water for drinking and irrigation purposes. Some simple and cost-effective measures, such as the transportation of water by tankers and the development of water reuse strategies, could assist communities in the short-term. Programmes that focus on geological mapping and water quality monitoring to help reduce the incident of water-borne diseases could be implemented immediately. While there are conservation and protection measures in place for water supplies within the Ramgad watershed, the lack of water quality monitoring has made it difficult to assess the effectiveness of such measures. Based on the SLD, community groups have endorsed these potential resilience interventions as high priority.

Although there has been extensive research into the use of climate resilient varieties of seeds to maintain or increase food production and conserve water, there is a need to implement a long-term programme to improve food security and conserve water resources. Maintaining road connectivity was viewed by stakeholders as an important issue to prevent long-term isolation and economic loss through the inability to transport produce to markets and distribution centres. Local materials such as wood could be used to repair bridges damaged as result of extreme weather events and flash flooding. The installation of check dams (first order streams) to prevent excessive erosion, would also help to ameliorate some of the consequences (slope failures, landslides, debris and mud flow) resulting from intense rainfall events.

The institutionalization of sustainable forest management practices to enable forest panchayats to manage forests more sustainably was viewed as an important intervention strategy by the Stakeholder Group, but requires a more comprehensive programme that will integrate all disciplines (natural, economic and social aspects) into the one programme. Furthermore, there is also a need for the delineation and management of fire lines in forests to ensure a more sustainable forest fire management regime. The farming community viewed wild native animals as a major problem because of their tendency to consume food crops. A potential resilience intervention strategy would be to ensure an adequate food supply is available in forests to prevent animals from moving to farm land in search of food. Clearly, this would require a strong focus on maintaining and protecting ecosystem services. Unfortunately, ecosystem services were not highlighted as a rural system in this IAP but should form the basis of future work.

3.6.1 Integration into Rural Plans

Through extensive consultation with planning authorities and the Stakeholder Group, each resilience intervention developed as part of this IAP was then assessed to determine whether it belongs to an existing programme or whether it is an ongoing/upcoming or planned intervention. Around half of the intervention strategies were either planned or were on-going in their status.

4. CONCLUSION

The Ramgad watershed is experiencing dramatic social, economic and environmental pressures. The application of the IAP highlighted some key vulnerabilities to the impacts of climate change as well as some

Rural System	*Climate Risks (Climate Fragility Statements)*	*Potential Resilience Interventions*
Availability and Supply of Water for Drinking and Irrigation	A decrease in winter rainfall and an increase in temperature during winter will increase the gap in the demand and supply of water.	• Tanker use • Afforestation with broad leaf species • Check drains • Infiltration trenches • Rainfall water harvesting • Water reuse at the household level • Revive traditional sources of water management • Storing seasonal water in tanks • Water resource management & governance • Awareness regarding afforestation, water conservation & reduction of waste water
	An increase in rainfall and a decrease in summer temperatures will lead to high intensity rainfall and a change in groundwater dynamics (high intensity rainfall may lead to greater runoff and less infiltration).	
	Incidences of high intensity rainfall will disrupt and damage water infrastructure and distribution system.	
	Water sources may become dry due to prolonged droughts affecting water availability.	
Road Connectivity	Incidences of high intensity rainfall will disrupt roads and bridges which will in turn affect the rural economy, livelihood and community health.	• Geological mapping and survey to identify and reduce risks • Adequate construction codes for roads & the need to follow engineering plans and guidelines & retaining walls • Construct good drainage systems like culverts • Afforestation beside roads • Use of oxen or horses for transporting goods temporarily • Installation of check dams (first order streams) • Temporary accessibility managed by local materials like wooden bridges, wherever possible
Community Human Health and Wellbeing	Reduced availability of water will impact the rural food system, hygiene, sanitation and community health.	• Awareness programmes on hygiene and sanitation for local people • Availability of good medical facilities in community health centres • Use of climate resilient varieties of seeds to maintain/increase food production • Revise Below Poverty Line (BPL) list to improve access to food security • Educational and socio-economic empowerment of women to improve hygiene, sanitation, & the health of the entire family • Water quality checks of water sources like streams in villages • Water quality checks of water sources like streams in villages • Promote Household level purification of water, chlorine tablets, boiling of water, etc. • Maintenance of water sources, conservation and protection of sources from contamination
Rural Livelihoods and Economy	A decrease in rainfall, frequent droughts and increasing incidences of high intensity rainfall will affect crop-rotation, agricultural productivity, livelihood, tourism and the rural economy.	• Use new varieties of seeds that use less water • Reallocation of agricultural land use, revise cropping patterns • Action should be taken to protect crops from wild animals (i.e. pigs & monkeys, etc.) • Protection of forests to ensure livelihood protection of forest produce users • Develop a sustainable land use policy (Needs to be done at a State level) • Diversification of livelihoods – bee keeping, fishery, poultry, etc., alternative sources of employment to prevent out migration • Create awareness to conserve local ecosystem – to maintain ecosystem services • Sustainability of agricultural business models, assessment and improvement of producer consumer nexus, e.g. formation of cooperatives, establishing market linkages, food processing units, etc. (Mukteshwar Kisan Producer Company)
Forest Resources	Increase in temperature and a decrease in rainfall will increase the incidence of forest fire, loss of biodiversity, depletion of medicinal plants and a reduction in the availability of fuel-wood and fodder.	• Institutionalization of sustainable forest management & use practices - Strengthen forest panchayats to manage forests sustainably using good practices • Sustainable use of forest resources • Wild animals should be protected but consideration should be given to protecting farmers' livelihoods. Efforts to cultivate food in forested areas for wild animals to eat could be considered as a way of ameliorating the consumption of food crops. • Replace firewood with alternative energy sources such as solar & wind • Create awareness of medicinal plants to improve livelihoods and the economy • Delineation and management of fire lines in forests for forest fire management

TABLE 5. IDENTIFICATION OF Potential Resilience Interventions for each rural system.

practical adaptive measures that can be implemented to strengthen community resilience in light of the impending challenges that lie ahead.

The first time the IAP Toolkit was used in a rural context was in the jurisdiction of Panchkhal in Nepal. This region shares similar characteristics to those of the Ramgad Basin in India. On this basis, we believed that the IAP approach would also work in the Ramgad. In conclusion, the IAP Toolkit showed that in both jurisdictions and with minor modifications, it is possible to assess the risks and level of vulnerability to climate impacts even though the IAP was developed for use in urban environments.

Reflecting on the outcomes of the IAP for the Ramgad region, the workshop participants found that rural resilience scores were all "low" compared to those of urban environments such as Nainital. Understandably, rural areas typically have less resources available to measure threats and impacts in the rural system. This is also compounded by the physical distances between cities that have better infrastructure and resources at their disposal (i.e. better hospitals and equipment, human resources etc.) and rural environments that quite often lack basic amenities, infrastructure as well as the ability to mobilise human resources en masse. This area of research should be explored and tested in more detail in future IAP studies that examine the adaptive capacity of rural environments.

The IAP revealed several challenges facing the Ramgad watershed. Perhaps the most pressing problem revealed by the IAP gap analysis and vulnerability assessment was the lack of data on stream discharge and its associated impact on the supply of fresh drinking water. This finding highlighted the need for the implementation of improved water governance and management practices.

An equally important issue was the lack of reliable climate data for forecasting future climate and hydrological shocks. Reliable climate information is essential to the quantitative assessment of climate impacts in mountain regions and for improving regional resilience and adaptive capacity to such impacts. The Ramgad watershed can be classified as a hydro-meteorological data deficit region. With a deficiency in weather stations and available climate data, it is almost impossible to create a spatial representation of rainfall and temperature across the entire watershed. Software programs that use an elevation-dependent algorithm, such as ANUSPLIN (Hutchinson and Xu, 2013), to create spatial representations of rainfall and temperature in mountainous regions should form the basis for further work in this area. The climate surface maps generated from these software packages can then be used with a high degree of confidence to model rainfall/runoff in agricultural catchments by using a suite of hydrological software. The results from this analysis can inform policymakers on a range of watershed management issues including the optimization of rainfall capture and storage and to predict the bioclimatic distribution of organisms in response to a changing climate, by using some popular and easy-using bioclimatic modelling packages such as ANUCLIM (Xu and Hutchinson, 2013).

A lack of information on how climate change is affecting the region and how to respond to it was found to be a major barrier to adaptation. The IAP revealed a major deficiency in the accessibility and flow of information to those most in need. The development of a Knowledge Management Framework can help improve the flow and accessibility of information to farmers, tourist operators, forest managers, community leaders and policymakers. This is achieved through the development of a Knowledge Management Platform to encourage the collection and sharing of critical information and knowledge at multiple levels. Therefore, efforts should be made to initiate planning for the establishment of Knowledge Management Framework Platform.

Lastly, ICLEI with support from the Rockefeller Foundation, has finalized the IAP for the City of Nainital, which is approximately 40 km from the Ramgad watershed in the state of Uttarakhand, India. Because of the proximity of these two IAP study regions, future work should identify and examine crucial climate change adaptation linkages between the urban and rural sectors, and could form the basis for a new research endeavour.

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A framework for water security assessment at basin scale

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HIGHLIGHTS

» An operational framework to assess water security was developed.

» The framework includes five dimensions and eight indicators.

» The framework results in a quantifiable water security index.

» The study informs decision-making for practical enhancement of water security.

ABSTRACT

The objective of this study was to develop an operational water security assessment framework for basin-scale analysis using an indicator-based methodology. Because operationalization of water security enhancement will require a bottom-up approach, the study considered basin-scale analysis instead of the traditional national-scale analyses. The DPSIR (Driving Forces-Pressures-State-Impact-Response) framework was used to identify the pertinent driving forces, corresponding dimensions and indicators of water security that are applicable at a basin scale. Furthermore, because the study aimed to operationalize water security, stakeholder meetings with public sector actors were conducted to consider their point of view in making the water assessment framework robust and implementable. As a result, five broad dimensions (measured by eight indicators) were fixed—water availability (which is a measure of how well the domestic, agricultural and industrial water demands are met); water productivity (which estimates the economic value of water used in the basin for revenue generating activities); watershed health (which emphasizes on the indirect factors such as land use, river health, environmental flows, etc., that will ultimately have a bearing on water security in the basin); water-induced disasters (which considers the effects of floods and droughts on the overall water security); and water governance (which sheds light on how well water is managed through policies and institutions).

KEYWORDS

Basin-scale analysis, DPSIR framework, Indicator-based methodology, Water security assessment, Water security index

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1. INTRODUCTION

Water is at the heart of basic human security—food, energy, culture, aesthetics. How water is managed will have repercussions on almost every aspect of human security, which is why achieving adequate water security is among the top priorities of government policies across the globe. While formulating policies to enhance water security are important, even more crucial is monitoring the changes brought about by implementing these policies. As the adage goes, "we cannot manage what we cannot measure". In today's time, operationalizing water security is becoming urgent. Water security assessment frameworks, therefore, need to have the potential to monitor the plans and policies that are taken to ensure water enhancement. Such plans and policies are usually implemented within administrative or hydrological boundaries within a country. Therefore, the objective of this study was to develop a framework for water security assessment at a basin level that would subsequently inform decision making on enhancing water security.

Measuring water security is not new. A number of studies have done so at different scales (e.g. Falkenmark, 1989; Gleick, 1990; Heap, Kemp-Benedict & Raskin, 1998; GWP, 2000; Sullivan, Meigh, & Giacomello, 2003; Zeitoun, 2011; ADB, 2013; Srinivasan, Konar, &

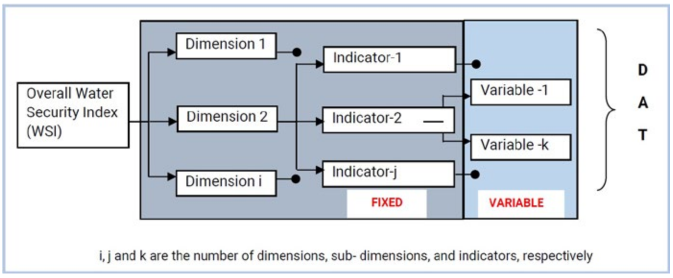

FIGURE 1. Water security assessment framework basin-scale analysis.

Sivapalan, 2017; Varis, Keskinen, & Kummu, 2017; Zende, Patil, & Patil, 2018, Jensen & Wu 2018; among others). Most of these assessments are made at a national or regional scale and consider specific aspects of water security. For example, the work of Falkenmark (1989) was associated mostly with water scarcity and proposed the widely accepted water stress indicator. Similarly, Sullivan, Meigh, and Giacomello (2003) also worked on the water scarcity aspect proposing the water poverty index as a measure of scarcity. Srinivasan, Konar, and Sivapalan (2017) argued for a case of assessing dynamic water security to account for human adaptation to environmental change and increasing spatial specialization in the modern world. Jensen and Wu (2018) focused on the water security of urban areas. A common feature with these assessments of water security is the use of simple (but effective) indicators, which help in quantifying the various aspects of water security. However, very few studies (e.g. ADB, 2013) have attempted to capture multiple perspectives of water security into an assessment. This study builds on previous work on water security by firstly evaluating the water security at a basin-scale to account for hydrological boundaries and, secondly, considering all the relevant components of water security that are applicable at a basin level.

2. METHODOLOGY

The study began with a thorough literature review on water security assessments to develop an academic context of the subject matter. In order to get a sense of the "operational" context of water security, stakeholder consultations with various government and non-governmental agencies were conducted in India, Thailand and Vietnam. The feedback received from the stakeholders was amalgamated with scientific understanding to arrive at a first draft of the water security framework. This draft framework was again presented to the stakeholders to solicit critical feedback, especially for the operationalization potential of the water security assessment. The framework was then fine-tuned to account for the critical feedback received from stakeholders and finalized.

The project used the DPSIR (Driving forces– Pressure–State–Impact–Response) approach to develop the framework for water security assessment. The DPSIR approach was developed in the late 1990s and proposed by the Organization of Economic Co-operation and Development (OECD, 2003) to show the cause-effect relationships between environmental and human systems. The DPSIR approach has been widely used for monitoring and evaluation studies in a wide variety of sectors such as environmental management (e.g. Malekmohamaddi &Jahanishakib, 2017); forestry (e.g. Scriban, Nichiforel, Bouriaud, Barnoaiea, & Barbu, 2017); urban infrastructure (e.g. Spanò, Gentile, Davies, & Lafortezza, 2017); climate change mitigation (e.g. Zhou, Singh, Wu, Sinha, & Frostell, 2015); hydrology (e.g. Sun, Wang, Liu, Cai, & Xu, 2016), among others. Details of the DPSIR approach can be found elsewhere (e.g. Tscherning, Helming, Krippner, Sieber, & Paloma, 2012).

The water security assessment framework developed in the study has an overall water security index (WSI) that comprises of various water security dimensions. These dimensions take into account the various driving forces that have an impact on water security. Each dimension is represented by one or more indicators. The indicators conform to the SMART (specific, measurable, attainable, relevant and time-bound) criteria of assessment. Each indicator is then measured with respect to specific variables. The framework is presented in Figure 1.

The framework has two shaded portions. The portion shaded in grey is the generic (and fixed) part of the framework, which will be applicable to a geographic area. The portion shaded in blue is the variable part of the framework that will depend on site-specific conditions and data availability.

In order to assess water security, it is important to first quantify it. Hence, all the variables suggested in the framework are quantitative in nature. The variables are to be normalized in the range 1 to 5 in order to facilitate easy interpretation of the water security index. This normalization can be based on threshold/reference values from literature, expert opinion or other sources. For example, ADB's Asian Water Development Outlook (ADB, 2013) recommends a score of 1, 2, 3, 4 and 5 for agricultural water productivity (agricultural revenue/agricultural water use) corresponding to 0-0.1; 0.1-0.2; 0.2-0.35; 0.35-1; and >1 USD/m3respectively. It is important to note that for this study the threshold/reference values may change from place to place because the objective of developing this framework is not for comparison/benchmarking purposes. Rather, it has been developed to facilitate operationalization of water security, which will depend upon the environment in which it is being operationalized.

In order to quantify water security, an aggregation method is used. The variables measuring each indica-

Dimension	*Indicator*	*Potential variables*	*Suggested ways to measure*
Water availability	Sustainable basin exploitation	1. Per capita water availability	Surface runoff/Population (Falkenmark, 1989)
		2. Water scarcity	Annual per capita water resources availability (Babel and Wahid, 2008)
		3. Water variation	The coefficient of variation of precipitation over the last 50 years (Babel and Wahid, 2008)
Water productivity	Economic value of water	1. Commercial/industrial revenue per drop	Non-agricultural GPP/Non-agricultural water use in the basin (ADB, 2013)
		2. Agricultural, aquaculture and livestock revenue per drop	Agricultural, aquaculture and livestock GPP/ Agricultural, aquaculture and livestock water use in the basin (ADB, 2013)
Water-related disasters	Drought factor	1. Drought damage	Economic damage caused by droughts
		2. Proportional area under drought	Drought area/Total area (Xiao, Li, Xiao, & Liu, 2007)
		3. Drought occurrence frequency	Number of drought occurrence per year (Koontanakulvong, Doungmanee, & Hoisungwan, 2013)
		4.Ratio of the area with water-saving irrigation to the total area of arable land	Area of irrigation/ Area of arable land (Xiao, Li, Xiao, & Liu, 2007)
	Flood factor	1. Flood damage	Economic damage caused by floods
		2. Proportional area of flooding	Flooding area/Total area (Xiao, Li, Xiao, & Liu, 2007)
		3. Flood occurrence frequency	Number of flood occurrence per year (Koontanakulvong, Doungmanee, & Hoisungwan, 2013)
		4. Percentage of population living in hazard-prone areas	Population living in hazard-prone areas/Total population (Mehr, 2011)
		5. Flood control capacity	Ratio of the water reserved in dams at the end of the year to the total water utilization (Xiao, Li, Xiao, & Liu, 2007)
Watershed health	Health of water bodies	1. Surface water quality factor	Dissolved oxygen concentration/Permissible limit
		2. Groundwater quality factor	Concentration of site-specific pollutants /Permissible limits of these pollutants
		3. Average class water quality rivers	Country-specific conditions (ADB, 2013)
		4. Biochemical oxygen demand (BOD) in water bodies	BOD 5-day values of river water samples. (Mehr, 2011)
	Vegetation cover	Natural vegetation factor	Natural vegetation area/Basin area
Water governance	Overall management of the water sector	Institution factor	Questionnaire
	Potential to adapt to future changes	Adaptability factor	Questionnaire

TABLE 1. Framework for basin-scale assessment of water security

tor are normalized between the range 1 and 5 by using reference values from literature, logical deductions, and expert opinion. These are then aggregated together using equal weights. This implies that each variable contributing to an indicator is equally important. However, if there is a case where one of the variables is more significant than the other, weights in proportion to significance can be used. The aggregation of variables will result in each indicator receiving a score between 1 and 5. Using a similar procedure, the indicators are aggregated into dimensions, and dimensions into the overall WSI which will also have a score between 1 and 5.

3. RESULTS AND DISCUSSION

Table 1 presents the framework developed for basin-scale assessment. The framework comprises of five dimensions and eight indicators. Following is a description of the framework.

Dimension 1: Water availability: Arguably this is the fundamental dimension of water security that is associated with water availability in the basin to sustain all kinds of human activities that include domestic, agriculture, commercial, recreational, and others. The indicator used to represent this dimension is sustainable basin exploitation, which throws light on how much water is available in the basin to sustainably carry out various activities. There are a number of variables reported in the literature that can measure this indicator. A commonly used one is 'per capita water availability' introduced by Falkenmark (1989) that calculates the total annual renewable water resources per capita (m3/capita/year). Babel and Wahid (2008) used the water scarcity variable that relates water resources with population and is defined as the ratio of Falkenmark's threshold (1,700 m3/person/year) for water stress and annual per capita water resources availability in the basin. Babel and Wahid (2008) also used the 'water resources variation' variable to depict the water availability situation in the basin. Variation of water resources over the years determines the reliability of annual available water resources. To reflect the long-term variation of water resources, they used the coefficient of variation of rainfall over the previous 30 years and setting 0.30 as the critical level of variation.

Dimension 2: Water productivity: This dimension considers the economic aspect of water security. It seeks to evaluate the economic value of the water used for all commercial activities in the basin. A single indicator, 'economic value of water', has been identified to represent this dimension. This indicator is expected to throw light on how judiciously is water used in terms of economic benefits. Two variables have been suggested to measure this indicator. Both have been used in the Asian Water Development Outlook (2013) for national-scale assessments. The first is 'commercial/industrial revenue per drop', which calculates the revenue generated by the commercial/industrial sector water use (USD/m3). In basins where agriculture is a major sector, the 'agriculture, aquaculture and livestock revenue per drop' could be a very significant variable.

Dimension 3: Water-related disasters: This dimension is intended to capture the effects of floods and droughts in the basin. Hence, two indicators have been used to represent this dimension. The first indicator is the 'drought factor' to evaluate the effects of droughts in the basin, and the measures taken to mitigate the impacts. Among the potential variables to measure this indicator is 'drought damage' which takes into account the economic losses (e.g. in USD) caused by the effects of droughts. Another variable to measure the impacts of droughts in terms of spatial coverage is 'proportional area under drought' as proposed by Xiao, Li, Xiao, and Liu (2007), which looks at what portion of the total basin area is affected by droughts. Koontanakulvong, Doungmanee, & Hoisungwan (2013) introduced the 'drought occurrence frequency' variable which essentially is a count of the number of drought events in a year. Given that droughts are slow-onset events, this variable is likely to be more useful in dry and arid basins. Xiao, Li, Xiao, and Liu (2007) also proposed a proxy variable in the form of 'ratio of irrigated area to arable area' to evaluate the measures taken to minimize the effects of droughts. This ratio calculates the portion of the arable area which receives irrigated water from planned supplies. The second indicator is the 'flood factor' to evaluate the effects of floods in the basin, and the measures taken to mitigate impacts. The variables used to measure this indicator include 'flood damage' to quantify the losses caused by floods; 'proportional area under floods' (Xiao, Li, Xiao, & Liu, 2007) that looks at the spatial coverage of flooding events; flood occurrence frequency (Koontanakulvong, Doungmanee, & Hoisungwan, 2013) that provides a count of the number of flooding events; population living in hazardous zones (Mehr, 2011) that provides a count of the number of people living in flood prone areas; and flood control capacity (Xiao, Li, Xiao, & Liu, 2007) that evaluates if the storage capacity of the dams is enough to prevent the onset of a flood.

Dimension 4: Watershed health: This dimension captures the environmental angle of water security in the basin. Two indicators have been used to represent this dimension. The first is 'health of water bodies' in the basin, which throws light on the current condition of the major river bodies and groundwater in the basin. A potential variable to measure this indicator is 'surface water quality factor' that considers the frequency with which the permissible limit for dissolved oxygen is breached in the water bodies. A similar variable can be used to assess the groundwater situation through the 'groundwater quality factor'. Another variable as proposed by AWDO (2013) is the 'average river class'. Most countries categorize their rivers into different classes based on the water quality. Hence, the average class of the rivers in the basin will provide useful information about the overall river health situation in the basin. Mehr (2011) used 'Biochemical Oxygen Demand' of surface water to evaluate the river health, which can be used if found appropriate. The second indicator is 'vegetation cover' that depicts the state of natural vegetation cover in this basin. This is a new indicator proposed by the study. The premise for including this variable is that in an age of rapid urbanization and economic activities, land use changes have a significant impact on the health of water bodies. The variable used to measure this indicator is 'natural vegetation factor' that measures the proportion of the basin area that is covered by natural vegetation.

Dimension 5: Water governance: Although water governance is central to the judicious management of water resources in the basin, it has rarely been considered in water security assessment frameworks in

Water Security Index Score	*Water security condition*	*Description*
1	Very poor	The basin is highly insecure with respect to most of the dimensions of water security. The basin is affected by severe water-related problems. Furthermore, the management and governance in the basin are inefficient.
2	Poor	The basin is insecure with respect to most of the dimensions of water security. The basin is affected by some water-related problems. The management and governance in the basin need improvement.
3	Average	The basin has mixed water security with respect to the dimensions of water security. There are patches of water-related problems in the basin. Governance and management instruments are in place but are still to yield the intended results.
4	Good	The basin is quite secure with respect to most of the dimensions of water security. There are hardly any water-related problems in the basin. The governance and management instruments are yielding most of the intended results.
5	Very good	The basin is highly secure with respect to all the dimensions of water security. There are no water-related problems in the basin. The governance and management instruments are yielding the intended results.

TABLE 2: INTERPRETATION OF the Water Security Index

the past. A possible reason for this could be that water governance is implicitly reflected in the assessment of every dimension of water security. However, for this study, we decided to make this important aspect explicit, and assign a dedicated dimension for water governance. This dimension captures the ability of the government to manage the water sector and plan for anticipated changes. Two indicators have been used to represent this dimension. The first of these is the overall management of the water sector that depicts the picture of the overall management of the various elements of the water sector in the basin. The suggested way to measure this is through a questionnaire to evaluate how the management practices of the major water-related institutions in the basin (institution factor). The second indicator is the potential to adapt to future changes that evaluate how well equipped the basin is to cope with emerging pressures on water security. The suggested way to measure this is also through a questionnaire to examine if the plans and policies for water sector development consider long-term drivers of water security.

As described in Section 2, the dimensions and indicators of the water security framework are fixed and can be cross-scaled to any basin of interest. However, the choice of variables (both type and number) depends upon the user and should account for the site-specific requirements and conditions.

Using the aggregation technique described in Section 2, the variables are to be aggregated to arrive at an indicator score between 1 and 5; then the indicators are to be aggregated to represent the dimension score; and finally the aggregation of dimensions will lead to the overall WSI, which will also have a score between 1 and 5.

Hence, WSI = (Score for DIM1 + Score for DIM2 + Score for DIM2 + Score for DIM4 + Score for DIM5) / 5, where:

DIM1 = Water availability,
DIM2 = Water productivity,
DIM3 = Water-related disasters,
DIM4 = Watershed health, and
DIM5 = Governance.

The interpretation of the different magnitudes of the WSI is presented in Table 2.

4. CONCLUSION

Achieving water security is a complex process that requires a holistic understanding and treatment of the various elements (or dimensions) of water security. This study has developed a framework to assess water security with respect to these varied dimensions, at a basin scale. Although the framework has been designed to be generic in nature so that it can be applied in diverse climatic and socioeconomic conditions, it has a provision for site-specific nuances to be reflected in the assessment of water security. In order to apply the framework in a specific area, the data corresponding to the selected variables should be collected from reliable sources. The data must be then examined for consistency and quality. The variables should then be estimated quantitatively or qualitatively as presented in the framework. These variables must then be normalized between the range 1 and 5 by using a combination of reference values from literature, logical deductions, and expert opinion. The variables contributing to particular indicators are aggregated and averaged to get an indicator score between 1 and 5. Similarly, the indicators contributing to a dimension are aggregated and averaged to obtain a dimension score. Finally, the dimensions scores are aggregated and averaged to get the overall water security index. It is expected that the outcome of this study should help inform decision making on water security enhancement and infrastructural development, which in turn will have a spiralling benefit for human health as well as economic development.

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Benefits and costs of risk insurance in selected countries of Asia

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HIGHLIGHTS

- The benefit-cost ratios (BCR) of risk insurance were largely positive but varied across the countries.
- Profitability of insurance in terms of BCR ratios differ from country to country. The benefit-cost ratio was found to be 2 in India and 1.5 in the Philippines; it was highest in Malaysia (9.6).
- The BCR ratios also change depending on the frequency of disasters. For example, in the Philippines, where disasters occur annually, crop production without crop insurance can be possible. However, having insurance increases the BCR ratio further. Hence, availing of crop insurance will increase the financial profitability of crop production.

ABSTRACT

Several risk insurance initiatives have been implemented at the grassroots level for reducing the vulnerability of communities to natural disasters. Despite these efforts, the penetration of risk insurance in developing Asia is poor compared to many developed countries due to several barriers that this sector is facing and the cost of insurance premiums is an important one. Against this background, this study aimed to assess the benefits and costs accrued through community-level risk insurance experiences in the Asia region, evaluate barriers limiting its penetration, and identify interventions for greater risk insurance penetration leading to climate change adaptation and disaster risk reduction. The benefit-cost analysis presented in this paper was based on household surveys conducted in three countries including India, Malaysia and the Philippines. The study has indicated several benefits accrued from risk insurance in the case study countries and a positive benefit-cost ratio. The net positive benefit-cost ratios provide an impetus to promote risk insurance by governments and an important evidence for potential subscribers to consider investing in insurance. Subsidized premiums played an important role in the positive benefit-cost ratios, which helped them in enrolling and in continuing in the insurance schemes. Short-term risk reduction benefits were seen including the avoidance of distress sale of assets and continuation of normal life aftermath of the disasters. However, the impact of risk insurance on long-term risk reduction and in terms of related investments by the insured could not be well supported by our findings.

KEYWORDS

Agriculture, Benefits, Climate change adaptation, Costs, Disaster risk reduction, Risk insurance

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1. INTRODUCTION

The Asia-Pacific region is one of the most vulnerable regions to a range of primary hydro-meteorological hazards such as storms, floods and droughts. In the Asia-Pacific region, hydro-meteorological disasters claimed the lives of 0.22 million people with estimated total economic damage costs of US$ 285 million during 2001–2012 (Prabhakar et al., 2013). An increase in the number of catastrophic disasters and related insured and uninsured losses has been reported. These disasters are undermining the developmental gains across the Asia-Pacific region and indeed the world. In this context of high vulnerability, insurance has been suggested as an important risk management tool at all levels as it pro-

Category	*Costs*				*Benefits*			
	Justification	*Costs*		*Source*	*Justification*	*Benefits*		*Source*
		Direct	Indirect			Direct	Indirect	
Social	Income stress due to high premium cost. Difficulty in paying premium.	Increased loans taken for premium payment.	Reduced consumption.	Mechler et al., 2008	Consumption smoothing No income fluctuation	Steady income in loss month	Reduced Debts Preserved assets Increased Investment expenditure	Rosenzweig, and Wolpin, 1993; Rosenzweig, and Stark, 1989; Townsend, 1994
	Opportunity costs insurance premium	Forfeited profits from alternated investments		Mechler et al., 2008	Improved creditworthiness Increased opportunity for increasing livelihood profitability	Increased bank loans taken for high yield crop/farm practices (machinery investments etc.)	Increased farm profits	Hazell et al.,1986; Mishra, 1994
Economic	Basic risk, losses from un-covered Risks	Uncompensated crop losses, payout does not reflect losses		Clark et al., 2012; Merchler et al., 2008; Gosh and Yadav, 2008	Increased confidence, post-disaster liquidity, ability to recover from disaster	Increased high risk high yield variety crops planted, increased monoculture, increased investment in livelihood assets, funds available for post-disaster investments for livelihood and rebuilding	Increased profits, preserved assets, reduced debts	Hazell, 1992; Venkatesh, 2008

TABLE 1. Potential costs and benefits of insurance at household level (Source: Authors based on references cited in the table).

motes emphasis on risk mitigation compared to response, provides a cost-effective way of coping with the financial impacts, supports climate change adaptation by covering the residual risks not covered by other risk reduction mechanisms, stabilizes rural incomes, provides opportunities for public-private partnerships, reduces the burden on government resources for post-disaster relief and reconstruction, and helps communities to renew and restore their livelihoods (Prabhakar et al., 2015).

Though there are several policy and institutional initiatives to promote insurance in the Asia-Pacific region, the region has not been able to utilize the full potential of insurance. The problems facing insurance include poor internalization of insurance benefits, high insurance costs, poor access and availability of weather data, poor risk mitigation, lack of enabling policies, imperfect information, and technical complexity. A deeper problem is the lack of clear assessment and understanding of insurance benefits and costs in terms of disaster risk reduction, climate change adaptation and sustainable development among the stakeholders engaged in insurance policy-making and delivery.

Part of the problem also lies with the traditional understanding of insurance effectiveness that revolves around the delivery of contractual obligations, i.e. payouts as agreed in the contract. Insurance effectiveness is thus mainly assessed based on the number of people insured, avoidance of moral hazards and adverse selection, as well as minimization of basis risk. However, these indicators provide an inadequate and even misleading understanding of insurance effectiveness in the context of climate change adaptation and disaster risk reduction. Traditionally, the insured are often not required to invest payouts in better risk mitigation practices. As a result, every disaster and the resulting payouts can perpetuate the risk. From this basic observation, it is clear that the assessment of insurance effectiveness in the contexts of DRR and CCA requires consideration of appropriate indicators. There is a need to change from a cycle of risk perpetuation to a cycle of risk reduction.

In order for insurance to make a real difference in terms of risk reduction, there is a need to understand the benefits and costs associated with risk insurance so that the insurance can be designed to enhance the benefits while keeping the costs low. Keeping this in view, this project has conducted case studies to assess the benefits and costs associated with risk insurance in India, Philippines and Malaysia using structured household surveys.

1.1 Costs and benefits of insurance

Insurance can provide several costs and benefits both to the subscriber and to society as a whole at a macro

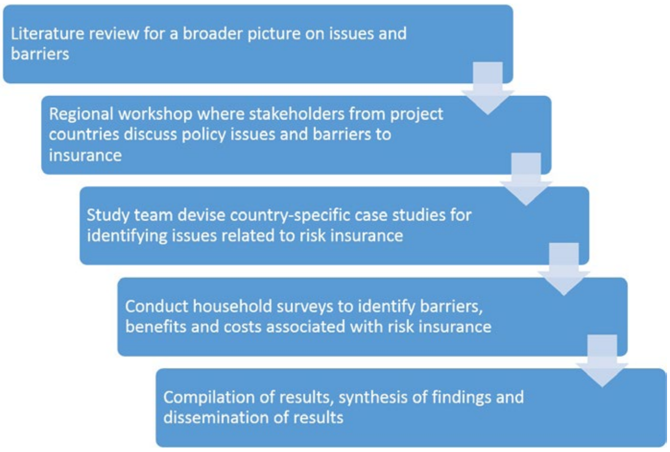

FIGURE 1. Steps involved in identifying the barriers, benefits and costs associated with risk insurance.

level. Table 1 lists several costs and benefits associated with insurance as reported in the literature. These benefits and costs can be grouped into social and economic costs and benefits. Costs can be both direct and indirect. Direct costs are easy to assess as they are visible to the one who is paying them. However, indirect costs are difficult to assess and can lead to subjective conclusions if they are not properly defined and the association is well established, hence the reason why very few indirect costs were identified in the published literature and in Table 1. The same can be said for both direct benefits and indirect benefits. The published studies indicated that household incomes could be stressed if insurance premiums are high, sometimes even leading to borrowing to pay premiums, and could lead to fortified profits due to alternated investments. Uncompensated losses could result if insurance losses were not satisfactorily assessed and delayed payments could have compounding impacts on the insured that may not be undone by the payouts received after the delay.

In terms of benefits, insurance could result in consumption smoothing, i.e. less difference in consumption between a good year and a disaster year, reduced debt and improved creditworthiness over the years. More indirect benefits were reported than indirect costs indicating possible overall benefits associated with insurance. However, insurance could lead to instances where the insured may indulge in risk-seeking behaviour resulting in adverse selections that could stress the insurance market and insurance providers.

2. METHODOLOGY

The project team has devised a multi-country case study-based methodology that looks into country-specific circumstances of risk insurance and assesses the benefits and costs of risk insurance and stakeholder perspectives (Figure 1).

2.1 Insurance background in the case study countries

Both India and the Philippines have a long history of risk insurance in the form of agricultural insurance. Agricultural insurance products in both countries have undergone significant changes over the years through continuous efforts to fine-tune the insurance delivery mechanisms and by delivering multiple insurance products targeting various sub-sector requirements. For the purpose of the study, paddy crop insurance was chosen in these two countries. In India, the insurance was weather index insurance linked to the crop loan, while in the Philippines it was indemnity-based insurance offered by the Philippine Crop Insurance Corporation. Plantation insurance is prominent in Malaysia. However, access to the plantation owners was not possible due to limited access to these stakeholders by the study team. Hence, homestead insurance for floods was chosen for assessing the benefits and costs associated with insurance.

2.2 Household surveys

Household and stakeholder surveys were carried out in three countries to assess stakeholder perspectives and benefits, and costs associated with the risk insurance. For this purpose, agriculture insurance was chosen as a form of insurance that is targeted at the predominant livelihood of the people in the project countries except in Malaysia where homestead insurance was considered due to lack of an active agriculture insurance in the country. Household surveys and consultations were conducted using a multi-method approach consisting of focus group discussions, structured questionnaire surveys, and small farmer group workshops.

Detailed structured questionnaire surveys were implemented at the community level to understand needs and perception issues to be considered for formulating effective insurance programmes and to understand benefits and costs associated with risk insurance at the local level. The structured questionnaires consisted of questions on the demographic background of the respondent, the past crop loss experience, opinion on the insurance currently enrolled (in case of insured) and on available insurance options (in case of non-insured and in Malaysia where there is no crop insurance in place). A generic questionnaire developed commonly for all the countries was further modified before implementing the survey by the respective country partners taking into consideration the individual country contexts such as type of insurance product being offered. The sample size was determined based on the resources at hand rather than the size determined based on the statistical sampling. However, households were selected randomly based on the stratified random sampling procedure. The elicited responses were analyzed for specific preferences among communities for certain form of risk reduction based on self-evaluation of their experience in crop insurance and presented as a percentage of responses.

2.3 Benefit-cost analysis

Benefit-cost analysis (BCA) is a major decision support tool that is used by stakeholders to organize and understand the socio-economic benefits and costs and inherent trade-offs of decisions made (Mechler, 2016). BCA has come to the forefront notably for the appraisal of efficiency of disaster management projects, development projects and public interventions (Mechler, 2005). Overall, BCA can provide valuable information that goes beyond the rhetoric and help in the selection of contextual and best-suited interventions. BCA was used to identify the impacts of crop insurance on households, classifying these impacts into benefits and costs, and identifying and quantifying the economically-relevant impacts. The benefit-cost ratio was calculated using the following generic formula.

Benefit-cost ratio = $$BCR = \sum_{t=0}^{T} \frac{B_t/(1+r)^t}{C_t/(1+r)^t}$$

Only direct benefits and direct costs were considered in all the countries. Direct costs included the price of the premium paid and direct benefits included the insurance payout received after the insurance was triggered. Moral hazard was calculated as an amount of insurance payout that was used for other than replacing or repairing the damaged property such as crop field or house. Transaction costs were not separately considered since the premium price is taken as a whole unit. No transaction costs were considered from the buyer side. The indicators for benefits and costs were developed using literature review and experts' opinions (Figure 1) and the identified indicators were used in the development of questionnaires.

Detailed structured questionnaire surveys were implemented at the community level to understand needs and perception issues to be considered for formulating effective insurance programmes and to understand benefits and costs associated with risk insurance at the local level. The structured questionnaires consisted of questions on the demographic background of the respondent, the past crop loss experience, opinion on the insurance currently enrolled (in case of insured) and on available insurance options (in case of non-insured and in Malaysia where there is no crop insurance in place). A generic questionnaire developed commonly for all the countries was further modified before implementing the survey by the respective country partners taking into consideration the individual country contexts such as type of insurance product being offered. The sample size was determined based on the resources at hand rather than the size determined based on the statistical sampling. However, households were selected randomly based on the stratified random sampling procedure. The elicited responses were analyzed for specific preferences among communities for certain form of risk reduction based on self-evaluation of their experience in crop insurance and presented as a percentage of responses.

2.4 Study locations

In India, the study was conducted in the Khammam and Warangal districts in Telangana. Fifty eight households were surveyed to assess the benefits and costs associated with agricultural insurance. The surveys were conducted in two villages, Perumala Sankeesa and Rajolu. In Malaysia, the data was collected from 30 households through structured questionnaire surveys. In Malaysia, the respondents were householders in Kemaman, a district in Terengganu. In the Philippines, the data was collected through a household survey of farmers in the municipalities of Sta. Cruz and Sta. Maria, in the Province of Laguna, involving 563 farmers. These surveys were complemented with focus group discussions (FGDs), field observations and photo documentation. Due to the limited sample size, the associated results should not be construed for their representation to the study locations but only those of the respondents who participated in the study.

3. RESULTS AND DISCUSSION

In this section, results from the three case study countries are presented. Overall, it can be observed that insurance has helped households to cover part of the losses associated with a disaster. Subsidizing of premiums have played a significant role in improving the access and acceptability of insurance. However, instances were observed where the premium levels paid by the insured and the payouts received after the insurance triggered varied significantly. Such discrepancies may have led to lack of trust on the insurance providers and the loss estimation procedures employed. Overall, the insurance has provided a positive BCR for the insured in all the case study countries.

3.1. India

The study indicated that uninsured farmers prefer to invest money for the purchase of livestock (46% among insured compared to 17% of insured farmers)

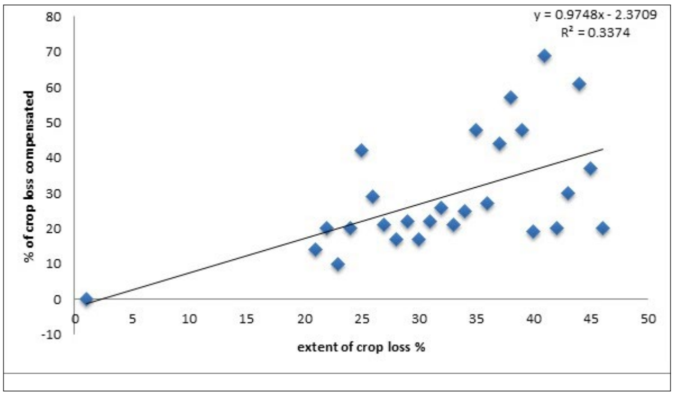

FIGURE 2. Correlation between loss and insurance payout.

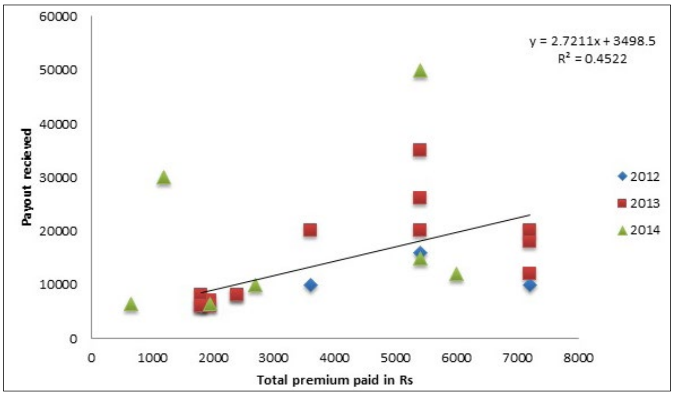

FIGURE 3. Correlation between insurance premium and payout.

and more insured farmers (28%) have made significant investments, particularly in small business compared to uninsured farmers. Furthermore, only 10% of insured farmers felt that there was even a moderate potential for implementing alternate strategies to insurance. A significant downside of crop insurance is the potential lack of correlation between payment and actual losses (Figure 2). The survey revealed a correlation coefficient of 0.2 between the percentage of crop loss covered by the insurance payout to premium paid in loss years 2012, 2013 and 2014. This low level of correlation indicates that the premium does not reflect the payment for losses. Similarly, comparing the percentage of crop loss to the percentage of crop loss that was compensated by the insurance the correlation is only 0.14, indicating that the level of correlation between the actual loss and compensation received is quite low (Figure 3).

Eighty five percent of insured farmers reported making household consumption adjustments during the last season of crop loss. This was higher than 75% of uninsured farmers who made household consumption adjustments during the same period. This indicates that insurance has not had a significant impact on household income fluctuations and in effect the need for consumption adjustments during periods of crop loss. The plausible explanation for this could be that the smaller farmers who are not enrolled in insurance are highly subjected to consumption adjustments while the farmers who could afford insurance are not.

The survey showed that in the previous crop loss year, 64% of uninsured farmers sold assets to cover losses compared to 36% of insured farmers. Forty three percent of uninsured farmers reported selling livestock during the loss season; of these farmers, 50% reported that they had to sell their cattle below market price. This suggests that insurance has reduced the need for farmers to sell assets to cover losses. For the same loss year, 64.2% of uninsured farmers reported taking loans to cover crop losses, 39% of farmers reported that they took these loans from banks as well as money lenders, and 53% of farmers reported that they had partially repaid the loan. The prominent reason for taking the loan was unexpected household expenses (46.4%). Eighty two percent of insured farmers reported that they took loans during the season they suffered crop loss; of these farmers, 74% of insured farmers reported that they borrowed money from money lenders.

Farmers perceived that the biggest cost of insurance was the income stress caused from paying premiums (42.8%). This is reflected in the majority of farmers' opinion that the premium should be completely subsidized by the government (67.8%). Unavailability of cash during crucial periods was also identified as a cost of insurance; the average time between claims and payout was 7 months. Consumption smoothing was perceived to be the biggest benefit of agricultural insurance (64.2%) and this is followed by an increase in confidence (57.14%) and ability to recover from disasters (42.8%). Based on the assessment of benefits and costs of agricultural insurance, the benefits and costs that can be monetarily quantified are used to obtain a Benefit-Cost Ratio (BCR) calculated at the household level. The calculated BCR for the agricultural insurance programme averaged for the sample insured households was 2.0, which indicates that the programme had a positive impact, and the overall benefits outweighed the costs.

3.2. The Philippines

Table 2 shows the summary of the BCR. With catastrophic events assumed to occur annually, the net present value (NPV) for a 10-year period at 15% discount rate was about PHP 110,375 per ha (USD 2155) and PHP 62,925 per ha (USD 1229) for rice production with and without crop insurance, respectively. The corresponding BCR was found to be 1.49 for insured farms and 1.31 for uninsured ones. These results suggest that in the case where catastrophic events occurred annually, rice production without crop insurance is still financially profitable as can be seen from NPV greater than zero and BCR greater than 1. However, availing insurance increases the ratio further. Availing of crop insurance can increase the financial profitability of rice production since farmers with insurance have higher NPV and BCR compared with farmers without insurance. Overall, there is an incentive to avail crop insurance given that the difference between the NPV of insured and uninsured (PHP 47,450 or USD 927) is quite significant. In addition, the premium paid in present value terms (PHP 22,244 or USD 424) is only about 32% of the payout received (PHP 69,694 or USD 1361).

Scenario	*BCR*
With catastrophic events every year	1.49
With catastrophic events based on actual data	1.32
Without catastrophic events	1.18

TABLE 2. Summary of benefit-cost analysis results in the Philippines.

A similar trend has been observed in the scenario with catastrophic events based on actual data. With catastrophic events occurring at 60% probability (6 out of 10 years), the NPV of insured farms have reduced to PHP 72,956 per ha (USD 1425) and the BCR to 1.32. Nonetheless, these are still higher than uninsured farms with NPV of PHP 62,925 per ha (USD 1229) and BCR of 1.31. Overall, it is still financially attractive to avail crop insurance since premiums paid in present value terms are also relatively smaller than the payout received by the farmers.

In the scenario without catastrophic events, rice production for both insured and uninsured farmers was still profitable but this time uninsured farms have realized a higher benefit than those who availed of crop insurance. It is, therefore, not financially attractive to avail of crop insurance when catastrophic events are not realized at certainty in any year since farmers will just incur additional costs of premium payment for the insurance coverage without receiving any compensation at all. This implies that crop insurance is only useful when catastrophic climate events are known with certainty. Since catastrophic events are not predictable, it is suggested that crop insurance may need to be obtained every year.

3.3. Malaysia

In Malaysia, the study focused on house insurance against floods. Contrary to expectation, this study did not find evidence of significant difference between insured and uninsured in terms of the number of lost working days, household adjustment on consumption, amount spent for repairing a damaged house, willingness to invest in DRR efforts and economic status 6 months after a flood occurrence.

Table 3 provides the estimated benefits and costs of flood insurance for a community. The data is based on a three-year interval of a flood event. None of the respondents incurred interest charges due to borrowing thus the value is nil. Only two respondents indicated that they had to borrow, the need to borrow is minimal as the district office has allocated sufficient support (food and shelter) during and after the flood occurrence. Only one respondent indicated using the insurance payout for house improvements (increased precautionary measures).

Measures	*Value per household (RM)*
COSTS	
Premium	184
Moral Hazard	500
BENEFITS	
Insurance pay-out	4,662.50
Restoration of damaged houses	1506.25
Increase awareness of precautionary measures	375
Opportunity cost of borrowing	0
BENEFITS – COSTS	5,859.75

TABLE 3. Estimated benefits and costs of insurance to households.

A number of respondents indicated that they used all the insurance pay-out for house repairs and that only a partial amount of the compensation was used for repair cost. The respondents were unwilling to spend full repair cost due to the anticipation that they may face future flood damages.

Although respondents have received compensation for the flood losses, none indicated that they have recovered fully. Nonetheless, all respondents assert that insurance is an important tool to help them to recover from losses due to flood. The majority of respondents did not feel that the money invested in insurance premiums can be used for more gainful livelihood activities and they indicated their intention to renew the insurance policy.

4. CONCLUSIONS

This paper presented the benefits and costs accrued from insurance in a study carried out in India, the Philippines and Malaysia using household surveys among the insured populations. The findings discussed in this paper suggest that insurance may assist communities to recover and may positively influence disaster risk reduction, as the estimated benefits of insurance outweigh the estimated cost. The positive BCR indicated that, overall, crop insurance was successful as an economic tool.

However, as a large proportion of the variables could not be quantified into monetary values due to lack of sufficient data, the BCR does not portray a complete encompassing value of benefits and costs.

Results indicate that insurance helped communities to make additional investments when compared to the uninsured indicating the positive impact on the savings of the insured. Insurance also avoided distress sale of assets. However, insurance did not completely stop the insured from taking loans to cover the losses. This indicates that insurance payouts were not sufficient to cover losses accrued from disasters. In addition, instances were seen where the insured had to make consumption adjustments during disaster years akin to that of the uninsured indicating that the insurance was not able to smooth the income fluctuations. Despite the subsidized premiums, insurance premiums were felt to be costly by most of the insured and delayed payouts have stressed the insured especially in India where payouts were reported to be delayed as late as 7 months. Insurance can increase the NPV, compared to the uninsured, and makes economic sense to invest.

From the results presented in this study, it is evident that the higher benefits compared to costs accrued to the insurance subscribers provides an impetuous for further promoting insurance in the case study countries in specific and in the Asia region in general. Subsidizing the premiums has certainly played an important role especially in making insurance accessible, even though some of the respondents felt the insurance premiums costly even after subsidy. In addition, subsidized premiums have played a significant role in keeping the positive BCR.

The results presented in this paper should be interpreted keeping in view the following limitations. The cost of ineffective implementation of the insurance programme, particularly the long period between loss and payment of claims, could not be included in the BCR. Insurance has demonstrated particular proficiency in assisting farmers with short-term coping, however, this has been hindered by inefficient payout delivery systems. Delayed payments are a significant cost that also has the potential to diminish the beneficial impacts of insurance, particularly the loss coping benefits. In the absence of timely payouts, farmers will turn to informal and unsustainable coping strategies, such as loans from money lenders and sale of productive assets. This can be aggravated when farmers make decisions based on the security provided by insurance; uncompensated and delayed payments can lead to an income shock to the household. Uncompensated losses due to basis risk in yield-based insurance or due to uncovered losses is a significant impediment to farmers' confidence in insurance.

Significant long-term impacts of insurance on farmers' livelihoods in the region have yet to be materialized; changes in farmer behaviour relating to confidence building and associated positive impacts on farm management practices are yet to be realized, and significant impacts on profits and assets are only slowly emerging. In India, 90% of farmers said that there was very low potential for implementing alternatives to crop insurance. Primary drivers for the uptake and preference for insurance are its mandatory linkage to crop loans and subsidies on premiums. Nearly all the insured farmers stated that accessing credit from banks was the primary reason they had taken crop insurance, especially in India.

Dissemination of knowledge regarding on-farm risk management strategies could be useful to strengthen risk management capacities of farmers. In conclusion, although theoretically the benefits clearly outweigh the costs, further efforts are required to completely realize the potential of insurance. Based on responses given by the respondents, it is recommended that corrective measures should be done by the government and insurance providers to improve insurance programmes particularly on its delivery system and the payout amount.

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Climate change impact on groundwater recharge and suggested adaptation strategies for selected Asian cities

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ABSTRACT

Currently, 54% of the world's population live in urban areas, and this figure is expected to increase to 66% by 2050. Major cities and municipalities in the region rely either wholly or partially on groundwater. Four Asian cities, namely Bangkok, Bandung, Ho Chi Minh City, and Lahore, are selected for the study as their groundwater dependency is in the critical range of 45% to 100%. Therefore, this study aims to assess current and future climate, quantify changes in climatic drivers, analyse the vulnerability of groundwater recharge systems to such changes, and then formulate adaptation strategies to reduce the vulnerability to groundwater resources in these cities. The methodology includes model-backed analysis of groundwater recharge vulnerability, which is later discussed with stakeholders (policymakers, scientists, and local water users) to prescribe possible adaptation options. The results show that Ho Chi Minh City and Bandung will receive less rainfall and Lahore and Bangkok more rainfall in the future. Bangkok is the only city in which minor fluctuations in future temperature is observed, while the remainder have significant increases (up to 3.1 °C). In line with the rainfall projections, Ho Chi Minh City and Bandung are projected to experience decreased groundwater recharge while the other two cities, Bangkok and Lahore are expected to have higher groundwater recharge in future.

KEYWORDS

Groundwater, Climate change, Bangkok, Bandung, Ho Chi Minh City, Lahore

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HIGHLIGHTS

- The future climate of four Asian cities: Bangkok, Bandung, Ho Chi Minh City (HCMC), and Lahore were projected using multi-climate models
- A water balance/hydrological model was developed to simulate groundwater recharge in four Asian cities
- Future temperature is projected to increase in all four cities in accordance with global trends
- Rainfall in HCMC and Bandung is projected to decrease, whereas it is projected to increase in Bangkok and Lahore
- In line with the rainfall patterns, groundwater recharge is expected to decrease in HCMC and Bandung, while projected to increase in Bangkok and Lahore

1. INTRODUCTION

1.1 Background

Around two billion of the rural and urban population are using groundwater as the primary source of drinking water, accounting for roughly 32% of the total drinking water supply (Morris et al., 2003). Currently, 54% of the world's population live in urban areas, and this figure is expected to increase to 66% by 2050. Projections show that urbanization, combined with overall global growth could add another 2.5 billion people to the urban population by 2050, with close to 90% of such increase concentrated in Asia and Africa. Major cities and municipalities in the region rely either fully or partially on groundwater as a part of the water supply network, where it is also used by small-scale rural or town water supply systems. For example, groundwater dependency is 70% for domestic and 60% for industrial water demand in Bandung, Indonesia (2007 estimate; Tirtomihardjo, 2015), 45% in HCMC, Vietnam (2012 estimate;

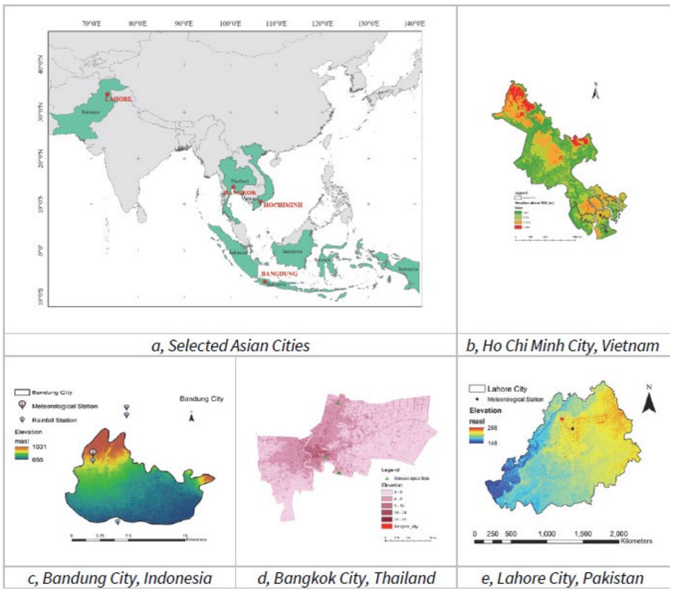


FIGURE 1. Location of selected Asian cities: Bangkok, Bandung, Ho Chi Minh City, and Lahore

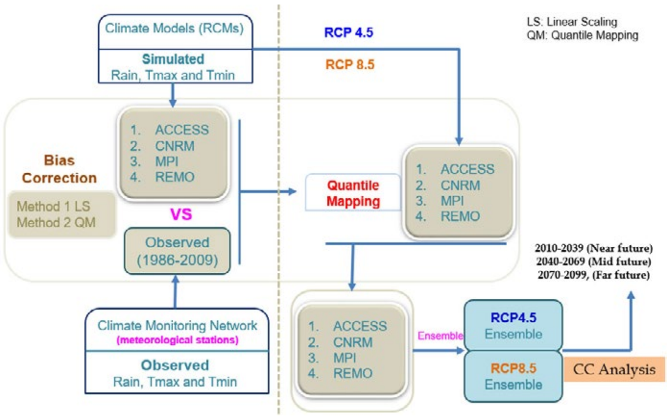


FIGURE 2. Future climate projection methodology adopted in this study

Vuong, Long, & Nam, 2015) and 100% in Lahore, Pakistan (Basharat, 2015). Despite the significance of groundwater for sustainable development, it has not always been adequately managed, often resulting in depletion and degradation of the resource. Due to various pollution sources and climate change in urban areas, the quality and quantity of groundwater have become critical issues for urban groundwater environments (Collin & Melloul, 2003). The strategic importance of groundwater for global water and food security will probably intensify under climate change as more frequent and intense climate extremes (droughts and floods) increase variability in precipitation, soil moisture, and surface water (Taylor et al., 2013). The predicted impact of climate warming on groundwater include changes in the magnitude and timing of recharge (Hiscock et al., 2012), typically with a shift in seasonal mean and annual groundwater levels depending on changes in the distribution of rainfall (Liu, 2011) and snowmelt (Jyrkama & Sykes, 2007; Okkonen & Kløve, 2010). The predicted changes in recharge may be more significant than for precipitation (Ng, McLaughlin, Entekhabi, & Scanlon, 2010).

The purpose of this study is to assess the current and future climate, quantify changes in climatic drivers, analyse vulnerability of groundwater recharge systems to such changes, and then formulate adaptation strategies to reduce the vulnerability of groundwater resources in selected Asian cities, namely Bangkok, Bandung, HCMC, and Lahore, through the collaborative effort of scientists, policymakers, and relevant stakeholders.

The selected Asian cities are highly dependent on groundwater since it is the major source of drinking water, and water for industrial and other commercial uses. The groundwater dependency of these selected cities ranges from 45% to 100%, and thus, assessment of groundwater vulnerability in the context of a changing climate is essential for sustainable groundwater management.

1.2 Objectives

The overall objective of this study is to assess the climate change impact on groundwater recharge and formulate adaptation strategies in four selected Asian cities. Specific objectives are to:

- assess the current and future climate and related trends in the selected Asian cities;
- assess the vulnerability of groundwater recharge systems to climatic change in those cities; and
- formulate adaptation strategies for reducing the vulnerability of groundwater recharge to climate change.

2. METHODOLOGY

2.1 Study Areas

The selected four fast-growing cities in Asia consist of Bangkok, HCMC, Bandung, and Lahore (Figure 1). Addressing water shortage problems and pressure on groundwater use requires greater attention and decisive action in these cities. Not only is the increase in water demand posing stress on groundwater use but the adverse impact of climate change is also apparently taking place, resulting in groundwater depletion and groundwater-related problems. Understanding the impact of future climate on groundwater resources would facilitate effective water management in the four cities. This examines the physical science relating to climate change and hydrology using multiple modelling approaches. The four cities were selected for this research on the basis of their groundwater dependence, which ranges from 45 to 100%.

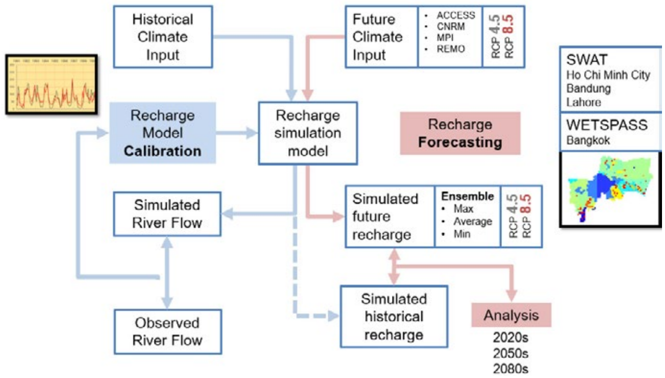


FIGURE 3. Method for simulating groundwater recharge in the four cities

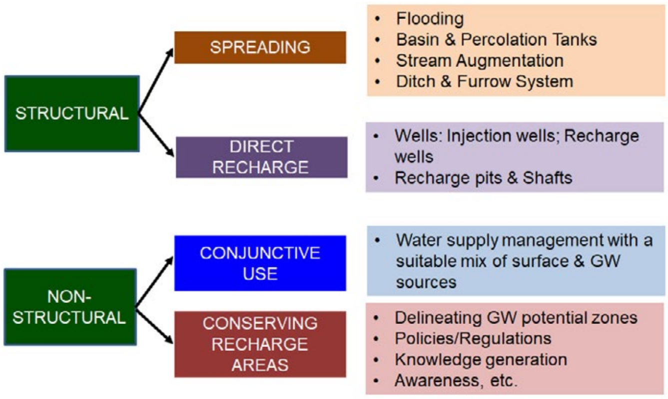


FIGURE 4. Potential adaptation options identified from a literature review

Bandung is the capital of the West Java Province in Indonesia. It is the nation's third most populous city, with over 2.6 million people (2015). The city lies on a river basin surrounded by volcanic mountains. As a rapidly developing metropolitan region, the Bandung Basin is experiencing increasing problems with groundwater, with an imbalance between discharge and recharge. The groundwater levels have dropped by more than 50 metres from their original level, forming a cone of depression in the water table and creating a critical zone, especially in industrial areas.

HCMC is the economic capital of Vietnam. It is situated in a transition zone stretching from the hilly areas in the middle of Vietnam to the lowlands of the Mekong Delta. HCMC is enclosed by Tay Ninh and Binh Duong Provinces in the north, Dong Nai, and Ba Ria-Vung Tau Provinces in the east, and Long An Province in the west. The southern part of HCMC is bounded by the East Sea with a 30 km stretch of coastline. The city covers an area of 2095 km², extended in the northwest to southeast direction, with a maximum length of 100 km and a maximum width of 45 km. It is crisscrossed by the canals and tributaries of the Dong Nai-Sai Gon River system with an elevation decreasing from north to south. Most of the city area has a low elevation from 0 to 2 m above MSL as shown in Figure 1. HCMC is currently the most important economic centre of Vietnam. In 2012, its GDP was around 30 billion USD, making up 21.7% of the total national GDP (Shrestha, Pandey, Thatikonda, & Shivakoti, 2016). The present population of the city is 7.7 million, which has increased rapidly with a growing net emigration rate as well as increased urbanization, construction activities, and groundwater use. HCMC has a total of 257,216 wells with an extraction rate of 717,246 m³/d.

Lahore is the capital of Punjab Province in Pakistan. It is the nation's second most populous city, with over 11 million people (Basharat, 2015). The city lies on a river basin surrounded by agricultural lands and other relatively less crowded cities. As a rapidly developing metropolitan region, Lahore is experiencing growing problems with groundwater due to an imbalance between discharge and recharge. The groundwater levels have dropped at an annual rate of 0.45 to 1.50 m; more than 45 m from their original level, forming a cone of depression in the water table and expanding the critical zone.

Bangkok is the capital of Thailand and the most populated city in the country. The city is home to more than 13% of the country's population, and the hub for most of the commercial and economic activities in the kingdom. At the same time, the city is very popular with visitors and appreciated for its versatility and multiple points of interest. The economy of Thailand has been rising dramatically over the past 50 years to which Bangkok has made a significant contribution. The city of Bangkok is in the southern part of Thailand and occupies a total area of 1570 km².

2.2 Methods and Data

The methodology used to assess the climate change impact on groundwater recharge consists of three parts: (1) climate change analysis (CCA) for projecting the future climate of the cities; (2) groundwater recharge modelling based on future climate projections; and (3) the adaptation option. The methodology for CCA is shown in Figure 2, while Figure 3 shows the methodology to simulate groundwater recharge in the four cities. Adaptation options were identified following the flowchart presented in Figure 4.

The data used for the study was collected from various sources, consisting of hydrological, meteorological, soil type, and land use/land cover. Future climate data was obtained from four Regional Climate Models (RCMs) under Representative Concentration Pathways (RCP) 4.5 and 8.5. The RCP8.5 represents a rising radioactive forcing pathway leading to 8.5 W/m² (~1370 ppm CO_2 equivalent by 2100) (Riahi et al., 2011). RCP6.0 represents stabilization after 2100 without overshooting the

RCM	*Parent GCM*	*Resolution (degree)*	*Hindcast*	*Forecast*	*Developer*
CCAM	ACCESS1.0	0.5	1970-2005	2006-2099	Australian Bureau of Meteorology, Australia
CCAM	CNRM-CM5	0.5	1970-2005	2006-2099	National center for Meteorological Research, France
RCA4	MPI-ESM-LR	0.5	1970-2005	2006-2099	Max-Planck-Institute for Meteorology, Germany
REMO 2009	MPI-ESM-LR	0.5	1970-2005	2006-2099	Climate Service Center, Germany

TABLE 1: Four selected RCMs for the study and their properties

pathway to 6 W/m^2 (~850 ppm CO_2 equivalent) (Masui et al., 2011). The RCP4.5 gives stabilization without overshooting the pathway to 4.5 W/m^2 (~650 ppm CO_2 equivalent) after 2100 (van Vuuren et al., 2011). The RCMs were selected based on experience and the literature review. Since three out of the four cities are in Southeast Asia, the researchers selected climate model results proven as being better suited for CCA studies in the region by McSweeney, Jones, Lee, and Rowell (2015). Out of the 28 GCMs evaluated, they found ACCESS 1-0, CNRM-CM5, and MPI-ESM-LR to be among the "satisfactory" performing models in South East Asia. Brief information on the selected models is provided in Table 1.

The hydrological models, Soil and Water Assessment Tool (SWAT), and Water and Energy Transfer between Soil, Plants and Atmosphere under Steady State condition (WetSpass) were used to estimate the groundwater recharge in this study. The SWAT is a semi-distributed hydrological model, which forms a hydrological domain (Arnold, Srinivasan, Muttiah, & Williams, 1998). SWAT was applied to Lahore, HCMC, and Bandung cities. In the case of Bangkok, it was difficult to cover the city within a hydrological catchment and thus the WetSpass model was used instead. WetSpass is a physically based model for estimating the spatial variations of groundwater recharge, surface run-off, and evapotranspiration. WetSpass uses a cell by cell water balance approach and thus does not require the model domain to be a hydrological catchment (Batelaan and De Smedt, 2001).

Both models were calibrated and validated in the respective cities. The SWAT consists of numerous parameters that govern the response of the model. These parameters are process-based and must be within a realistic uncertainty range (Arnold et al., 2012). Sensitivity analysis was performed to determine the most sensitive parameters for a given watershed. Sensitivity analysis of the catchments was performed using the SWAT-CUP (SWAT Calibration and Uncertainty Programs) tool. The sensitive parameters were then used to calibrate the model against the observed discharge data. Auto-calibration was then performed using SWAT-CUP followed by fine-tuning via manual calibration. Model validation was conducted to ensure that the model would be capable of accurate simulation using new sets of input data. Based on this hydrological calibration of the model, it was concurred that the spatially varied recharge output could also be validated. The efficiency of the model (NSE and R^2) was greater than 0.5 and hence considered to be satisfactory.

In the case of WetSpass, the initial groundwater levels were interpolated at each cell from the groundwater measurement stations to initialize the model. After model calibration, future bias- corrected climate data was input to obtain future groundwater recharge projections. Altogether there were eight probabilities for future groundwater recharge from four RCMs and two RCP scenarios. An ensemble (average) between the RCMs was considered to be the representative projection for each RCP4.5 and RCP8.5.

3. RESULTS AND DISCUSSION

3.1 Annual Rainfall Trends

Annual rainfall trends are presented in Figure 5. Each graph is divided into four frames, with the historical period 1978–2005 as the baseline in the first frame. The future period depicted on the right-hand side is broken down into three periods; the 20s (2006–2040), 50s (2040–2070), and 80s (2070–2100).

The combined graph in Figure 6 presents the changes in annual rainfall pattern for the four cities during the twenty-first century under RCP4.5 and RCP8.5. The precipitation prediction for the future period was compared with the past of 1978–2005. In general, future rainfall in Lahore and HCMC is projected to follow an upward trend, while in Bandung and Bangkok it is predicted to decrease.

For Bandung, HCMC, and Lahore the past trend shows decreased rainfall in recent years, while in con-

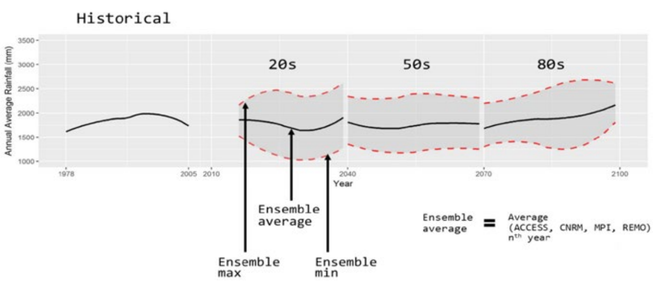


FIGURE 5. Annual rainfall graph components

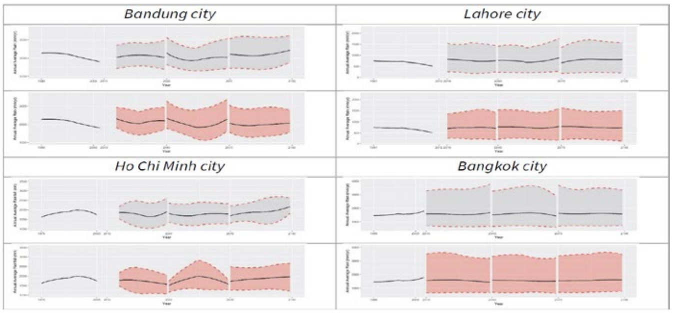


FIGURE 6. Annual future rainfall patterns for Bandung, HCMC, Bangkok, and Lahore. Grey – RCP4.5, Red – RCP8.5

trast, Bangkok shows a gradual rise in historical rainfall. Compared to the baseline period, the Bandung RCP4.5 ensemble (average) projects a slight decrease overall with an increase in the 80s, and for RCP8.5 there is an overall decrease with the average plunging below 2000 mm per year. As with Bandung, the future precipitation pattern of Bangkok will slightly decrease under both RCP4.5 and RCP8.5.

It is predicted that for the near future, by 2040 the rainfall might continuously decrease in HCMC. Under RCP4.5 scenario, the future rainfall showed a slight downward trend overall with some increment from the 2080s, while the predicted rainfall under RCP8.5 varied considerably. Up to 2070, HCMC might face drier years, after which the rainfall could start to increase again.

For Lahore, the past trend shows decreased rainfall in recent years. Compared to the year 2005, RCP4.5 projects a slight increase overall, with a variation in the 50s and 80s. While under RCP8.5 there is an overall increase throughout the twenty-first century with a slight decrease in the 80s. Detailed monthly rainfall trends and a summary of percentage changes for the future period relative to the baseline are presented in Figure 7.

In summary, Bandung future climate projections show that the rainfall is going to decrease in the dry season and increase slightly in the wet. However, the overall decrease is negligible for RCP 4.5 and -3.5% for RCP 8.5. Similarly, future rainfall in HCMC might follow a downward trend. Projections show that the amount of rainfall is going to decrease in both the dry and wet seasons, by varying degrees under RCP8.5 (-4.2%) and RCP4.5 (-3.3%).

In contrast, Lahore future climate projections indicate that rainfall is going to increase significantly in the dry season and slightly in the wet. Average rainfall is likely to increase by 11 to 14.5% during the twenty-first century under RCP4.5 and RCP8.5, respectively. For Bangkok, the average annual rainfall is going to increase in all periods under RCP8.5, except the 2050s. The projected rainfall during the dry season under both RCP scenarios is going to increase; however, during the wet season, it is predicted to increase under RCP4.5 and decrease under RCP8.5.

3.2 Temperature Trends

The temperature in all four cities is projected to increase in line with future global temperature trends. The maximum and minimum temperatures in the selected cities are presented in Figure 8.

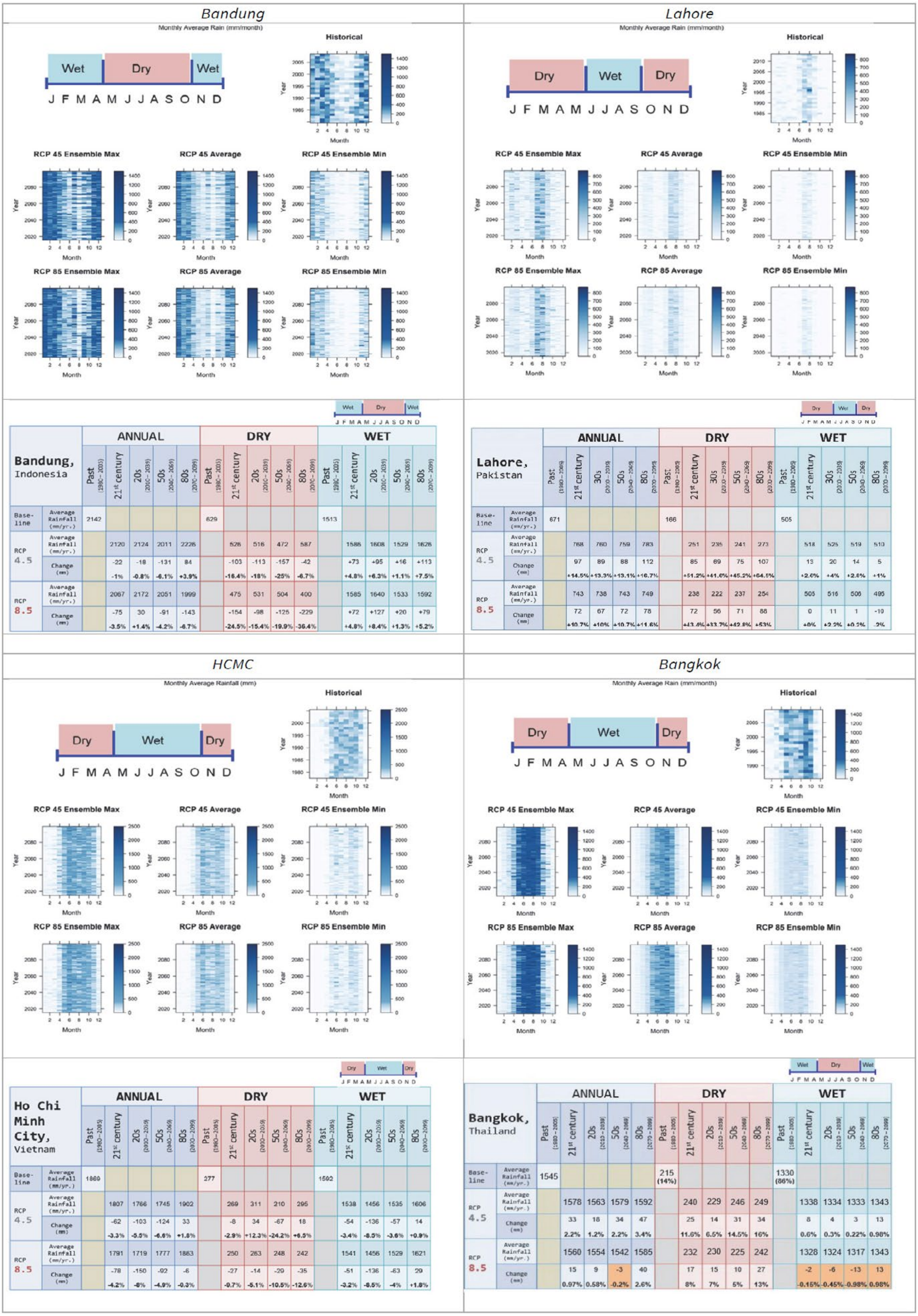
Maximum temperature trends for Bandung are showing increasing trends in recent years. According to RCP4.5, there will be an overall increase of 1 °C by the end of the century, with a plateau in the 80s (compared to the 2005 value). Whereas, for RCP8.5, the overall increase will be almost 3°C by the end of the century, with continually increasing trends over the 20s, 50s, and 80s (compared to the 2005 value).

For HCMC, an upward trend in maximum temperature is indicated under both RCP4.5 and RCP8.5 compared to the historical period (1978–2005). The RCP4.5 predicted that the maximum temperature would rise by 1 °C by the end of the century, and by almost 2.5 °C under RCP8.5, with continuously increasing trends over the 20s, 50s, and 80s.

The historical trend of maximum temperature for Lahore shows mixed patterns of decreasing and increasing trends, which are set to continue in the coming years. There will be an overall increase in maximum temperature of 1.5 and 4.5 °C by the end of the century for RCP4.5 and RCP8.5, respectively. Maximum temperature shows possible variations in the 50s for RCP4.5. However, for RCP8.5 a consistent increase until the end of the twenty-first century is observed.

For Bangkok, the baseline period presents an increasing trend in recent years of 0.02 °C/year. According to RCP4.5, there will be increases of between 0.42 and 1.01 ºC during the 50s and 80s period, respectively and an overall decrease of 0.14 ºC during the 20s [compared to the baseline value of 33.28 °C]. Whereas, for RCP8.5, the overall increase will be 0.34, 0.37, and 1.77 ºC during the 20s, 50s, and 80s, respectively. Consequently, a constantly increasing trend can be observed in maximum temperature over the 20s, 50s, and 80s.

A summary of the comparative change in average annual rainfall and average annual maximum and minimum temperatures under RCP4.5 and RCP8.5 for the four cities is presented in Table 2. The change in projected climate varies between the four project cities. Regarding rainfall, HCMC is going to see a greater decrease than in the past of around 3 to 4%. Bandung is also projected to receive less rainfall, especially according to the RCP 8.5 scenario. Whereas, Bangkok and to a greater extent Lahore, are expected to receive a boost in annual precip-



Bandung, Indonesia		ANNUAL Past (1980–2005)	ANNUAL 21st century	ANNUAL 20s (2010–2039)	ANNUAL 50s (2040–2069)	ANNUAL 80s (2070–2099)	DRY Past (1980–2005)	DRY 21st century	DRY 20s (2010–2039)	DRY 50s (2040–2069)	DRY 80s (2070–2099)	WET Past (1980–2005)	WET 21st century	WET 20s (2010–2039)	WET 50s (2040–2069)	WET 80s (2070–2099)
Base-line	Average Rainfall (mm/yr.)	2142					629					1513				
RCP 4.5	Average Rainfall (mm/yr.)		2120	2124	2011	2226		526	516	472	587		1586	1608	1529	1626
	Change (mm)		-22 -1%	-18 -0.8%	-131 -6.1%	84 +3.9%		-103 -16.4%	-113 -18%	-157 -25%	-42 -6.7%		+73 +4.8%	+95 +6.3%	+16 +1.1%	+113 +7.5%
RCP 8.5	Average Rainfall (mm/yr.)		2067	2172	2051	1999		475	531	504	400		1585	1640	1533	1592
	Change (mm)		-75 -3.5%	30 +1.4%	-91 -4.2%	-143 -6.7%		-154 -24.5%	-98 -15.4%	-125 -19.9%	-229 -36.4%		+72 +4.8%	+127 +8.4%	+20 +1.3%	+79 +5.2%

Lahore, Pakistan		ANNUAL Past (1980–2005)	ANNUAL 21st century	ANNUAL 30s (2010–2039)	ANNUAL 50s (2040–2069)	ANNUAL 80s (2070–2099)	DRY Past (1980–2005)	DRY 21st century	DRY 30s (2010–2039)	DRY 50s (2040–2069)	DRY 80s (2070–2099)	WET Past (1980–2005)	WET 21st century	WET 30s (2010–2039)	WET 50s (2040–2069)	WET 80s (2070–2099)
Base-line	Average Rainfall (mm/yr.)	671					166					505				
RCP 4.5	Average Rainfall (mm/yr.)		768	760	759	783		251	235	241	273		518	525	519	510
	Change (mm)		97 +14.5%	89 +13.3%	88 +13.1%	112 +16.7%		85 +51.2%	69 +41.6%	75 +45.2%	107 +64.5%		13 +2.6%	20 +4%	14 +2.8%	5 +1%
RCP 8.5	Average Rainfall (mm/yr.)		743	738	743	749		238	222	237	254		505	516	506	495
	Change (mm)		72 +10.7%	67 +10%	72 +10.7%	78 +11.6%		72 +43.4%	56 +33.7%	71 +42.8%	88 +53%		0 +0%	11 +2.2%	1 +0.2%	-10 -2%

Ho Chi Minh City, Vietnam		ANNUAL Past (1980–2005)	ANNUAL 21st century	ANNUAL 20s (2010–2039)	ANNUAL 50s (2040–2069)	ANNUAL 80s (2070–2099)	DRY Past (1980–2005)	DRY 21st century	DRY 20s (2010–2039)	DRY 50s (2040–2069)	DRY 80s (2070–2099)	WET Past (1980–2005)	WET 21st century	WET 20s (2010–2039)	WET 50s (2040–2069)	WET 80s (2070–2099)
Base-line	Average Rainfall (mm/yr.)	1869					277					1592				
RCP 4.5	Average Rainfall (mm/yr.)		1807	1766	1745	1902		269	311	210	295		1538	1456	1535	1606
	Change (mm)		-62 -3.3%	-103 -5.5%	-124 -6.6%	33 +1.8%		-8 -2.9%	34 +12.3%	-67 -24.2%	18 +6.5%		-54 -3.4%	-136 -8.5%	-57 -3.6%	14 +0.9%
RCP 8.5	Average Rainfall (mm/yr.)		1791	1719	1777	1863		250	263	248	242		1541	1456	1529	1621
	Change (mm)		-78 -4.2%	-150 -8%	-92 -4.9%	-6 -0.3%		-27 -9.7%	-14 -5.1%	-29 -10.5%	-35 -12.6%		-51 -3.2%	-136 -8.5%	-63 -4%	29 +1.8%

Bangkok, Thailand		ANNUAL Past (1980–2005)	ANNUAL 21st century	ANNUAL 20s (2010–2039)	ANNUAL 50s (2040–2069)	ANNUAL 80s (2070–2099)	DRY Past (1980–2005)	DRY 21st century	DRY 20s (2010–2039)	DRY 50s (2040–2069)	DRY 80s (2070–2099)	WET Past (1980–2005)	WET 21st century	WET 20s (2010–2039)	WET 50s (2040–2069)	WET 80s (2070–2099)
Base-line	Average Rainfall (mm/yr.)	1545					215 (14%)					1330 (86%)				
RCP 4.5	Average Rainfall (mm/yr.)		1578	1563	1579	1592		240	229	246	249		1338	1334	1333	1343
	Change (mm)		33 2.2%	18 1.2%	34 2.2%	47 3.4%		25 11.6%	14 6.5%	31 14.5%	34 16%		8 0.6%	4 0.3%	3 0.22%	13 0.98%
RCP 8.5	Average Rainfall (mm/yr.)		1560	1554	1542	1585		232	230	225	242		1328	1324	1317	1343
	Change (mm)		15 0.97%	9 0.58%	-3 -0.2%	40 2.6%		17 8%	15 7%	10 5%	27 13%		-2 -0.15%	-6 -0.45%	-13 -0.98%	13 0.98%

FIGURE 7. Monthly future rainfall and summary of percentage change in annual, dry, and wet season rainfall for Bandung, HCMC, Bangkok, and Lahore

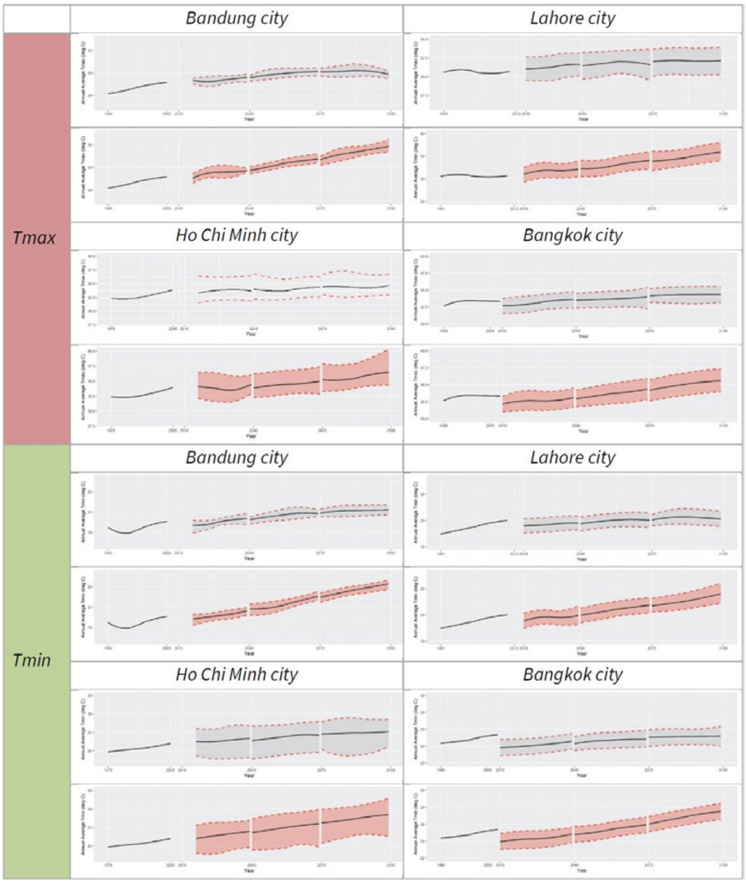


FIGURE 8. Annual temperature trends for Bandung, HCMC, Bangkok, and Lahore

Climate Change Projections in the 21st century		Project Cities			
		Bandung	Lahore	Ho Chi Minh	Bangkok
Rainfall % against baseline	RCP 4.5	-1.0 %	+14.5 %	-3.3 %	+2.2 %
	RCP 8.5	-3.5 %	+10.7 %	-4.2 %	+0.97 %
Maximum Temperature Degree C	RCP 4.5	+1.1	+1.2	+1.2	+0.43
	RCP 8.5	+1.7	+2.6	+1.7	+0.47
Minimum Temperature Degree C	RCP 4.5	+1.9	+1.1	+1.9	-0.16
	RCP 8.5	+3.1	+2.2	+2.6	+0.7

TABLE 2. Climate change projection for the four cities

GW Recharge Projections in the 21st century % against baseline		Project Cities			
		Bandung	Lahore	Ho Chi Minh	Bangkok
Annual	RCP 4.5	-2.9 %	+82.9 %	-13.8 %	+111 %
	RCP 8.5	-10 %	+74.1 %	-14.4 %	+120 %
Dry Season	RCP 4.5	-8.2 %	+99.0 %	-33.2 %	+84.6 %
	RCP 8.5	-14.7 %	+87.3 %	-38.5 %	+101 %
Wet Season	RCP 4.5	+2.0 %	+62.3 %	-4.0 %	+147 %
	RCP 8.5	-5.6 %	+57.0 %	-2.2 %	+147 %

TABLE 3. Groundwater recharge projections for selected Asian cities

itation, with the former having an increase in rainfall of +10 to +14.5% and the latter up to +2.2%.

As for temperature, Bangkok is observed to experience the least fluctuation from the baseline during the twenty-first century. Whereas, the three other cities are all expected to receive an increase in temperature in the range of +1.1 to +3.1 °C. However, minimum temperature was observed to be more affected by climate change compared to the maximum daily temperatures.

3.3 Groundwater Recharge Trends

The spatial and temporal variation in future groundwater recharge is presented in Figure 9. A greater variability in groundwater recharge is expected for all cities in the future. The groundwater recharge in Bandung is projected to decrease by -2.9% and -10.0% based on RCP4.5 and RCP8.5, respectively. The larger proportion of the decrease is seen in the dry season with a -8.2 and -14.7% decrease in comparison to +2 and -5.6% fluctuations during the wet season for RCP4.5 and RCP8.5, respectively.

For Lahore, groundwater recharge is projected to increase by 82.9 and 74.1% based on RCP 4.5 and RCP8.5, respectively. The proportional increase is larger during the dry season at 99 and 87.3%, compared to 62.3 and 57% in the wet season for RCP4.5 and RCP8.5, respectively.

For HCMC, groundwater recharge is projected to decrease by -13.8 and -14.4% based on RCP4.5 and RCP8.5, respectively. The proportional decrease is larger in the dry season at -33.2 and -38.5% compared to -4 and -2% in the wet season for RCP4.5 and RCP8.5, respectively.

The groundwater recharge for Bangkok is projected to increase by 111 and 120% based on RCP4.5 and RCP8.5, respectively. The proportional increase is larger in the wet season at 154 and 162% under RCP4.5 and RCP8.5, respectively. Recharge during the dry season also shows a positive change, although to a lesser extent than in the wet season.

A summary of the changes in future groundwater recharge under RCP4.5 and RCP8.5 for the four cities is presented in Table 3. Climate model input based on the modelling of groundwater recharge projection shows different results for the four cities. On the one hand, Bandung and HCMC are both projected to have declining groundwater recharge in the upcoming decades. While on the other hand, Bangkok and Lahore are expected to receive a considerable increase in groundwater recharge. This is in line with the projected changes in rainfall for the four cities. However, in the case of Bangkok, the

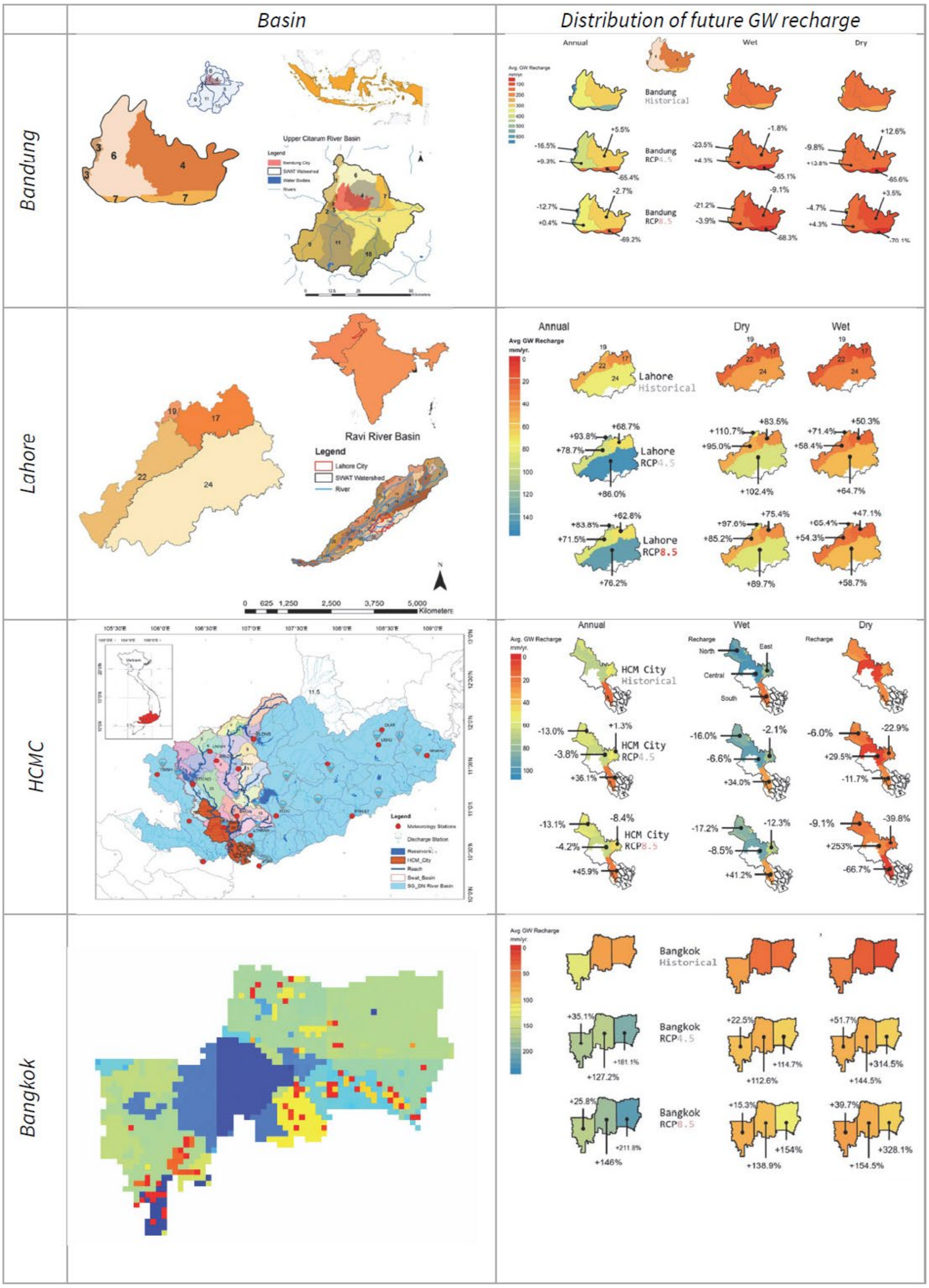


FIGURE 9. Groundwater recharge model domain and distribution of future groundwater recharge for Bandung, HCMC, Bangkok, and Lahore

minimal changes in temperature seem to have played a prominent role in simulating a substantial groundwater recharge increase in the future compared to the baseline.

For Bandung and HCMC, the decrease in groundwater recharge is more severe in the dry season with the latter projected to suffer as much as a -38.5% decrease in recharge rates. In the case of Lahore and Bangkok, the rate of recharge increase is higher in the dry season for the former and lower for the latter.

3.4 Adaptation Options

A group discussion was organized on 8 and 9 September 2017 at the Asian Institute of Technology (AIT) to identify potential adaptation options for reducing the vulnerability of groundwater to climate change in each city. The participants included those involved in the project from each of the cities under study and invited groundwater experts. During the workshop, a detailed report on projected changes in climatic variables and the subsequent impact on groundwater recharge obtained from the model-based study was presented before the group discussion. Based on the typical characteristics of participating cities, suitable adaptation options were then identified and prioritized as discussed below:

Bandung City

In general, groundwater recharge (annual and seasonal values) for Bandung is projected to decrease. The following adaptation options are expected to be useful in dealing with climate change impact on groundwater resources:

- » Estimate safe yields and potential groundwater critical zones for adoption in groundwater planning and regulations
- » Conjunctive use of surface and groundwater sources
- » Stream augmentation using constructed check dams
- » Integrate the recharge agenda with the flood control agenda and vice-versa
- » Strengthen groundwater monitoring networks
- » Arrange regulatory provision for groundwater abstraction
- » Address mainstream groundwater issues or other similar city-wide initiatives in resilient cities

Lahore

Projected recharge in the Lahore aquifer is expected to increase in both the near and far future. However, the soil is predominantly loam and, therefore, strategies for enhancing recharge on a larger scale may be less useful. In this context, Lahore needs strategies to regulate groundwater abstraction. The following adaptation options, in decreasing order of priority, are identified:

- » Direct recharge using recharge wells (same as the abstraction well) fed by rainwater harvesting
- » Augment river flow by constructing check dams
- » Enhance agricultural return flow by increasing irrigation intensity (water allocation)
- » Regulate groundwater abstraction from groundwater depression zones and combine with rainwater harvesting techniques and conjunctive water use or re-use of water
- » Identify potential groundwater recharge zones and formulate regulations for their protection
- » Establish a groundwater level monitoring mechanism for both networks and institutions
- » Address mainstream groundwater issues or other similar city-wide initiatives in resilient cities

HCMC

The following three problems in relation to groundwater in HCMC were identified during the second regional workshop: i) groundwater is being depleted for various reasons, and different locations may experience varying degrees of depletion in the future; ii) saline water intrusion, and iii) land subsidence. The following adaptation options are identified and listed in order of decreasing priority to address the issue of groundwater depletion:

- » Calculate safe yield complying with existing regulations for current and future time periods
- » Identify areas experiencing greater groundwater depletion for current and future conditions
- » Integrate recharge agenda with flood control agenda and vice-versa
- » Install bank infiltration structures at suitable locations
- » Move the well-field towards the northern part of the city

Bangkok

Groundwater management in Bangkok is already at an advanced stage compared to other cities. The Groundwater Act has been in place for some time and includes financial instrument provisions. Critical zones for groundwater abstraction are already identified. A project for artificial recharge along the Chao Phraya River is also in place. Therefore, adaptation strategies are slightly different to those in the other cities. The adaptation options identified during the second regional workshop are listed hereunder in decreasing order of priority:

- » Regulatory mechanisms for increasing groundwater abstraction in the areas of rising groundwater levels to keep them within a safe depth
- » Increase stakeholder awareness on rising groundwater levels at the post-regulation stage
- » Evaluate/update safe yield at regular intervals to maintain the groundwater level at a particular depth
- » Address mainstream groundwater issues or other similar city-wide initiatives in resilient cities

4. CONCLUSIONS

Groundwater is very important to the sustainable development of many Asian cities. In addition to rapid population growth, urbanization, and pollution, climate change is an emerging challenge to groundwater development and management. Therefore, the aim of this study was to investigate the impact of climate change on groundwater recharge and identify adaptation options in four Asian cities namely, Bangkok in Thailand, Bandung in Indonesia, HCMC in Vietnam, and Lahore in Pakistan.

An integrated approach was used to conduct this study. Firstly, climate change in the cities was projected using four RCMs with future climate data input into the hydrological models to simulate future groundwater recharge. An expert consultation workshop was organized to identify the adaptation options for managing groundwater recharge in the four cities.

The results of the study show that all four cities are expected to be warmer in the future. The highest increase (2.6 °C) in maximum temperature is expected for Lahore whereas the highest increase (3.1 °C) in minimum temperature is expected for Bandung under RCP8.5 scenarios by 2100. However, variability in rainfall is expected in all cities. HCMC and Bandung are expected to receive less rainfall in the future and Lahore and Bangkok are expected to receive more. The recharge modelling study shows that climate change is expected to decrease groundwater recharge in HCMC and Bandung and increase it in the other two cities of Bangkok and Lahore.

Various adaptation options were identified to reduce the vulnerability of groundwater to climate change in all four cities. These adaptation options are categorized into structural measures such as rainwater harvesting and artificial recharge, and non-structural measures such as groundwater regulations and monitoring. The results of this study will be very helpful for groundwater managers in each city. However, a detailed socio-economic and environmental impact analysis is recommended to consider all adaptation options for implementation.

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Integrating ALOS-PALSAR and ground based observations for forest biomass estimation for REDD+ in Cambodia

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ABSTRACT

Forest cover change is an important aspect of global environmental change because of rapid deforestation in tropical areas. Anthropogenic activities and natural phenomena can cause deforestation and forest degradation that adversely impacts biodiversity and ecosystem services. In 2008, the United Nations Convention on Climate Change (UNFCCC) programme on Reducing Emissions from Deforestation and forest Degradation (REDD+) was launched to curb deforestation and forest degradation in tropical countries. The UNFCCC COP21 Paris Agreement highlighted "encouragement for Parties to implement existing frameworks for a REDD+ mechanism". For effectively implementing a REDD+ mechanism, a robust cost-effective Measurement, Reporting and Verification (MRV) system should be developed. Geospatial data has been key for the implementation of REDD+ MRV system. In this research, aboveground biomass (AGB) of forests in Cambodia was estimated using a bottom-up approach based on field estimated biomass and PALSAR backscattering (σ^o) properties. The relationship between the PALSAR σ^o HV and HH/HV with field-based biomass was strong with adjusted R squared (R^2_{adj}) = 0.66 and 0.54, respectively as compared with HH polarization. PALSAR estimated biomass shows better results in deciduous forests as compared with evergreen forests of Cambodia because of less saturation of L-band SAR data in deciduous forests.

HIGHLIGHTS

- » PALSAR is effective in monitoring biomass and its changes without limitations of clouds
- » National level biomass information is useful in implementing sustainable forest management practices required for REDD+
- » Empirical, remote sensing and modelling studies can be useful for generating biomass information for REDD+ MRV implementation

1. INTRODUCTION

Forests play an important role in global carbon cycling as they are potential carbon sinks and sources to the atmosphere CO_2 (Muukkonen & Heiskanen, 2007; Pachauri et al., 2014). Tropical forests store about 40% of terrestrial carbon (Page et al., 2009). According to the FAO (2015), total forest area declined by 3% from 4128 M ha to 3999 M ha in 1990 and 2015, respectively. Natural forest area declined from 3961 M ha to 3721 M ha between 1990 and 2015, while planted forest increased from 168 M ha to 278 M ha. The Intergovernmental Panel on Climate Change (IPCC) has pointed out that reducing or preventing deforestation is a mitigation option for climate change (Angelsen A., 2010; Pachauri et al., 2014). The Clean Development Mechanism (CDM) under the Kyoto Protocol is not sufficient to mitigate climate change by adopting afforestation and reforestation because deforestation releases more greenhouse gases (GHGs) than afforestation and reforestation (Schoene, 2005). Forest conservation is only one of many possible options by which permanent land-use change may be avoided (Skutsch et al., 2007). REDD+ prevents carbon emissions being released into the atmosphere by conserving existing carbon stocks. The basic idea of REDD+ is to reward individuals, communities, projects, and countries that reduce GHG emissions from forests (Angelsen, 2008). Implementation of REDD+ policies require effective biomass and deforestation monitoring systems that are reproducible, provide consistent results, meet standards for mapping accuracy, and can be implemented at the national level (DeFries et al., 2007).

There are various methodologies for biomass estimation but, currently, no methodology gives a clear view on how to report carbon pools and their fluxes and the resulting accuracy and uncertainty of biomass monitoring. Therefore, the need for biomass mapping has become urgent in order to assess and produce data on forest carbon stocks and change in stocks on a national level (Maniatis & Mollicone, 2010). Van der Sande et al. (2017) studied the strength of empirical, remote sensing and ecosystem modelling approaches in evaluating biodiversity effects on carbon storage in a case study in lowland Bolivia. They proposed the integration of all three approaches to climate change mitigation. Global biomass map (Saatchi et al., 2011) shows uncertainties of about 30-50% in Indo-China countries. Therefore, there is a need to develop a regional or national level biomass map to overcome limitations of global biomass map. National or regional biomass information can be useful to design policies for a particular region based on country-specific information.

The most accurate way of calculating biomass is destructive sampling and forest inventory data using allometric equations (Anitha K. et al., 2015). However, these traditional techniques are often time-consuming, labour intensive, and difficult to implement, especially in remote areas, and they cannot provide the spatial distribution of biomass in large areas (Avtar, Takeuchi, & Sawada, 2013). Moreover, forest inventory databased methods cannot give historical information about forest biomass if there were no existing forest inventory data. To overcome this limitation most of the scientists suggest using remote sensing satellite supplemented with low forest inventory data. This can provide a cheap and fast estimation as well as historical information about forest biomass at regional or local scale (Avtar, Suzuki, Takeuchi, & Sawada, 2013). Most remote sensing techniques are based on optical and synthetic aperture radar (SAR) systems. Gizachew et al. (2016) used Landsat-8 to estimate living biomass in low woodlands of Tanzania and concluded that Landsat-8 based NDVI is a useful parameter to estimate biomass in low biomass regions. The disadvantages of optical sensors are not related to plants' structural parameters, acquisition of cloud-free images in tropical countries, the low saturation level of spectral bands and various indices (Gibbs, Brown, Niles, & Foley, 2007). Therefore, dependency on SAR sensors has increased because SAR can provide data without limitation of clouds and solar illumination. Penetration capability of SAR allows the extraction of information about plants' structural parameters and hence has the ability to measure biomass (Lu, 2006).

The successful launch of the Advanced Land Observing Satellite (ALOS) PALSAR in 2006 has increased the potential to use radar to measure biomass. This is the first long-wavelength (L-band, 23-cm wavelength) SAR satellite sensor to have the capability of collecting single, dual, full and Scan-SAR mode with cross-polarized (HV, horizontal-transmit, vertical receive) and co-polarized (HH, horizontal-transmit, horizontal receive; VV, vertical-transmit, vertical receive) data. The HV polarization is useful because it interacts with trees and produces a strong response (Mitchard et al., 2011).

Various studies have analyzed the retrieval of Above Ground Biomass (AGB) using radar data in tropical regions (Mitchard et al., 2009; Gama, Dos Santos, & Mura, 2010; Englhart, Keuck, & Siegert, 2011). Longer wavelength SAR systems have proven to be more useful because of an increasing backscatter range with changing biomass (Dobson et al., 1992; Luckman et al., 1997; Castro, Sanchez-Azofeifa, & Rivardastro, 2003; Lu, 2006). These biomass estimations are valid up to a certain threshold where saturation occurs, (Lucas et al., 2007; Mitchard et al., 2009). In general, the saturation level of SAR depends on the frequency of SAR systems as well as forests structure (Imhoff, 1995). The sensitivity of SAR decreases with the increase of biomass in the dense forests (Kasischke, Melack, & Dobson, 1997). In recent studies use of airborne laser scanning is also one of the effective methods to monitor above ground biomass precisely, however, use of airborne laser scanning is expensive and can't cover global data (Chen, McRoberts, Wang, & Radtke, 2016; Ene et al., 2017). This study is an attempt to overcome the saturation problem of PALSAR appropriately. The main aim of this study is to estimate national level biomass using PALSAR mosaic data based on a bottom-up approach to support REDD+ and forest management practices in Cambodia.

2. METHODOLOGY

2.1 Field data

The study area was visited in November 2010 and January 2011 to collect forest inventory data (Diameter at Breast Height (DBH), tree height, species, tree density, and forest types). Seventy-nine sampling plots were selected based on analysis of forest cover map, Landsat data, and SRTM-DEM data. We selected homogeneous forests for in-situ data collection. During the selection of sampling plots spatial homogeneity, eco-climatic conditions and forest types were considered. Most of the sampling plots were selected in the plane area to minimize the topographic effects of SAR data. 30×60 m and 30×30 m sampling plots were used in deciduous and evergreen forests respectively depend on the homogeneity of the site. The sampling plots were identified using GPS (Garmin 62s) in the field. We used the Cambodia-based allometric equation developed by Kiyono et al. (2010) as previous studies mentioned that a country-specific allometric equation is better than a global allometric equation (Angelsen, 2008). To check the accuracy of biomass estimation, we compared the allometric equation-based biomass of Kiyono et al. (2010) with that of Brown (1997) and Kenzo et al. (2009) allometric equations-based biomass. The comparison indicates that the allometric equation-based biomass estimation by Brown (1997) shows over-estimation and that by Kenzo et al. (2009) shows under-estimation. Therefore, we decided to use the allometric equation by Kiyono et al. (2010) allometric equation. The biomass value obtained from each tree were summed and normalized algebraically to calculate the total biomass of each plot in t/ha. In the estimation, we considered trees ≥ 10 cm DBH, which are likely to comprise of most of the woody biomass of the plots. The common plant species in Cambodia are Aporusa filicifolia (Bail Krong), Dipterocarpus tuberculatus (Roxb Khlong), Swietenia macrophylla (Krobaek), Garcinia schomburgkiana (Tro-moung/Tro-meng), Ardisia helferiana (Chhom pou prey), Cananga latifolia (Chke sraeng), Dacrydium elatum (Srol kraham). Table 1. Sows the major tree species in Cambodia and their inventory parameters in some of the field plots. The following allometric equations were used (Kiyono et al., 2010):

$$\text{Leaf biomass (kg)} = 173 \times (BA^{0.938}) \quad (1)$$

$$\text{Branch biomass (kg)} = 0.217 \times (BA^{1.26}) \times (D^{1.48}) \quad (2)$$

$$\text{Stem biomass (kg)} = 2.69 \times (BA^{1.29}) \times (D^{1.35}) \quad (3)$$

where BA stands for Basal area and D is stem density.

2.2 Satellite data

Forest cover map based on ASTER 2005 data, SRTM-DEM data, Landsat ETM+ 2009, 2010 data were used to select the sampling sites. PALSAR FBD 50 m mosaic data was downloaded from the Japan Aerospace Exploration Agency (JAXA). The processing of PALSAR data was started with the terrain corrections using methodology by Akatsuka, Takeuchi, Rakwatin and Sawada (2009) and Shimada (2010) in order to minimize the topographic effects of PALSAR in a mountainous area. The digital number (DN) was converted to the normalized radar cross section (NRSC, or σ^0). The backscattering coefficient was calculated using the following equation (Shimada, Isoguchi, Tadono, & Isono, 2009).

Major species	*Max DBH (cm)*	*Max Height (m)*
Dipterocarpus costatus	128.0	41.4
Dipterocarpus intricatus	87.2	26.2
Melaleuca cajuputi	30.0	17.2
Irvingia malayana	117.5	26.5
Shorea siamensis	34.0	16.2
Lagerstroemia calyculata	108.4	45.6
Dalbergia cochinchinensis	66.8	28.1
Shorea obtusa	53.6	24.5
Schima wallichlii	67.5	27.1
Peltophorum dasyrrhachis	77.3	31.6
Terminalia mucronata	78.2	32.1
Irvingia malayana	157.2	42.8
Dipterocarpus obtusifolius	42.8	26.9

TABLE 1. Major species in the field plots and their maximum height and DBH.

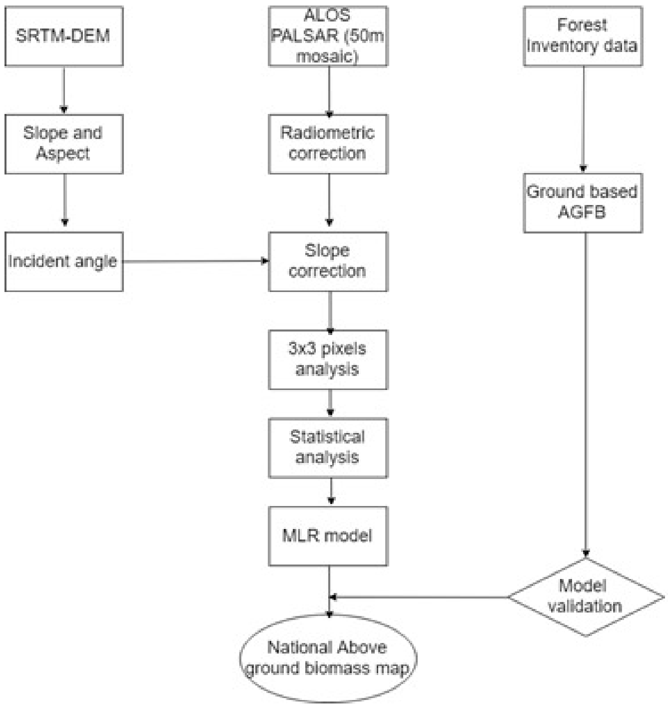

FIGURE 1. Flowchart of the methodology.

$$\sigma^0 = 10 \times \log_{10}(DN^2) - 83 \quad (4)$$

The PALSAR data was co-registered with Landsat ETM+ orthorectified data. We did not consider the climatic conditions of PALSAR 50 m mosaic data because the information was not available.

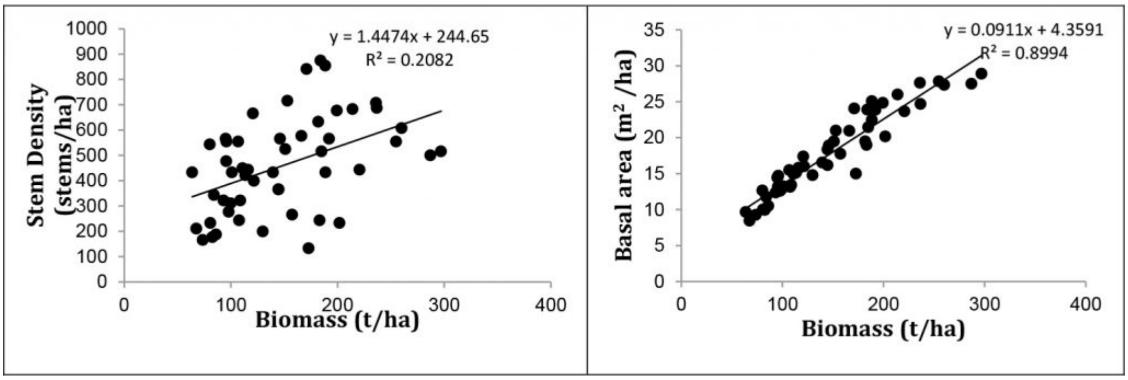

FIGURE 2A. Scatter plot and equation between Biomass for the field plots against stem density

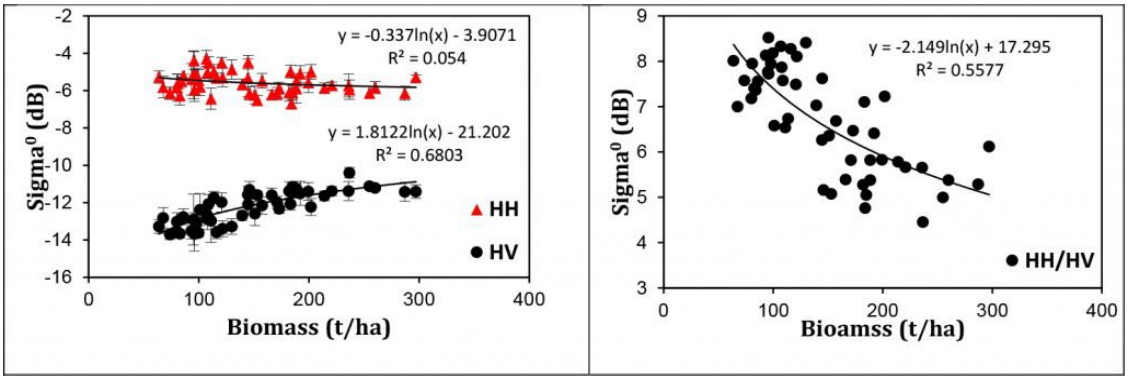

FIGURE 2B. Scatter plot and equation between Biomass for the field plots against basal area.

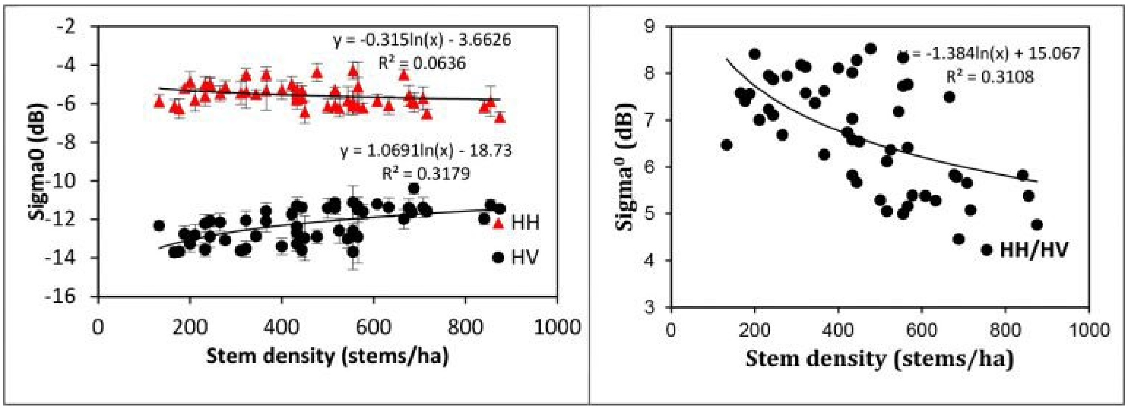

FIGURE 3. PALSAR 2009 σ⁰ HH, HV, and HH/HV plotted against biomass (a, b) and stem density (c, d).

2.3 Statistical Analysis

Multi-linear regression (MLR) method was applied relating the field calculated biomass with the backscattering properties of PALSAR. We consider biomass as a dependent variable and PALSAR backscattering (HV, HH/HV) as an independent variable. We used 3×3 pixels window size analysis for MLR model development and this MLR model was applied to the PALSAR 50 m mosaic data to estimate biomass of forests for Cambodia. Finally, validation was used to evaluate the accuracy of the model by comparing PALSAR estimated to the field derived AGB. The methodology is shown in Figure 1.

3. RESULTS AND DISCUSSION

Statistical analysis was undertaken to correlate the forest inventory data. Figures 2a and 2b show the relationship of biomass with the stem density and basal area, respectively. Figure 2a does not show good correlation ($R^2 = 0.2$) between biomass and tree density because tree density depends on tree species, site conditions, and forest type. Figure 2b shows strong correlation ($R^2 = 0.9$) between biomass and basal area because the basal area is a function of tree density and DBH. Data from a total of 79 plots were analyzed. Fifty-one plots were used for the MLR model development and 23 plots were used for model validation. Five plots were excluded from the analysis because their locations were either too near to roads or there were some degraded trees.

Figure 3a shows the relationship between PALSAR σ^0 (HH) and (HV) and biomass. Field measured biomass shows a significant relationship with the σ^0 HV (R^2_{adj} = 0.66) as compared with σ^0 HH (R^2_{adj} = 0.05). High σ^0 HH in low biomass region has been observed because of the high surface scattering from the plots covered by dry leaves and grass, which increases surface roughness. The reason why σ^0 HV polarization produces a better correlation than HH is due to the volume scattering in forest areas, which enhances the cross-polarization returns as an increase in biomass. Other studies also reveal that the

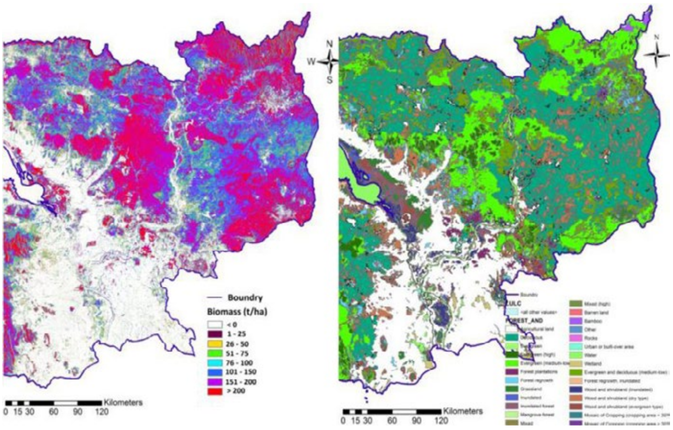

FIGURE 4. (a) PALSAR derived biomass map of Cambodia (b) Forest Cover map of the area.

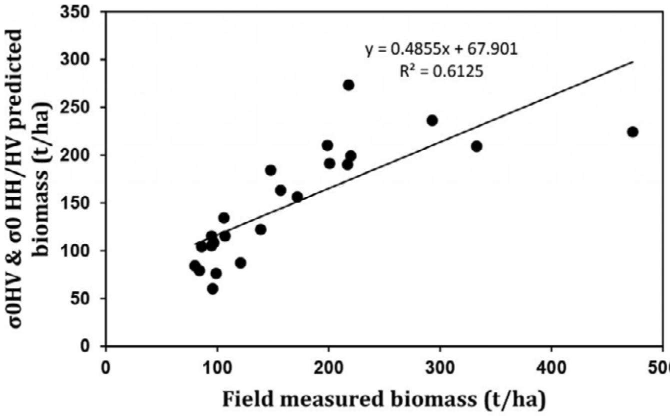

FIGURE 5. Relationship between PALSAR predicted biomass plotted against field measured biomass.

σ^0 HV is more sensitive to forest biomass compared to σ^0 HH (Le Toan, Beaudoin, Riom, & Guyon, 1992; Harrell et al., 1995). We observed different backscattering properties from the same biomass region (Figure 3a at biomass 100-150 t/ha) because of the difference in canopy and their distribution. Evergreen forest, having a multi-storey tree structure, shows high backscattering as compared to deciduous forests of the same biomass class. A loss in sensitivity of the PALSAR signal appeared to occur at approximately 150-200 t/ha biomass (Figure 3a). Figure 3b shows a strong relationship between PALSAR σ^0 HH/HV with biomass (R^2_{adj} = 0.54). Therefore, the polarization ratio is a useful parameter for biomass estimation. Figure 3c shows a poorer relationship between PALSAR σ^0 HH and HV with the stem density (R^2 = 0.06 and 0.32, respectively). This is mainly because tree density depends on the forest types, tree species, and site conditions, etc. Figure 3d also shows a poor relationship between σ^0 HH/HV with tree density (R^2 = 0.3).

We have used PALSAR σ^0 HV and HH/HV to generate MLR model because HV and HH/HV shows a strong correlation with biomass as compared to HH polarization. PALSAR σ^0 HV is dominated by volume scattering from woody elements of trees so that HV is strongly related to AGB (Le Toan et al., 2011). The MLR model was developed using dependent (biomass) and independent (HV, HH/HV backscattering) variables. The model was applied to the PALSAR 50 m mosaic data to generate a national-level biomass map. Figure 4a shows the biomass map with 8 classes of biomass for Cambodia. The deforested area shows a very low value of biomass. Figure 4b shows the forest cover map of the same biomass region. If we compare the biomass map (Figure 4a) with the forest cover map (Figure 4b) then the high biomass region (>200 t/ha) mostly falls into the illustrated categories of evergreen high and medium-low class in forest cover map. However, in the mountainous area (northern part) the biomass map shows variation because of the topography. The results from this study show the potential of PALSAR 50 m mosaic data that is freely available.

Figure 5 shows the validation results of PALSAR derived biomass. The accuracy of PALSAR predicted AGB decreases as the biomass increases because of saturation of the PALSAR signal. The result shows a significant coefficient of correlation R^2 = 0.61. The overall root means square error (RMSE) for the data is 63 t/ha, however, this decreases to 19 t/ha if values only below 100 t/ha are considered and to 21 t/ha using values up to 200 t/ha. The high variation in errors are present in the high biomass region i.e. >200 t/ha. We predicted two types of uncertainties: a) calculating biomass from field data using allometric equation because we have not used species-specific allometry as well as small plot size and trees having DBH < 10 cm was not considered, and b) saturation of PALSAR signal at high biomass region as well as topographic effects. Essentially, this study shows the importance of PALSAR backscattering and its interaction with vegetation to estimate various biophysical parameter estimation. High penetration capability of L-band SAR data can be effective to monitor forest volume.

4. CONCLUSION

Spatial information about forest biomass is useful to calculate the total amount of forest carbon in specific areas at a specific time. Biomass information is useful to calculate CO_2 emissions due to deforestation. This study demonstrates that a combination of PALSAR data and field data is useful to generate biomass maps that show the importance of forest inventory data. However, in high biomass regions, the PALSAR data become saturated. Biomass maps are not precise but can provide information about biomass distribution, which is needed for forest management practices. This methodology can be used to estimate biomass of other tropical countries using PALSAR and PALSAR-2 data more precisely. Cambodia biomass map is a vital data source for national level REDD+ mechanism implementation. The information will not only help enhance carbon stock in forests by implementing sustainable forest management practices but also enhance the livelihoods of the local communities as they depend on forests and their products. National level biomass maps will be useful for establishing effective national-level forest management plans and policies for REDD+ implementation.

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The rise and flaws of green growth

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ABSTRACT

Green growth has gained ground in environmental governance deliberations and policy proposals in the last decades. It was initially presented as a fresh and innovative agenda centred on the deployment of engineering sophistication, managerial acumen, and market mechanisms to redress the environmental and social derelictions of the existing development model. But can the green growth project deliver environmental sustainability, social justice and the achievement of economic life upon a materially finite planet? The article argues that green growth has several theoretical flaws and empirical limitations. Even though economic growth has brought tremendous benefits to society, continued economic growth in rich countries faces difficulties, and growth per se is not delivering the benefits for the wider society in terms of quality of life, happiness and health, and environmental sustainability. Unlimited growth poses tremendous challenges to the planetary health, with implications in the long term. Within this context, the article ends with a discussion about the merits and demerits of alternative strategies and policies, asking the vital question: If not green growth, then what?

KEYWORDS

Capitalism, Ecological modernization, Environmental Kuznets Curve, Green growth, Neoclassical economics

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HIGHLIGHTS

- There are many theoretical and empirical shortcomings in the ideas behind green growth
- The experiences of green growth in practice have not presented the promised results
- Ecological modernization has several limitations to keep the planetary boundaries
- Several alternatives to the green growth discourse exist
- The core of the alternatives is re-establishing social control over the economy

1. INTRODUCTION

"Green growth", together with the related 'green economy,' represents the latest phase in the reconstruction of political discourse in face of ecological challenges and environmental movements. It encompasses approaches ranging from geo-engineering mega-projects to routine "efficiency strategies". By such means, green growth promises to stem the environmental crisis and mitigate its consequences whilst simultaneously addressing social challenges of destitution and disempowerment by accelerating economic growth. Green growth is a project with a utopian charge, depicting a path to the future that, thanks to scientific insight, engineering sophistication and managerial smartness, claims to be capable of redressing the accumulated harms of the "old" industrial paradigm. At the same time, at least in its mainstream variants, it claims to embody a sober realism: the route towards a sustainable future maintains, and even reinforces, the institutional and normative territory of the current political economic prevalent ideas.

Taken at face value, green growth appears impervious to critique. Economic growth is taken as good, imperative, essentially limitless, and a matter of pressing concern for society as a whole. And green growth owes much of its influence given that it charts a pathway for continued economic growth even in the face of the environmental crisis and criticisms thereof. Further, the project of economic growth is not easily dislodged. It flows from fundamental societal transformations associated with the advent of modernity (the linearization of time, the notion of progress, the dissolution of just wage norms, and the quantification of processes of wealth, production and distribution). Institutionally, the growth imperative is an inherent attribute of the capitalist mode of production exacerbated under the neoclassical economics paradigm. This capitalism "distinguishes itself from all other socio-economic systems in human history by the movement towards the infinite"; its totalising logic penetrates society in all its facets and converts "almost the entire world into a field of valorisation" (Mahnkopf, 2016) through "the process of competitive, blind accumulation that grants to capitalism its distinctive requirement for relentless growth" (Meadway, 2016).

In an early effort to characterize and justify the economic growth paradigm, Adam Smith speculated that it is "in the progressive state," when society "is advancing to the further acquisition, rather than when it has acquired its full complement of riches that the condition of the labouring poor, of the great body of the people, seems to be the happiest" (Smith, 1776, p. 81). It is in a state of continual economic growth that emancipatory potential is achieved, and not just wealth. And, indeed, the subsequent two centuries of industrial capitalism did significantly advance the "acquisition of riches," as well as raise life expectancy, erode feudal and patrimonial forms of personal economic dependence, and catalyse advances in individual liberty and democracy that, although geographically very uneven in quality and application, were global in scale and momentous in scope.

This narrative of the "progressive state" of capitalist modernity is now struggling to retain its coherence in three respects. One is internal to the growth paradigm itself. The system's own yardstick of success, GDP per capita growth (annual %), has for several decades followed a flat and even downward trajectory in many countries (World Bank, 2017). Although global capitalism is systemically "compelled towards growth," it appears to be "decreasingly able to deliver it" (Meadway, 2016). The second is a scepticism vis-à-vis the "Smithian promise" that growth will emancipate the poor. Against a backdrop of vulgar levels of income inequality, the supposed connection between economic growth and social wellbeing has been increasingly called into question by prominent studies (Stiglitz, Sen & Fitoussi, 2009). Some critics argue that "just when the human species discovers that the environment cannot absorb further increases in emissions, we also learn that further economic growth in the developed world no longer improves health, happiness or wellbeing" (Pickett & Wilkinson, 2009; p.215).

The third is a growth scepticism fuelled by concerns over the diminishing ecological space available to supply non-renewable resources and to absorb the effluents of ongoing growth. Ecological thresholds are being breached, and "tipping points" appear to be upon us (Rockstrom et al., 2009). To this, the dominant response has long been one or another variant of "green growth": the idea that investment in the production of knowledge and science, the resulting innovations in technique, environmental awareness that purportedly comes with rising incomes, and a structural shift toward less resource- and energy-intensive service sector industries will "save the planet" (Tierney, 2009). In its formalized version, this idea came to be known as the Environmental Kuznets Curve (EKC). The EKC holds that, after a certain point, economic growth correlates strongly with greater efficiency in resource use. However, the idea that a simple, inverse relationship exists between per capita income and environmental stress has been challenged on a number of counts. For example, the idea that caring about the environment is a privilege of rich people is baseless; it ignores the "environmentalism of the poor" (Down to Earth, 1993, Martinez-Alier et al., 2016 and Kothari, 2016). Moreover, the EKC hypothesis has held in particular conditions, with respect for example to pollutants that have short-term costs, such as particulates, and not with respect to accumulating wastes or to pollutants involving long-term costs, such as greenhouse gas emissions (GHGs). The EKC hypothesis ignores the fact that reduced pollution in developed countries is often part of the same processes—above all, the outsourcing of manufacturing, and consequently pollution, to developing countries—that determine the expansion of resource-intensive production elsewhere (Sunderlin, 2003, p. 161).

A major hope of green growth advocates, on which much of their case rests, is that efficiency gains will negate overall increments in attendant energy and material throughput, including a dramatic reduction of GHG emissions. But this is much too sanguine, not least because it neglects to consider the "Jevons Paradox", which postulates that the improved technological efficiency in the utilization of a natural resource, within a capitalist framework, tends not to decrease but to increase its overall rate of consumption, because its relative cost is lessened and thereby increasing demand and freeing up capital for alternative uses (Jeavons, 1865). This is a key reason why the ability of efficiency strategies to successfully address the crisis in society-nature relations is likely to remain limited.

2. GREEN GROWTH IN PRACTICE

On the one hand, energy efficiency measures have been adopted in different sectors by a large number of countries. Mandatory efficiency regulation on final energy consumption has reached almost 25% in 2014 (IEA, 2015). Indeed, primary energy intensity has declined in 80% of surveyed countries since 2014 through different measures such as energy efficiency programs and regulations, GHG regulations and transformation of economic activities (WEC, 2016). Primary energy intensity has improved in all regions of the world in the last two decades (ESCAP, UNEP, UNU & IGES, 2016; see Figure 1). However, even though energy efficiency and clean energy have led to significant improvements in carbon intensity, there has been a sharp increase in global emissions, particularly in rapidly developing countries. This is because improvements in energy efficiency have not been sufficient to offset the rapid economic growth in emerging economies. For example, even though China reduced carbon emissions from fuel combustion per unit of GDP by 55% between 1990 and 2011, its emissions per capita tripled in the same period, and are now larger than the EU27 average, even though China is still much poorer (Hoffmann, 2016). The Republic of Korea, the main proponent of green growth, has also more than doubled its emissions per capita in the same period, though efficiency of carbon emissions from fuel combustion per unit of GDP increased by more than 8% in the same period. Indeed, South Korea's National Strategy for Green Growth and Five-Year Plan for Green Growth revealed by former president Lee was criticized for being based on nuclear energy expansion, land reclamation, canal cutting and dredging, and the construction of a multitude of dams and weirs—all of which would place further strain upon the country's beleaguered natural environment. It was little surprise when Lee's initiatives faced a barrage of criticism, and that the subsequent governments, under President Geun-hye Park, considered "ditching" green growth altogether (Shin, 2013).

Green growth is not expected to change the high growth in energy demand in emerging economies expected until 2040 (IEA, 2015). In order to offset emissions to reach the goals of the Paris Agreement (less than 2°C increase in average temperature), the rate of decarbonisation needs to reach 6.3% per annum until 2100; in contrast the achieved rate in 2016, despite a marked improvement over historical rates (0.8% between 2000 and 2011) was 2.6% (PricewaterhouseCoopers LLP, 2017). The future of this trend is unclear, at best. For instance, improvement in energy efficiency seems to have weakened recently: its annual rate declined from 1.6% between 2000 and 2008 to 1.3% since then (WEC, 2016).

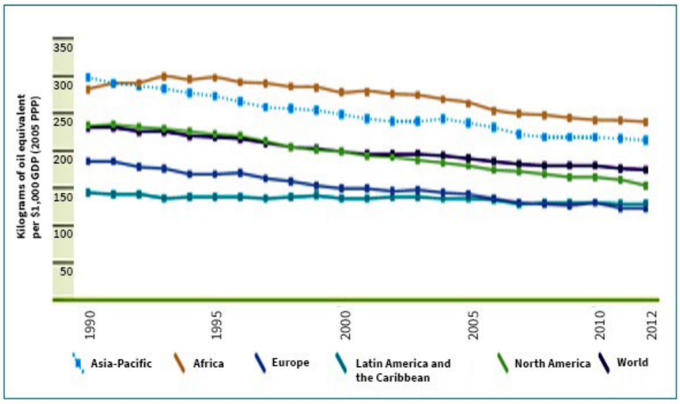

FIGURE 1. Primary energy intensity by region (1990–2012). Sources: ESCAP, UNEP, UNU and IGES, 2016 from ESCAP Asia Pacific Energy Portal, based on data from the International Energy Agency, World Energy Statistics and Balances and the United Nations Statistics Division National Accounts Main Aggregates Database.

3. ALTERNATIVES

Thus, greater efficiency (technical and economic) in the throughput of matter and energy is a necessary but insufficient condition for guiding energy and resource use policies in the present context. Sufficiency, along with efficiency, is an urgent necessity. Alternatives challenge the ideological commitments, policy choices and the resulting political economy that have shaped the contemporary world.

Green growth advocacy is not the last word in environmentalism, even if it is one of the loudest voices. Other voices point to different types of non-growth oriented forms of social organization. The question of alternatives may be unfolded from an analysis of the prevailing socio-economic system.

"Unbounded accumulation, the continuous extraction of surplus labour, is not simply a process of exploitation but undergirds a nexus of processes of alienation: of workers from the labour process, their products, their fellows, and their selves; and of labour itself—and human society in general—from nature. The system as a whole is administered by political institutions that service the requirements of capital and oversee the management and policing of population. Viewed in this way, a sustainable society will, ultimately, require the transcendence of, or breaking away from, the systemic, objective logic that dictates capital's ceaseless motions to produce and reproduce itself in ever widening spaces of commodified nature and society." Connected through these shared experiences of alienation and exploitation "labour struggles are environmental struggles, and vice versa" (Lohmann, 2016).

However, the convergence of different movements around transformative goals is never automatic. All social movements are criss-crossed with contestation and dialogical relations, internal debates and tensions.

They find themselves pulled between imperatives to resist structures of capitalist power and to accommodate to it. The dilemmas faced by movements seeking sustainable alternatives to technocracy and to the capitalist growth model, and theoretical questions associated with them, are at the heart of the alternatives.

Progressive social movements recount numerous examples of resistance and creativity that demonstrate a radically different logic to that of industrial capitalism and state-led economic development. Among many cases in India, the "Dongria Kondh" adivasis, an indigenous group in the state of Odisha who decided not to allow a multinational mining company to take over their lands," justified their actions in terms of a logic radically different from the externalization and commodification of nature, namely the "sacredness of the land and forest, and their own notions of well-being" (Kothari, 2016).

In an effort to distil the principles that inform these efforts, labelled Radical Ecological Democracy (RED) (Kothari, 2016) distinguishes attributes that intuitively, if not explicitly, counter the totalizing logic of industrial capitalism. These include, but are not limited to, decentralized embedded political governance adhering to the principle of subsidiarity, the decentralization of economic life and economic localization, the recognition of equity and protection of diversity and breaking artificial boundaries and hierarchies of knowledge systems. Illustrations such as these point to a lived reality of alternative logics that fundamentally differ from the externalizing, commodifying, accumulation logic of state-led economic development. However, "peoples' movements will also have to recognize the fine line between policy-based expansion of democratic spaces that aid fundamental transformation, and those that the state uses to soften or even co-opt peoples' movements" (Kothari, 2016).

In another example of alternative, the community-based energy utility pioneered in the state of Delaware, USA, represents an effort to move the energy sector away from the conventional approach of atomized households served by a distant centralized utility with energy mined from an externalized, commodified nature (Taminiau & Byrne, 2016). Teasing out the operative mechanism that grants the conventional energy-society relationship its daunting momentum, civil society has become reduced to a "consumer democracy" in which the ability of end-users of energy "to influence entrepreneurial and capitalistic activity is limited to their daily vote on the means of production through the global marketplace." As a Sustainable Energy Utility (SEU), the Delaware initiative envisions steering the energy sector away from "consumer democracy" to a role where consumers are also producers and, further, are envisioned as "sustainable citizens" engaged in energy conservation, energy efficiency and renewable energy commons. The SEU seeks to integrate energy (nature) and society in a democratically organized, decentralized and mutually co-producing relationship, representing a marked contrast to the centralized, and undemocratic nature-society model of the standard energy utility and its atomized customers. The SEU is an effort to reinterpret and reintegrate ideas of "commonwealth" and "community trust" into the energy discourse long severed from shared, commons-based practice and sensitivities.

Individuals and movements today stand upon terrain that is shaped by neoclassical economics. One of the more illuminating discussions of the possibilities and constraints in this regard is Heather Rogers' Green Gone Wrong. It explores, inter alia, experiments in agroecological farming, in which contingent successes could be achieved, with the deployment of efficient ecologically sustainable agricultural techniques, and the successful infusion of community engagement. Nonetheless, all enterprises, however mutual, social and ecological, face pressures to cut costs or risk losing customers to rivals: "The rules of the marketplace support the big guys"; "Small farmers typically can't make a larger environmental impact because our political and economic system won't let them" (Rogers, 2010). On one hand, many social movements for alternative political economies, such as workers' cooperatives, alternative currencies, and community-based agroecological farming, were driven by the application of creativity, innovation and idealism, combined with principles of mutuality and self-management, to serve goals of community, equality and ecology (Böhm, Misoczky, Watson, & Lanka 2016). On the other hand, in each case compromises were made with major business concerns and with state power: the Small and Marginal Tribal Farmers Mutually Aided Cooperative Society (SAMTFMACS) in India and the Landless Workers' Movement (MST) in Brazil, the world's most powerful land reform movement, has in its capacity as economic agent entered into agreements with a transnational corporation, in a process that led the MST farmers involved to see themselves as "service providers" responding to market demands more than as the collective producers of "new socio-economic subjectivities" (Böhm et al., 2016).

In sum, alternatives may not happen without larger societal transformations through different governance structures to scale up the existing viable opportunities or local niches, as some discussed above, to the national and regional level. At the international level, both a sense of urgency and political change are needed to build up the political and economic interests required to reach a broad consensus over an effective governance structure that includes planetary limits in economic decisions and not only provide market-based solutions to environmental problems, which can exacerbate the problems. Indeed, the emphasis on growth and use of market mechanisms to promote sustainable development is already facing criticism in the international arena.

The underlying logic for finding alternatives to green growth is to move beyond the technocratic realm and the mainstream discourse propagating market capitalism as the only solution to the ecological and social crises of the 21st Century. Alternatives have to challenge the simple argument of mainstream "green economics" that the environmental crises can be solved by "internalizing" externalities through price mechanisms and changing the mix of inputs ("factors of production") in economic processes. Radical societal transformations ask for an overall change in the economic system and have many components, as pointed out by Ulrich Hoffmann (2016): we "...need to realize that the required transformation goes far beyond innovation and structural changes to include democratization of the economy, better distribution of income and wealth, power over markets, and a culture of sufficiency."

4. CONCLUSION

The language of green growth is alluring for a political economy mired in lingering economic lethargy, persistent poverty, rising inequality and stubborn environmental crises that persist and expand despite four decades of modern environmentalism. Collectively, these crises have undermined confidence in economic orthodoxy's assertion that growth is good, even necessary. Greening growth, thus, is a promise to heal that distrust – growth is good because it can be "green." In practice, however, this proposal has not withstood scrutiny. It holds an excessively narrow, even contrived, notion that technological efficiency (enabled through surplus from economic growth) amounts to ameliorating the cumulative and continuing social and ecological impacts of economic growth orthodoxy. Green growth projects have turned to authoritarian politics in pursuit of investments in heavy infrastructure projects and thereby undermining the very institutional foundations of democratic decision-making long recognized in the sustainable development literature. What is apparent to dispassionate inquiry is the limited nature of ecological modernization strategies, be they authoritarian or democratic.

The democratic version is necessary, but insufficient to redress our present crises. Acknowledging this evidence, many civil society actors across the world are instead in pursuit of alternatives to economic orthodoxy. They have advanced alternatives that organize labour and control over consumption and production in ways that attempt re-embedding the economic system within society. These movements to counter the orthodoxy's arrangement of situating the economy in an autonomous and controlling position over society are foundational. They appear to proceed through resistance, innovation but also through accommodation. The path ahead is yet unclear but the goal is less so. Despite current ambiguity they are fertile and urgent grounds for innovation, experimentation and social change.

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