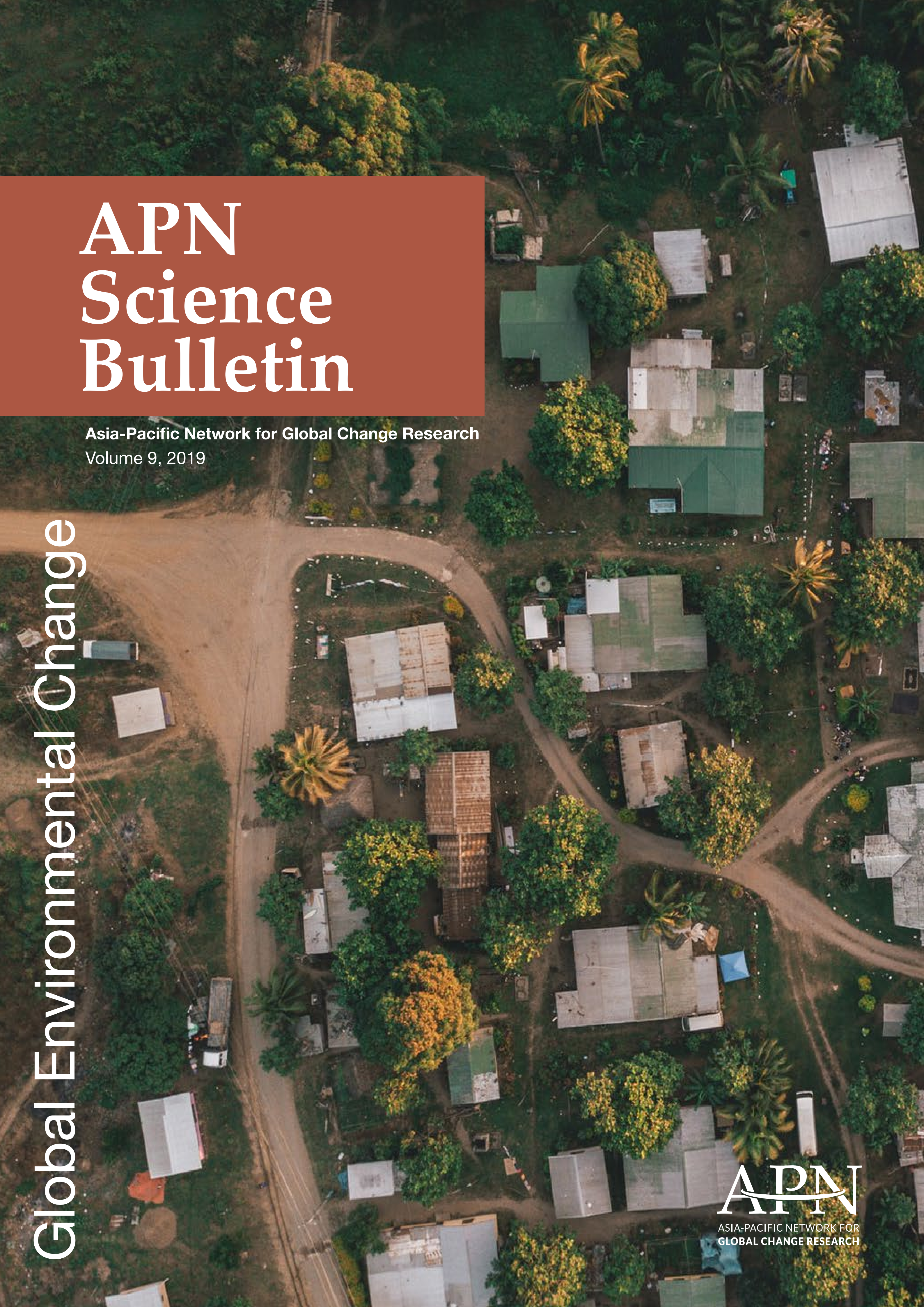

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Preface

On behalf of APN and its members, it is my pleasure to present you with the 2019 Science Bulletin, the ninth issue of APN's flagship publication. The Science Bulletin features the findings and outputs of APN projects conducted under our core scientific programmes of collaborative regional research (CRRP) and capacity development (CAPaBLE) in global environmental change and sustainable development. The issue also features three articles from our Climate Adaptation Framework.

We hope the information in the 2019 Science Bulletin provides useful information for all stakeholders including scientists and researchers, policy- and decision-makers, and practitioners working at the forefront of global environmental change and for the sustainable development goals.

The 2019 issue is the final edition in APN's fourth strategic phase 2015-2020 in which a total of 59 articles have been published in 5 issues. The 2019 edition features 14 articles, a record number of articles published in one year. In the two years since we introduced our web-based Science Bulletin, I am delighted to inform you that there have been more than 15,900 unique page views. Further, the 29 articles available on the web-based science bulletin site have received over 10,900 page views on the web. The web-based bulletin is available at https://www.apn-gcr.org/bulletin/.

This year, the key focus continues on resilience and adaptation to climate change and associated risks. Articles address ecosystem-based adaptation for integrated coastal zone management in Southeast Asia, understanding climate-associated risk and resilience in Pacific island communities; health risk associated with extreme temperature and adaptation strategies; compliance to safe building codes in Bangladesh and Nepal to increase resilience to disasters; and resilience strategies for urban water contaminants in India and Sri Lanka, among others.

On behalf of our members, we acknowledge the unwavering commitment of our 2019 editorial advisory committee (see front matter). Their expertise and advice have been instrumental in upholding the scientific rigour of our flagship publication. This year, our committee comprises 44 members from a broad geographical base—Southeast Asia (29%), South Asia (27%), Temperate East Asia (24%), the Pacific (16%) and the international community (4%) as well. We look forward to continuing our collaboration into the future.

Dr Linda Anne Stevenson
Managing Editor

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Ecosystem-based approach for planning research and capacity development for integrated coastal zone management in Southeast Asia

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ABSTRACT

Coastal ecosystems contribute significantly to socio-economic development in the Southeast Asia Region. The emerging question is how to achieve sustainable development through innovative thinking, smart planning and better insights derived from an ecosystem-based approach (EbA). Based on experience gained while implementing the Sustainable Management and Governance of Coastal Ecosystems (ENGAGE) project funded by the Asia-Pacific Network for Global Change Research (APN), we contribute to addressing this question by proposing an emerging EbA as a complementary concept for implementing Integrated Coastal Zone Management (ICZM). A strong emphasis on strengthening the capacity of development actors and local communities remains pertinent in formulating this eco-centric policy for resource governance. This synthesis is described in three sections presenting an overview of EbA and ICZM in selected countries in the region. The first section reflects the review of coastal management frameworks and institutions, with a focus on policy strengths and gaps in the integration of EbA, particularly in the context of climate change adaptation. The second section explains different procedures adopted or proposed in the region for sustainable development of coastal ecosystems. The third section demonstrates how regional-scale initiatives like ENGAGE can facilitate the exchange of data, information, and knowledge, and stimulate cooperation for realizing the 2030 Agenda for Transformation, and the coastal zone-related SDGs and targets.

KEYWORDS

Capacity building, Coastal ecosystem, Integrated management, Southeast Asia

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HIGHLIGHTS

» An up-to-date review of the status of coastal management applying ecosystem-based approach (EbA) in the Southeast Asia region.

» EbA is gaining momentum in the Southeast Asian region; accordingly, the capacity for upscaling and implementation is needed.

» Descriptions on how to steer sustainable coastal development through innovative thinking, smart planning and better insights derived from ecosystem-based approaches are crucial.

» Mapping capacity gaps and needs for integrated coastal ecosystem management by involving a variety of stakeholders is pertinent. Aligning conservation and development goals requires sharing existing best practices and case studies that demonstrate the potential for cross-scaling.

INTRODUCTION AND CONTEXT

Current debates in sustainability science endorse the need for EbA for resource management and planning. In the context of climate change adaption, the Convention on Biological Diversity (CBD) defined it as "the use of biodiversity and ecosystem services as part of an overall adaptation strategy to help people to adapt to the adverse effects of climate change." As the framework that includes various ecological services and benefits received by communities, EbA, when applied in the context of climate change adaptation planning and natural resource management derives its conceptual underpinnings from consideration of ecosystem services and benefits. The approach also anticipates assisting successful implementation of existing management frameworks vis-à-vis ICZM, while highlighting the need to strengthen stakeholder capacity at all levels of governance and resource management, thereby demonstrating a potential for monitoring and assessing risks in various socio-ecological systems (Nagabhatla et al., 2012).

Recent years have witnessed significant improvements in the development of tools and management frameworks (Hung, Nagabhatla, Tuan, Kathiresan, & Moon, 2017) and frameworks such as ICZM have proven to be a practical tool for conserving and protecting coastal and near-shore resources. Yet, to better support integrated and efficient management solutions, the need for up-to-date data and knowledge is urgent. ICZM also claims to maximize the integration of multi-sectoral needs as well as minimize conflicts in economic development planning, thus providing flexibility for integrating the synergistic advantages of an EbA. The approach assimilates the principles of sustainable management, conservation and restoration of ecosystems to provide ecological services (benefits) and could enable policymakers and local communities to outline a holistic, integrated and transdisciplinary framework, both for addressing current climate variability and long-term environmental change (United Nations, 2011; Visser, 2004)

Another critical aspect of integrated management is addressing capacity gaps and needs. Recognizing capacity development is a crucial means to implement, manage and restore ecosystem services and further increase awareness of the ecological benefits including the diverse values and cultural significance of coastal ecosystems. Capacity building can enhance the competency of environmental scientists, managers, administrators and communities to evaluate and address the vital questions related to policy choices and the modes of implementation of development options (UNCED & Johnson, 1993). Chapter 37 of Agenda 21 stresses that the ability of a country to follow sustainable development pathways is noted by its effort to strengthen the capacity of its people, and its institutions (Hens, Borden, Suzuki, & Caravello, 1998) . The 2030 Agenda and the SDG goals and targets are reemphasizing gaps and needs.

The Sustainable Management and Governance of Coastal Ecosystems (ENGAGE) project aimed to strengthen regional-level capacity development in Southeast Asia while addressing the science-policy interface and sustainable development (coastal ecosystems-related SDG goals and targets) implementation needs. The focus on an EbA framework, particularly the synthesis of the status of coastal management and identifying existing best EbA practices at local, national and regional levels are two primary outcomes of the project. The project was designed with activities to strengthen the capacity of selected participants (young professionals, academics, government officials, resource managers) on EbA and ICZM, and to provide a platform for identifying opportunities to integrate EbA into existing coastal management system approaches and strategies (full report of the project is available on the APN website).

The ENGAGE project adopted an innovative twin-framework (training-cum-workshop) model to advance the understanding of ecosystem-based approaches, jointly underline regional priorities and initiate discussions to fill data and information gaps. Experts from Southeast Asia (16 females and 15 males from 6 countries—Viet Nam, Malaysia, Indonesia, Thailand, Myanmar, Philippines and other invited experts from the US, Canada, India, and France) participated in the face-to-face module of the project, representing various disciplines, institutions and sectors as seen in Figure 1. The project team also organized a country scale synthesis on coastal characteristics and threats, status, overview of climate change governance, and how EbA initiatives can serve as a strategy for sustainable management. Cross-cutting aspects in EbA, namely nature-based solutions, water, food security, and disaster risk reduction to reduce the vulnerability of people and simultaneously generate a range of social, economic, and environmental co-benefits were reviewed in tandem.

OVERVIEW OF STATUS OF COASTAL MANAGEMENT IN THE SOUTHEAST ASIAN REGION

The region has an extensive coastline of nearly 173,251 km and has the most diverse coral reef ecosystems in the world (Asian Development Bank [ADB], 2009). Endowed with rich biodiversity and ecosystem spread namely mangrove forests, sea-grass and algal beds, estuaries, lagoons, sandy beaches, mudflats, and shallow coasts

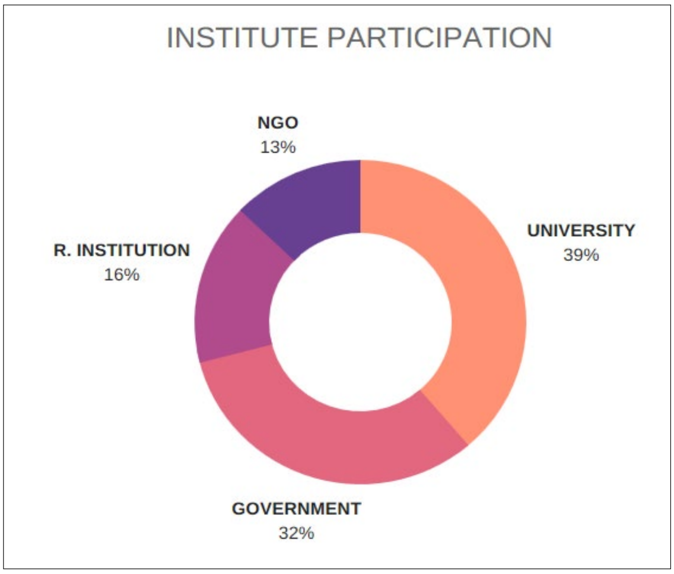

FIGURE 1. Stakeholder distribution in the ENGAGE Programme.

(Veron & Stafford, 2000). These ecosystems provide a wide range of economic services and benefits to communities inhabiting the coastlines, mainly in the sectors of sea trade, fisheries, fish production, and tourism (Brown, Daw, Rosendo, Bunce, & Cherrett, 2008). The region is populated by more than 600 million people who depend on coastal and marine resources for their livelihoods and well-being (Hughes, 2017). As a case in point, coastal and marine economic activities are estimated to account for some 25-30% of Indonesia's GDP while employing about 20 million people (ADB, 2009). The extensive shorelines, characterized by sensitive ecosystems and ecological resources, is being forced to compete with a range of intensive human activities such as settlement, agriculture, tourism, fisheries, mining, and communication. Exposed coastlines in the region face a multitude of stresses, including infrastructure development, harvesting of endangered species, ornamental trading, human-induced environmental degradation and pollution (Tabet & Fanning, 2012). Natural hazards and disasters such as cyclones and tsunamis, in addition to rising sea level and other anthropogenic pressures have exacerbated the degradation of coastal and marine resources.

The review undertaken by the ENGAGE project proved to be of relevance to recognize the need for future strategies, anticipating that existing and collective knowledge in the region can be scaled up to provide a guiding framework for regional collaboration and capacity development. The increasing and competing demands for coastal resources and ecosystems have led to the adoption of an economics-oriented development agenda in many parts of the world including in Southeast Asia, thereby creating conflicts and disputes between planners, policymakers and local communities, resource-users with economic interests, and conservationists. Often, interdisciplinary and participatory management approaches are not commonly integrated into policy and technological interventions or regulations related to the use of coastal and marine resources. Further, the allocation of coastal and marine resources for economic activities has not been systematically managed and more often unregulated (Wilson & Tisdell, 2003). Regional trends and patterns of regulatory frameworks show that countries are preparing to address coastal management issues by employing smart management strategies (Hung et al., 2017).

Some examples of regulations in Southeast Asia countries are outlined below:

In Indonesia, Act No. 27/2007 and Act No.1/2014 addresses integrated management of coastal areas and small islands through planning, utilization and supervision involving substantial involvement of the local community.

Malaysia has a five-year plan in place to address mapping the policy and development projects and activities to be adopted by the government, which includes environmentally oriented ordinances and embeds the ICZM framework (Wilson & Tisdell, 2003). The plan can be accessed at http://www.mof.go.tz/mofdocs/msemaji/Five%202016_17_2020_21.pdf.

The government of Myanmar is presently involved in formulating the Bay of Bengal Large Marine Ecosystem (BOBLME) programme that seeks to promote sustainable marine ecosystem management and sustainable coastal livelihood development. The programme aims to improve the lives of coastal populations through the efficient regional management of biodiversity and fisheries.

In the Philippines, Executive Order No. 533 released in June 2006, was issued towards the adoption of ICZM and is considered a future development strategy for coastal areas. To date, 8,265.2 km of coastline is covered by the programme, which comprised 22.8% of Philippines' coastline. Currently, local activities are implemented in 479 coastal localities out of a total of 822 (Rebuelta, 2012).

In Thailand, recent laws and enforcement measures initiated by the Department of Marine and Coastal Resources (DMCR) and agencies such as the Marine and Coastal Resources Management Promotion (MCRMP) Act B.E. 2558 has enabled strong leadership in providing local governments with the authority to act and support its national goals. The new fisheries law- the Royal Ordinance on Fisheries B.E. 2558 (2015) along with the recent National Maritime Security Plan (2015-2021) have strengthened the country's portfolio of regulatory measures for coastal and marine protection.

In Indonesia and Thailand, the impact of tourism is significant (UP-MSI, ABC, ARCBC, DENR, & ASEAN, 2002). Indonesia's policy of "open access" to people for coastal areas and small islands, is aimed at more diverse and competitive resource utilization activity (Hung et al., 2017). Coastal degradation in Malaysia is mostly due to rapid and ad hoc development, as well as economic expansion plans that are often intense land-based activities such as coastal construction. The relatively low tourism impact in Malaysia could be an underestimation or a strategy adopted to conceal the full extent of environmental degradation often associated with tourism development (Hung et al., 2017).

In Viet Nam, the Government Decree No. 25/2009/ND-CP calls for integrated management of resources and marine environmental protection and serves as a regulatory framework for ICZM implementation. Coastal provinces of Viet Nam actively promulgate legal regulations to guide and direct sustainable management. For example, the regions of Thai Binh, Hai Phong, Quang Ninh, Nam Dinh, Soc Trang, and Kien Giang have mechanisms to address challenges related to coastal ecosystems, even though they differ in practices adopted. Despite the availability of human, financial and technical resources for coastal resource management, enforcement and monitoring of activities are overburdened due to multiple responsibilities and insufficient support. In the Mekong basin, mangrove forests have been profoundly degraded both in area coverage and quality, particularly in the southern Mekong Delta. In Viet Nam, mangrove forests shrunk from 400,000 ha in 1950 to 270,000 ha in 2015. The impact of activities such as intensive fishing is reported to have severe impacts on coastal ecosystem services in Viet Nam (Hung et al., 2017).

Conversion of mangroves for export-oriented intensive shrimp production also remains a substantial threat in many parts of the region (Food and Agriculture Organization of the United Nations [FAO], 2016). Overall in the region, the impending impacts of climate change and environmental degradation add to the existing pressures faced by coastal ecosystems if sustainable use and management guidelines are not adopted.

A coordinated framework for coastal zone management at the regional scale can benefit a futuristic vision of ICZM in the region.

In the context of gaps and needs, some key points are highlighted. In Viet Nam, EbA adoption is not widespread because of a substantial gap between theoretical understanding and practical applications (Institute of Strategy and Policy on Natural Resources and Environment [ISPONRE], 2013). In general, contradictions in the legal instruments pose problems for implementing EbA projects. Initiatives in the Philippines are mostly governed, through local efforts, by cities and provincial governments. For example, Puerto Princesa in the province of Palawan, organizes a community- based celebration termed 'Love Affair with Nature' for the protection of coastal resources every year on 14 February. Indonesia's Coastal Education Programme provides mentoring activities for youth and students at local and provincial levels.

Overall, the synthesis reflects on existing solutions with a focus on EbA. It further provides references to Nature-based Solutions (NbS), i.e. 'living solutions inspired by, continuously supported by and using nature designed to address various societal challenges in a resource efficient and adaptable manner to provide simultaneously economic, social and environmental benefits' (Maes & Jacobs, 2017). NbS was considered more so in the context management of mangrove ecosystems. The need for understanding EbA towards designing and planning interventions for the sustainable management of coastal and marine resources is highlighted in recent studies (McCue, 2014; Wilson & Tisdell, 2003). The challenges with many current interventions are that the emphasis is solely placed on engineered solutions that may result in siltation and degradation of aquatic ecosystems. It was also found that integrated planning can help mitigate the effects of natural hazards and enhance coastal resilience. Further, urban areas with high population density integrated planning can also help maintain ecological structures and services (Nagabhatla & Metcalfe, 2018).

GLOBAL DEVELOPMENT AGENDA AND INTEGRATED MANAGEMENT APPROACHES

Adoption of participatory approaches involving local communities and other stakeholder groups to collaborate provides a holistic approach with opportunities for active engagement. Communities and decision-makers are interested in environmental impacts (FAO, 2016) and see the need to understand how scenarios of environmental degradation impact their livelihood and income generation prospects (ADB, 2009). In the developed world, stakeholder participation is becoming standard practice. Southeast Asia states and communities are also preparing to adopt this bottom-up approach as the norm in their development interventions. The success stories of joint forest or fisheries management produced in the Asian context is well known (Springate-Baginski & Blaikie, 2007). Formulating planning and policy measures to minimize multiple resource use and users inherent to natural resource systems remains crucial. Additional aspects like failure to recognize and respect rights of ownership, value systems, and local knowledge systems are also important while managing multi- stakeholder engagements (Burroughs, 2011). It is a fair assumption that participation and consultation with stakeholders, resource users and managers can positively contribute to achieving desired outcomes and impacts.

Coastal management status in Southeast Asia is tackled well as states are committed to achieving the SDGs while addressing and implementing smart coastal management strategies and the need to develop mechanisms for intergenerational knowledge-sharing networks and communication. The framework to disseminate information and expertise on complex issues can help to provide a clearer understanding of the interconnections and interdependence between local and scientific knowledge, adaptive capacity and bridging of knowledge gaps. Towards this, the ENGAGE project initiated a regional platform/community of practice to facilitate information and knowledge exchange. The social media group developed >500 members from the region and has regular exchanges on various topics.

The synthesis provided a potential framework with a wide-ranging portfolio of adaptation measures that employ sustainable management principles, conservation goals, and restoration objectives to ensure the provision of ecosystem services that facilitate human adaptation to the adverse impacts of multiple pressure, including climate change. The synthesis also provided a guiding framework for adopting EbA towards designing and planning interventions for the sustainable management of coastal and marine resources (Hung et al., 2017).

In 2015, the United Nations adopted a new development agenda, the SDGs, which focusses on improving the sustainability of member states. Rio+20 (June 2012) laid out these goals and the 2030 Agenda for transformation. The goals of the 17 SDGs comprising 169 targets is a collective programme to strengthen global governance. Specifically, the vision of Goal 14 is to "*sustainably conserve the oceans, seas and marine resources for sustainable development.*" SDG 14 sets out goals and targets to advance the sustainable use and conservation of coastal and marine ecosystems while developing effective strategies and management to combat the adverse effects of activities vis-à-vis overfishing, coastal eutrophication and over extraction amid other cases of unsustainable anthropogenic interference. Expanding protected areas for managing biodiversity, intensifying research capacity and increasing funding commitment are milestones that remain critically significant to preserve coastal and marine resources (https://sustainabledevelopment.un.org/sdg14).

As countries in Southeast Asia are in the process of developing plans that identify priority areas as well as action plans that address the SDGs, the present synthesis undertaken by the ENGAGE project can be a good source of reference.

THE ENGAGE PROJECT—REGIONAL INITIATIVE FOR STAKEHOLDER DISCUSSIONS ON EbA

The ENGAGE project initiated a regional discussion by aligning the EbA framework to complement existing management strategies for coastal ecosystems. Integrating EbA with development and climate-related discussions are on the increase. Open dialogue with experts, specialists and policy actors addressed common issues in aligning EbA and development planning is taking place though the creation of a regional multi-stakeholder group. Knowledge from current concepts, new methodologies and traditional practices with a focus on regionally-relevant sustainable management strategies are being shared in consultations with a broad range of stakeholders, including young professionals. A regional-scale review was also initiated to provide information especially where knowledge gaps exist.

The project also created a regional community of practice (CoP) of trained professionals (Facebook group with more than 500 members) who can take forward EbA as a policy support tool designed for ICMZ and EbA guidelines. The participants (including policymakers and members of local communities) gained knowledge, skills, practical experience, training and technical assistance to develop national-scale initiatives. For example, the participant from Thailand organized a national-scale workshop based on the experience and knowledge gained from participation in the ENGAGE project. Additionally, participants from Thailand, Viet Nam and Myanmar organized exchange visits and joint proposals on topics of common interest (details are on the Facebook page of the ENGAGE project). The initiative also demonstrated how regional-scale initiatives could facilitate exchange of data, information and knowledge, and stimulate cooperation for realizing coastal zone planning and implementation of related SDGs and targets.

CONCLUSION AND OUTLOOK

While research and application of EbA has increasingly gained attention from the international and local communities, the adoption and integration of this approach in natural resource management national development programme, planning and polices is still in an early stage. The Regional initiatives like the ENGAGE project serve to provide an example of dialogue and exchange between regional researchers and experts, and a platform for experiential learning for young professionals. The emphasis on the argument that, EbA and ICZM, if aligned, can also assist initiatives and commitments in the context of SDG13 (related to climate change), SDG14 (related to coastal and marine resources) and SDG17 (related to collaboration and partnerships) is among the central highlights of the project. It further elaborated on the EbA models and mechanisms of collaboration, participation and consultation, that diverse stakeholders, resource users and managers can adapt to achieving desired outcomes and impacts while implementing ICZM. The participants gained knowledge on integrated planning for coastal resources management, through deliberations on best EbA practices provided by a suite of expert and guest researchers.

During the project implementation, a discussion forum/web platform was created to facilitate dialogue, exchange knowledge and information, and address common queries on how climate change adaptation and EbA can be effectively integrated into coastal development planning and management. Discussions also emphasized practical and innovative solutions and methodologies for sustainable management of coastal ecosystems. The project was successful in promoting and encouraging EbA-related knowledge exchange between different stakeholders in the region. It was commonly agreed that the region can benefit from collaboration and exchange, participatory models of stakeholder's engagement and community empowerment, and promotion of integrated solutions such as EbA.

Key highlights of the ENGAGE project include:

Focusing on cooperation and collaboration of institutions for data exchange, building regional information on best management practices, and success and failure stories in the context of ecosystem services approaches to ICZM;

Steering collective efforts to build the capacity of regional stakeholders on current strategies, methods, and procedures for regional cooperation; and

Mapping gaps and needs towards strengthening capacity to adopt and implement ecosystem-based approach for management of coastal resources and building resilience of coastal communities.

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Exploring the effects of urban heat island: A case study of two cities in Thailand and Indonesia

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ABSTRACT

This study is part of a regional research project aimed at understanding the effects of Urban Heat Island (UHI) on urban residents. Using two case studies in Bangkok, Thailand and Bandung, Indonesia, the study focuses on the effects of UHI on household energy consumption and health and well-being. A survey questionnaire of 400 respondents from each city was employed. Household energy consumption is measured using a proxy variable of average monthly electricity consumption. UHI intensity is measured using a cooling degree days (CDD) variable constructed from the temperature difference between urban and suburban weather stations. The perceived health effect is measured by heat stress, physical health impacts, mental health impacts and health and well-being outcomes. The data are then analyzed through descriptive and inferential statistics. The result indicates that the presence of UHI in Bangkok plays a significant role in household energy consumption. UHI is found to have a positive association with the ownership of air conditioning equipment in Bangkok and Bandung and is found to increase the monthly electricity bill. In terms of health effects, it is found that UHI affects health directly through heat stress and indirectly through lowering the health and well-being outcomes. Results from the two case studies indicate that UHI has affected the daily lives of urban residents in terms of increasing household energy consumption for cooling and disruption of activities such as working, sleeping, and general health and well-being.

KEYWORDS

Bandung, Bangkok, Health and well-being, Household energy consumption, Sustainable urban development, Urban heat island

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HIGHLIGHTS

- UHI increases the household energy consumption for cooling.
- UHI indirectly affects health through heat interferences which caused disruption of daily activities such as working, sleeping, and general health and well-being.
- Local government needs to pay more attention to UHI mitigation strategies at the city level.

1. INTRODUCTION

The urban heat island (UHI) phenomenon generally refers to the higher temperature in cities or urban areas than in surrounding areas (Oke, 1995). UHI conditions increase the risk of climatic and biophysical hazards in urban environments including heat stress and heighten acute and chronic exposure to air pollutants (United States Environmental Protection Agency [US EPA], 2013). Climate change, which is caused by increased anthropogenic emission of carbon dioxide and other greenhouse gases, is a long-term effect with the potential to alter the intensity, temporal pattern, and spatial extent of UHI in metropolitan regions (US EPA, 2012). The UHI phenomenon occurs mostly at night because the roads and other surfaces absorbing solar radiation in the daytime release heat during the night (Oke, 1982). Anthropogenic heat, or heat caused by human activities, can be an important causal factor of UHI, especially in winter. Urban areas create more heat than rural areas because rates of transportation, population, industrial and some other activities are higher in urban areas (Kolokotroni, Zhang, & Watkins, 2007).

UHI can have both negative and positive effects on cities, and UHI developments alter the atmospheric characteristics of a region. The transformation of radiation, thermal, moisture, and aerodynamic factors are all affected by this change, which affects natural energy and hydrological balances (Oke, 1995). In summer, heat islands can have an enormous effect on air-conditioning load by increasing energy demand due to the higher temperatures in such areas, which can lead to power shortages and hikes in energy cost. A study conducted by Miner, Taylor, Jones, and Phelan (2017) that examined the economic cost of UHI found that the maintenance cost of air conditioning devices in major cities in the world is around 0.1–0.2% of a city's gross domestic product (GDP). Another study by Arifwidodo (2014) in Bandung city, Indonesia found a significant relationship between household energy consumption for cooling and increase in local temperature. Ewing and Rong (2008) also found a similar result—i.e., household energy consumption is associated with the incidence of UHI and the spatial pattern of the metropolitan region. The study finds that high-density areas with less green space experience higher UHI intensity, which results in higher household energy consumption for cooling in the summer. Household energy consumption for cooling is also found to be higher in tropical countries, where winter does not reduce the UHI intensity (Voogt, 2004).

UHI can also cause negative health impacts and human discomfort. It directly affects human health by creating heat waves, heat stress and spreading vector-borne diseases (Voogt, 2004), and can also cause heightened acute and chronic exposure to air pollutants and reduced physical health and well-being. Climate change, which is caused by increased anthropogenic emission of carbon dioxide and other greenhouse gases, is a long-term effect with the potential to alter the intensity, temporal pattern, and spatial extent of UHI in metropolitan regions (Arifwidodo, 2015). Table 1 summarizes the common health effects of UHI compiled from the literature.

Indirect Health Effect	*Direct Health Effect*
Increased mortality and morbidity rate in population	Cardiopulmonary disease: chronic bronchitis, pneumonia
	Ischemic heart disease
	Cerebrovascular disease
	Respiratory disease: influenza, common cold
Lower life satisfaction	Heat stress
	Sleep deprivation
	Less daily travel
	Higher sedentary behaviour
	Less activity during the hot period

TABLE 1. Major species in the field plots and their maximum height and DBH. Source: Oke, 1995; Tawatsupa et al., 2014; Guo et al., 2012; Tan et al., 2010.

Despite interest in the topic, empirical studies on the effects of UHI on household energy consumption and health are still limited, mainly because there are different methods of measuring UHI and its effects on daily lives of urban residents – for example, use of both air temperature or surface temperature to understand the microclimate conditions of an area (Henry, Wetterqvist, Roguski, & Dicks, 1989). Most studies on the effect of UHI on household energy consumption were mainly conducted in sub-tropical countries where the effects of UHI during winter were also pronounced, which presented a different situation compared to cities in tropical contexts (see Ewing & Rong, 2008; Arifwidodo, 2014). Prior research suggests that space heating and cooling and lighting are the most important determinants of household electricity consumption (see Randolph & Masters, 2008; Steemers, 2003); however, their associations with UHI and other climatic variability are still sparse (Sailor & Vasireddy, 2006).

Similarly, although the impact of UHI in the form of heat waves are well-documented in developed countries, few studies cover cities in the tropics (Tan et al., 2010). Studies conducted by Thawillarp, Thammawijaya, Praekunnatham, and Siriruttanapruk (2015) and Tawatsupa, Dear, Kjellstrom, Sleigh, and Samakkeekarom (2014) examined heat stress and heat-related illnesses in Thailand and found that there is an increasing prevalence of illnesses associated with rising temperatures. Therefore, it is important to understand these issues using case studies in tropical countries. The present study is based on the two case study areas of Bangkok, Thailand and Bandung, Indonesia because these cities represent two different geographical conditions of rapidly growing cities in Southeast Asia. Bangkok is a coastal city with maximum elevation of 4 m above sea level, while Bandung is a mountainous city 768 m above sea level and surrounded late tertiary and quaternary volcanic terrain rising to 2,400 m. These differences in geographical conditions means the cities experience different UHI effects. By using these two case studies, it is expected that the results can be generalized and the method used in the study be applied to other cities with similar characteristics.

2. METHODOLOGY

The study argues that UHI has significant effects on household energy consumption and public health. In measuring UHI, the study follows Tan et al. (2010) in measuring UHI intensity as the temperature difference (ΔT) between urban area (u) and suburban area (s). In both cities, the yearly average temperatures from three weather urban stations and one suburban station in Bangkok and Bandung were calculated. In linking household energy consumption with UHI, we calculated the cooling degree days (CDD) to investigate the effect of higher temperature on cooling energy consumption in Bangkok and Bandung. The CDD method is a common technique to investigate the effect of higher temperature on cooling energy consumption (Giannakopoulos et al., 2009).

The CDD profile for the model is derived from weather stations for each city, and used as one of the independent variables in the OLS regression to examine the electricity consumption and the direct effect of UHI on perceived health. CDD is calculated from the following equation,

$$CDD, i, d = \sum_{m=1}^{24} \frac{(Tm - Tb)\,(Tm - Tb) > 0}{24}$$

where CDDi is the cooling degree days for a particular day (d), Tb is the base temperature 24°C and Tm is the mean air temperature, considering only the positive values. The study follows Radhi and Sharples (2013) by using 24°C as the base temperature, since it is more appropriate for tropical countries than 18°C which is usually used in European and American cities. The study also collected the monthly average of electricity consumption as a proxy for household energy consumption. The data were then analyzed using the ordinary least square (OLS) regression model to understand the effect of UHI intensity (measured by CDD) on household energy consumption (measured with average monthly electricity consumption for year 2015) as the dependent variable.

In exploring the health effects of UHI, the study obtained survey data on perceived health stress and health outcomes. Previous studies such as Tan et al. (2010) and Thawillarp et al. (2015) have identified that UHI affects health through heat waves and heat stress, causing heat-related illnesses. Since Thailand has never experienced heat waves, the study uses heat stress as a measure of the health effect of UHI. Heat stress is identified as the uncomfortable feeling when doing daily activities and is measured using the following proxy questions: 'How often did the hot period of this year interfere with the following activities?' Sleeping; housework; daily travel; work; and exercise. The health outcomes were measured by three variables: physical health, mental health, and well-being. The data from the survey questionnaire were then analyzed using descriptive and inferential statistics to understand the patterns and characteristics of the perceived health effects.

The empirical analysis in this study is based on two data sets, which differ with respect to aggregation. The first data set is the monthly average temperature which was collected from three urban and one suburban weather stations. The second data set was obtained from the survey questionnaire for 400 households from each city. The study employed a stratified random sampling technique with each district as the unit of analysis. The study obtained a list of registered households and their addresses from the district office as a sample frame, and randomly selected the respondents proportionally based on the population in each district. The data used in the analysis are weighted to account for different probabilities and survey response. The study also geocoded the respondents home address to incorporate the temperature data into their responses and create a proxy variable for the UHI intensity. Table 2 summarizes the variables and definitions used in the analysis.

3. RESULTS AND DISCUSSION

3.1 Urban heat island in Bangkok and Bandung

Bangkok is the capital city of Thailand, and is located in the central part of the country on the low-flat plain of the Chao Phraya River which extends to the Gulf of Thailand. Its latitude is 13°45' North and longitude is 100°28' East, with an elevation of about 2.31 m above sea level. The city is divided into 50 districts and 154 sub-districts, with total area of around 1,568.737 square kilometres. As the centre of industry, manufacturing, economy, commerce, and construction, a large number of people are drawn to it from all over the country, leading to high growth of urbanization and industrialization. The population is about 10 million in the daytime, which is 16% of the total population of Thailand (NSOT, 2013). This rapid urbanization has led to several environmental problems such as air pollution, water pollution, land subsidence as well as problems from the presence of UHI, high energy consumption, and biophysical hazards (Arifwidodo, 2012). Generally, the climate of Bangkok is tropical (warm and humid), and the city is affected by the monsoon season. The relative humidity is high throughout the year at around 60–80%. There are three main seasons: Rainy (May–October), winter (November–January) and summer (February–April). The average wind velocity is 1.2 m/sec (4.3 km/hr). The average relative humidity is 73%, and the yearly average precipitation is 1,652 mm. The annual average ambient temperature is around 33–38°C, with absolute minimum of about 20°C and absolute maximum temperature of about 30°C. The rainy season temperature is around 25–32°C, the dry season temperature is around 20–25°C and the hot season temperature is around 40–42°C. In 2015, the maximum temperature difference between urban and rural areas of Bangkok was 7°C, which is the highest in the last 10 years.

Category	*Variable*	*Definition*	*Bangkok*		*Bandung*	
			Mean (stddev)	*% of 1*	*Mean (stddev)*	*% of 1*
UHI intensity	CDD24	Cooling degree days using 24°C as the base temperature	152.68 (32.11)	-	12.1 (6.57)	-
	TEMP	Average monthly temperature difference between urban and suburban stations	1.95 (1.97)	-	2.8 (1.8)	
Housing	HOUSETYPE	Type of housing unit, with 1 = detached house; 0 = other	-	46.8		
	AC	Number of Air conditioner units owned	1.8 (1.2)	-	1.52 (0.56)	-
	TYPEAC	Type of AC unit with 1 = split unit; 0 = other	-	78.3	-	98.4
Energy Consumption	USEAC	Frequency of using AC unit in the past year, with 1 = almost every day, 0 = rarely used	-	84.2	-	23.4
	ENRGYSAVE	Energy saving products owned in the house, with 1 = own; 0 = not own	-	76.3	-	65.4
	ENERGY	Total energy consumption, measured with the monthly average of electricity bill for this year in USD	26.69 (13.47)	-	14.45 (12.67)	-
Household	HHMEMBER	No. of household members	4.0 (1.82)	-	5 (2)	-
	INCOME	Average monthly income in the last year (in USD)	627.63 (266.87)	-	197.8 (142.96)	-
	AVAGE	Average age of respondent	39.6 (14.08)	-	46.15 (22.4)	
	EDUCATION	Education of the head of household, with = 1 if respondent has graduated from high school, 0 otherwise	-	70.8	-	54.2
	GENDER	Gender of the respondent, 0 = female, 1 = male	-	38.2	-	65.3
	MARITAL	Marital status of respondent, 0 = single, 1 = married	-	48.3		69.3
	HHSTAT	Status in the household, 0 = head of the household, 1 = other	-	46.7	-	54.8
	TENURE	Housing tenure of the respondents with 1 = own; 0 = rent/other	-	87.4	-	83.5
Health	PHYSICAL	Physical health effect of UHI measured by perceived energy level during the past 4 weeks, with 1 = very low, 5 = very high	-	13.4	-	10.1
	MENTAL	Emotional problems the last 4 weeks experienced by respondents, with 1 = very rarely, 5 = very frequently	-	16.5	-	13.6
	WELLBEING	Life satisfaction for the last four weeks, with 1 = very unsatisfied, 10 = very satisfied	-	11.4	-	9.8
	SMOKE	The respondent's smoking addiction, 0 = yes, 1 = no	-	88.7	-	56.4
	ALCOHOL	The respondent's alcohol addiction, 0 = yes, 1 = no	-	90.5	-	99.5
	ISCHEMIC	Does the respondent have an ischemic heart disease, 0 = yes, 1 = no	-	99.8	-	98.7
	CEREBROVAS	Does the respondent have a cerebrovascular disease, 0 = yes, 1 = no	-	98.6	-	96.4
	RESPIRATORY	Does the respondent have a respiratory disease, 0 = yes, 1 = no	-	90.9	-	95.9
	CARDIO	Does the respondent have a cardiopulmonary disease, 0 = yes, 1 = no	-	93.7	-	95.9

TABLE 2. Variable used in the analysis.

Bandung is the capital of West Java Province in Indonesia. It is considered the fourth most populous city in the country. The city is located on a river basin surrounded by volcanic mountains, and this topography provides a cooler year-round temperature than most cities in Indonesia, which makes Bandung famous for tourism. The annual temperature in Bandung is 24.72°C with relative humidity around 70%. Presently, Bandung is one of the biggest growth centres in Indonesia with mixed land use and a concentric urban structure. Being one of the national and regional centres of economic, social, political and administrative activities, Bandung has been experiencing dramatic changes in its landscape. Many critical urban issues relating to urbanization, such as urban infrastructure and basic service provision, decent housing and settlements, land for housing, are issues that urban planning in the city needs to tackle (Arifwidodo, 2014). Nonetheless, while flooding has annually occurred in some parts of Bandung Basin since the 19th century, the high rain intensity, which has been increasing since 2011, has caused a higher number of landslides, typhoons, and falling trees in Bandung in 2016 compared with 2015. While vulnerability to landslides increases at the beginning of the rainy season after a long dry season, it has been reported that typhoons caused falling trees, other damages, and even fatalities. Although typhoons may normally occur during the seasonal transition, their likelihood of occurrence has doubled since 1998 due to climate change. Urbanization in Bandung has caused a change in the microclimate. In 1995, the average temperature in the city was 18°C, which rose to 22°C in 2007 and 25°C in 2015, with a maximum temperature difference between urban and rural areas of Bandung of 6°C, which is the highest in the last 10 years.

Although the magnitude of UHI is increasing, policies and measures to tackle UHI and its impacts are still scarce in Bangkok and Bandung. Bangkok Metropolitan Administration (BMA), the institution responsible for the city development, has three different planning documents drafted by three different agencies related to UHI adaptation. Moreover, the implementation of each sector has only met with limited success, due to two reasons. First, there is no integrated plan to adapt and mitigate UHI. All planning documents related to UHI are part of efforts to solve the urban problem in different sectors. For example, UHI adaptation is included in a document to increase the number of green spaces in Bangkok as well as a document on the climate mitigation and adaptation plan. Second, the plans exist under three different implementing offices, which resulted in a lack of coordinated efforts between policies. In the case of Bandung, there is no direct policy for reducing UHI effects. The local government does not perceive mitigating UHI as important since Bandung's temperature is considered colder compared to other major cities in Indonesia. While several implicit policies aimed at mitigating and adapting to UHI effect exist, which can be found in the master plan, zoning regulations, building codes, and environmental policies, these policies are not purposively focused on combating the UHI effect despite their potential, if implemented, to positively contribute to mitigating and adapting to the city's increase in temperature.

Variable	*Bangkok*	*Bandung*
	Coeff (std.error)	*Coeff (std.error)*
CDD	0.0049 (0.0012)***	0.0007 (0.0003)**
AC	0.0738 (0.0311)***	0.0738 (0.0256)**
USEAC	0.1316 (0.0409)**	0.1264 (0.0373)
ENRGYSAVE	-0.1014 (0.0988)	-0.0400 (0.0788)
HOUSETYPE	-0.0260 (0.0610)**	-0.0271 (0.0274)**

TABLE 3. Result of OLS Regression model on the Effect of UHI on Household Energy Consumption. Note: *** = $p<0.001$, ** $p<0.05$. Adjusted R2 for Bangkok = 0.23 ($p<0.001$), adjusted R2 for Bandung = 0.21 ($p<0.001$). The model is adjusted for control variables HHMEMBER, INCOME, AVAGE, EDUCATION, GENDER, MARITAL, HHSTAT, TENURE. Dependent variable is ENERGY. Source: Author's analysis.

3.2 Urban heat island and household energy consumption

In Bangkok, a survey conducted by the National Statistical Office of Thailand in 2013 shows that the average energy expenditure is 2,084 THB (or 10.9% of total expenditure), among which 607 THB (29.1% of the total energy expenditure) is spent on electricity. The average electricity expenditure in Bangkok Metropolitan Area is 1,133 THB, higher than other regions in the country. This figure is slightly different from the result from the survey (854.35 THB for electricity expenditure). Seventy-two percent of households in the study area had air conditioning (AC) equipment in their housing units, and a positive correlation between income and number of AC units owned in the house exists (two-tailed t-statistics, $p < 0.0001$). This is because the higher the income, generally the bigger the floor area of households. The floor area of the house is also found to have a positive correlation with the frequency of AC use (two-tailed t-statistics, $p < 0.005$).

In Bandung, the sample appears biased towards the relatively higher income group. The average income of the sample is above that of the average socio-economic survey in 2007 conducted by Bandung Statistical Agency (Bandung Statistical Agency [BSA], 2007). The average income from our survey is 2,868,267.9 IDR, while it is 711,138 IDR from the socio-economic survey.

On average, households in the study area spend 163,455 IDR per month for electricity expenditure. Most of the respondents live in detached housing with permanent structures (76.3%). Table 3 summarizes the effect of UHI on household energy consumption in Bangkok and Bandung.

After controlling for other variables, the result shows that there is a statistically significant relationship between UHI intensity (measured by CDD) and household energy consumption both in Bangkok and Bandung. The result confirms that UHI magnitude has a positive association with the household energy consumption in two ways. First, energy consumption for cooling is higher when the UHI magnitude is higher, corresponding to seasonal variations. Second, energy consumption for cooling is higher in the area that suffers high UHI magnitude. This means that in the urban area, where the UHI is high, household energy consumption is higher compared to the suburban area. This finding is similar to that of Arifwidodo (2014) and Zhou, Zhuang, Yang, Yu, and Xie (2017), which suggests that household energy for cooling in the urban area is associated with higher volume of anthropocentric activities and microclimate. However, in Bandung, although the average monthly electricity usage for cooling was 262 kilowatt-hours or 85.34% of the average of total monthly household electricity usage, there were only 12.42% of respondents who had AC installed in their house. The fact that variable AC usage is not significant reflects the low percentage of AC equipment and usage compared to total monthly electricity usage of households, which was only 0.22% and 1.34% respectively.

3.3 Urban heat Island and perceived health effect

The UHI-related health effects in this study are defined as heat stress effects. Empirical evidences show that heat stress in tropical cities is increasing due to urban heat island and urbanization, especially in developing countries. Increasing heat stress has substantial adverse effects on population mortality and morbidity. Health impacts from heat stress in this study are categorized as physical health impacts, mental health impacts, and well-being. Although not as severe compared to other countries, Thailand has experienced an increased prevalence of heat-related illnesses (Langkulsen, Vichit-Vadakan, & Taptagaporn, 2010). A study on heat stress in the country has revealed that heat stress is a very serious problem (Tawatsupa et al., 2014), and the Thai Meteorological Department (2009) has predicted that the average temperature will increase by 4°C by 2100, which will contribute to excess mortality.

Table 4 summarizes the variables of heat stress from Bangkok and Bandung. The variables are constructed by

Variable	*Description*	*% of 5*		*% of agreement*	
		BKK	*BDG*	*BKK*	*BDG*
Sleeping 1	I have trouble sleeping because of summer heat	32.7	11.2	88.3	50.3
Sleeping 2	I need to turn the fan/AC on during sleeping at night	56.2	10.2	98.8	22.1
Housework 1	I do less housework in the afternoon because it is too hot	20.4	12.1	86.1	28.9
Housework 2	I turn the fan/AC on while doing housework	21.0	2.8	78.4	16.3
Daily travel	I have difficulty going to work because of the heat	25.5	10.1	88.7	46.1
Work	I have problems at work because of the hot weather	22.4	8.7	87.3	50.7
Exercise	I do less exercise because of the hot weather	14.1	9.4	76.9	58.4

TABLE 4. Heat stress category in Bangkok and Bandung. Note: % of agreement is arrived at by combining the 1–2 answer into meaning "no" and 3–5 into meaning "yes". Source: author's analysis.

Health Outcomes	*Percentage*	
	BKK	*BDG*
Overall life satisfaction (score ranged from 0–10)		
9–10 (very satisfied) high	13.2	11.3
8 (high)	23.6	22.1
6–7 (medium)	41.7	34.5
0–5 not very satisfied (low)	21.4	32.1
Energy level in the past 4 weeks		
Very much	5.6	66.5
Quite a lot	22.2	22.2
Some	58.9	66.3
A little or none	13.4	5.1
Emotional problems in the past weeks		
Not at all	12.0	70.2
Slightly	32.1	18.4
Moderate	39.4	4.2
Quite a lot	16.5	7.2

TABLE 5. Health and well-being outcomes. Note: the Likert scale for the overall life satisfaction is 1–10 with 1 = very unsatisfied and 10 = very satisfied. The scale for energy level is 1–5 with 1 = very rarely, 5 = very frequently. The scale for the emotional problem is 1–5 with 1 = very low, 5 = very high. The adjustment of the language did not change the grouping of data. Source: author's analysis.

Variable	*CDD*	
	BKK	*BDG*
Sleeping 1	0.077**	0.031*
Sleeping 2	0.099**	0.045*
Housework 1	0.135***	0.063***
Housework 2	0.047**	0.064**
Daily travel	0.001**	0.001**
Work	0.006**	0.007**
Exercise	0.119**	0.125**

TABLE 6. Association between UHI intensity and heat stress. Note: *** = p<0.001, ** p<0.05, * = p<0.01. Adjusted R2 for Bangkok = 0.11 (p<0.001), adjusted R2 for Bandung = 0.08 (p<0.001). BKK = Bangkok, BDG = Bandung. The dependent variables are Sleeping 1, Sleeping 2, Housework 1, Housework 2, Daily travel, work, and exercise. Source: author's analysis.

asking respondents to rank their agreement with statements in the questionnaire, where 1 = strongly disagree, 2 = disagree, 3 = neutral, 4 = agree, and 5 = strongly agree. The table shows that most respondents have problems with daily activities because of heat interferences. More than 80% of respondents have trouble sleeping at night and almost 100% of respondents require use of an AC or fan to help them sleep at night because it is too hot. Respondents reported that they do less housework in the afternoon and need to turn on the AC or fan while doing such chores. More than 80% of respondents have heat interference problems at work, and more than 70% of respondents exercise less because it is too hot.

In Bandung, due to relatively colder weather conditions, the result is slightly different from Bangkok. Only half of the respondents report that they have trouble sleeping because of heat and 22% of respondents need AC equipment to sleep at night. Contrary to Bangkok, only 29% of respondents in Bandung experience problems during their housework and only 16% need to use their AC. Another different result is revealed in daily travel, with only 46% of respondents in Bandung experiencing difficulties going to work compared to 88.7% in Bangkok. In terms of work and exercise, more than half of the respondents in Bandung report that they experience problems due to hot weather.

Table 5 describes the health and well-being outcomes in Bangkok and Bandung. Health outcomes are relatively similar, except for emotional problems. Respondents in both cities report that their overall life satisfaction is mostly at the medium level (6–7 on a 10 Likert-scale). More than half of the respondents in both cities also report that they have experienced a low level of energy in the past month. On the other hand, more than 70% of respondents in Bandung feel that they do not have emotional problems, while in Bangkok more than 87% suffer emotional problems during the past weeks.

To understand the association between health outcomes, heat stress, and UHI, two models of ordinary least squares OLS regression model are established. The argument is that UHI will disrupt daily activities through heat stress, and heat stress then eventually affects health outcomes. The first model is used to understand the association between UHI intensity (measured with CDD) and heat stress. The second model is to understand the association between heat stress and health and well-being outcomes.

Table 6 summarizes the association between heat stress and UHI intensity, measured with CDD. The data suggest that UHI intensity is significantly associated with all heat stress variables. The positive association means that the higher the UHI intensity, the higher the disruption of daily activities and cause of heat stress. It can be inferred that UHI directly disrupts daily activities of the respondents and causes heat stress. Only sleeping 1 and sleeping 2 variables show less significance (p<0.01) in Bandung, probably because of the weather conditions during the night, which is much cooler than Bangkok.

	Life satisfaction		*Energy level*		*Emotional problem*	
	BKK	*BDG*	*BKK*	*BDG*	*BKK*	*BDG*
Sleeping 1	-0.03***	-0.05**	-0.078	-0.045	0.196***	0.164**
Sleeping 2	-0.49*	-0.27*	-0.49	-0.23	0.93	0.73
Housework 1	-0.198***	-0.112***	-0.193***	-0.096***	0.215***	0.176***
Housework 2	-0.157***	-0.092***	-0.125*	-0.096*	0.046	0.022
Daily travel	-0.83**	-0.74**	-0.118*	-0.102*	0.136**	0.094**
Work	-0.153**	-0.113**	-0.190***	-0.128***	0.174***	0.153***
Exercise	-0.191***	-0.082***	-0.162***	-0.118***	0.183***	0.098***

TABLE 7. Association between heat stress and well-being outcomes. Note: *** = p<0.001, ** p<0.05, * = p<0.01. Adjusted R2 for Bangkok = 0.121 (p<0.001), adjusted R2 for Bandung = 0.115 (p<0.001). BKK = Bangkok, BDG = Bandung. The model is adjusted with control variables HHMEMBER, INCOME, AVAGE, EDUCATION, GENDER, MARITAL STATUS, HHSTAT, TENURE, SMOKE, ALCOHOL, ISCHEMIC, CEREBROVAS, RESPIRATORY, CARDIO. The dependent variables are life satisfaction, energy level, and emotional problems. Source: author's analysis.

The association between heat stress and health and well-being outcomes is summarized in Table 7. The data suggest that heat stress is associated with health and well-being outcomes, especially life satisfaction. Energy level variables have negative association with housework activities, daily travel, work and exercise. Emotional problem variable has positive association with sleeping, housework, daily travel, work, and exercise. Heat interferences to housework 1 is found to have the highest correlation value with all health and well-being outcomes in Bangkok and Bandung. The data suggest that respondents with heat stress problems will have lower life satisfaction, lower energy level, and experience more frequent emotional problems. These findings are similar to the results in the literature, i.e., that heat stress significantly reduces health outcomes and well-being. For example, Lan, Lian, and Pan (2010) found that people working in hot environments had lower motivation to work and experience negative moods during work. Guo, Punnasiri, and Tong (2012) found that there is an effect of increasing temperature on mortality in Bangkok, Thailand. This study found that heat stress not only affects their working life, but also interferes with other aspects of daily life such as sleep, daily travel, and exercise.

4. CONCLUSION

The study explores the effects of UHI on the household energy consumption and perceived health effects in Bangkok, Thailand, and Bandung, Indonesia. The effects on household energy consumption are examined using monthly electricity. The results show that UHI is associated with increasing AC equipment ownership and increase in household energy for cooling in both cities. The perceived health effect of UHI is examined using heat stress variables and health outcomes. Analysis of the data suggests that UHI increases heat stress and lowers health outcomes. The study indicates that UHI affects the daily lives of urban residents and that local governments need to pay more attention to it. Integrating UHI adaptation into decision-making processes is the logical implication of this finding. In the cities of developing countries where resources are scarce, a better understanding of the effect of UHI on urban areas can help local governments make better decisions in allocating resources and amenities and be more aware of when to promote growth or contain it, while minimizing any externalities that may occur.

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An integrated assessment of climate-affected long-term water availability and its impacts on energy security in the Ganges sub-basins

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ABSTRACT

The Ganges basin provides essential water for drinking, irrigation, industrial use and power generation. Global climate change will affect the water availability in the basin and inevitably intensify the competition for water among major users, particularly from thermal power generation. Knowledge on the spatial distribution of water supply-demand gaps and the water stress for meeting the cooling water requirements is crucial for effective energy planning and water resource management. This article presents the outcomes from the India case study based on an integrated assessment of the water-energy nexus in the Ganges sub-basins focusing on water stress assessment for thermal power plants up to 2050 under climate change conditions. The results from the hydrological modelling show that the overall water availability in the four studied sub-basins, namely Chambal, Damodar, Gandak and Yamuna, will increase by 13%, 33%, 21% and 28%, respectively, in 2050 compared with the levels in 2010 under the greenhouse gas Representative Concentration Pathway (RCP) scenario 4.5. However, water availability will not be evenly distributed throughout the year and in some sub-basins water will be less available in the dry seasons. For example, Yamuna will have 25% less water in the dry season in the 2050s. Steady growth of water demand will cause serious water deficit in 30 out of 40 districts in Yamuna and 18 out of 33 districts in Gandak in 2050 under RCP 4.5. Consequently, 40% of the existing and planned thermal power plants in Damodar and almost all in Gandak and Yamuna will face high water risks in the future, endangering the energy security in India. Energy development planning and water resource management therefore need to take into account the water risks posed to future thermal power generation and consider the relocation of the planned installations from water-stressed areas (particularly Gandak) to alternative locations with water surplus (such as Chambal). It is also important to adopt less water-intensive power generation technologies and cooling systems for the planned and new installations.

KEYWORDS

Ganges sub-basins, Integrated assessment, Water stress for thermal power generation, Water supply-demand gaps, Water-energy nexus

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HIGHLIGHTS

- » The results from the hydrological modelling for the Ganges sub-basins indicate that the overall water availability in Chambal, Damodar, Gandak and Yamuna will increase by 13%, 33%, 21% and 28%, respectively, in 2050; however, it will vary across seasons and locations.
- » In 2050, total water demand from irrigation, livestock, domestic, industrial and energy sectors as well as the environmental water requirement will increase steadily ranging from 34% (in Damodar) to 42% (in Yamuna).
- » Among the four sub-basins, Chambal and Damodar will have water surplus at the district level; however, 18 out of 33 districts in Gandak and 30 out of 40 districts in Yamuna will face severe water deficit in 2050.
- » Forty percent of the existing and planned thermal power plants in Damodar and almost all in Gandak and Yamuna are located in water-stressed or moderately water-stressed areas which will face high water risks in the future.
- » Energy planners and investors should attach importance to the potential water risks posed to future energy security in India. The water stress assessment at the district level provided by this study can be used as effective information supporting thermal power generation planning and site selection.

1. INTRODUCTION

Water and energy sectors are intrinsically interdependent from both supply and demand sides. Water is required for extracting, refining and processing primary energy, such as coal, natural gas and oil, but used for the cooling system required for electricity generation and hydropower generation. Approximately 8% of globally withdrawn water is used for energy generation (Bhattacharya & Mitra, 2013) and half of the world's thermal power plant capacity is threatened by water stress (Kressig, Byers, Friedrich, Luo, & McCormick, 2018). On the other hand, energy is needed to power modern water supplies and wastewater treatment. Unstable operation of thermal power plants constrained by water shortage can in turn impact on pumping the water to the users. Insecurity in either sector will impact on the nexus of water and energy which can further generate a ripple effect on the whole economy. Until recently, sectoral approaches have been used to address the surge in demand for water and energy, but which ignore the inherent linkages between them. A systems approach for addressing the water-energy nexus challenges around the world is gaining importance among policymakers and academia in recent years (Delgado, Rodriguez, & Sohns, 2015).

The Ganges basin is the world's second largest catchment area and home to more than 600 million people. It is a strategic river basin in South Asia providing more than 30% of the region's water resources (World Bank, 2015). The basin connects three riparian countries: Nepal, India and Bangladesh, and projected population growth together with rapid economic development will place great pressures on water resources here. The Ganges has been recognized as a water-stressed river basin, which issue will only heighten in the near future with the expected increase in water-intensive activities such as irrigation and thermal power generation. Rapid urbanization and the associated increase in water demand from households is another concern which may exacerbate water stress situation in the region.

The Ganges basin supplies water to thermal power generation systems with an installed capacity of more than 50 GW, accounting for more than 40% of the total thermal power capacity in the region (Sinha, 2014). Out of the total installed capacity, 92% uses coal with the wet cooling system which is the most water-intensive technology. Water stress will threaten the existing and planned thermal power plants located in this basin in the near future and up to 2050.

In addition, according to Gosain K., Rao, S., and Arora, A. (2011), the impacts of climate change on water resources are likely to affect irrigation, power generation and the environmental flows in dry seasons. The increasing pressures on water resources affected by climate change therefore threaten the livelihoods of 85% of the population in the Ganges basin that relies on agriculture and will harm the basin's long-term sustainable development.

Funded by the Asia-Pacific Network for Global Change Research (APN), we conducted a project entitled "Assessment of Climate-induced Long-term Water Availability in the Ganges Basin and the Impacts on Energy Security in South Asia" to help address the pressing challenges of water-energy nexus in the Ganges basin. The objective of the project is to provide an integrated assessment tool on water-energy nexus and inform relevant decision-makers and investors about water supply-demand gaps under the long-term impacts from climate change up to 2050 as well as the water stress for future thermal power generation in the Ganges basin. This article is prepared based on the methodology and the research results provided by the

APN project.

The three case studies for India, Bangladesh and Nepal were conducted with different foci and level of detail. This article covers the case study for India, and provides a comprehensive assessment on water supply, water demand and water stress for existing and planned thermal power plants in four selected sub-basins. For the other two case studies, please refer to the full research report (Zhou et al., 2018).

Section 2 presents the analytical framework of an integrated assessment of water-energy nexus. Section 3 provides the results of the case study conducted for India and relevant discussions. Section 4 concludes the paper with policy implications.

2. METHODOLOGY

Water security and the nexus issues of water-energy-food-climate centred around water aroused great attention from business leaders and international society at the World Economic Forum 2008 (World Economic Forum, 2008), which has since inspired many research works in the nexus area. Some recent reviews have provided latest developments in the nexus research (Bazilian et al., 2011; Hamiche, Stambouli, & Flazi, 2016; Endo, Tsurita, Burnett, & Orencio 2017; Zhang, Chen, Li, Ding, & Fu, 2018; Dai et al., 2018) by comparing the scope of the nexus issues (e.g., water-energy, water-energy-food, or water-energy-food-climate), scales (geographical and time), research objectives, issues focused on (e.g., water security, energy security, system performance), research methodologies (e.g., life cycle analysis, econometrics, computable general equilibrium modelling, system dynamics, or simulation and optimization models) and key messages, among the studies.

In this context, the present study focused on the issue of water scarcity as a threat to energy security in the sub-basins of the Ganges River. It mainly deals with the water-energy nexus focusing on the water risks of existing and planned power plants while taking into account the impacts of long-term climate change on water availability. For the methodology, this study developed a unique integrated, spatial assessment approach by combining the hydrological modelling of spatial water resource distribution and water demand assessment with field survey data collected from more than 20 thermal power plants in India. In addition to the desk research, this study conducted intensive consultations (five rounds in total) with various stakeholders including governmental organizations, thermal power plants, investors, NGOs and academia. The research objectives and methodology were the results of these consultations and the research outputs were conveyed effectively to relevant stakeholders. The methodology includes five modules, i.e. Water Supply Module, Water Demand Module, Energy Module, Water-Energy Nexus Assessment and the Water-Energy Nexus Assessment Web Tool (see Figure 1). Four sub-basins, namely Chambal, Damodar, Gandak and Yamuna, were selected

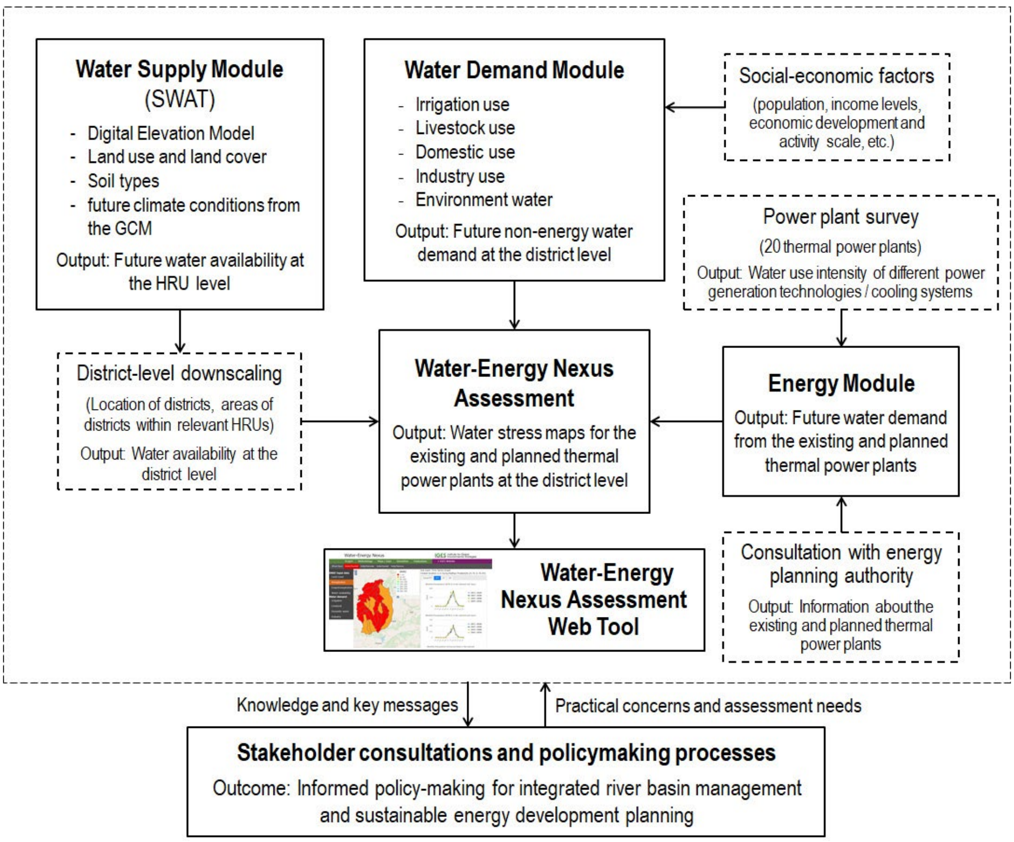

FIGURE 1. Methodological framework for an integrated assessment of the water-energy nexus under climate change impacts for the Ganges sub-basins.

Data type	*Data source*
Digital Elevation Model (DEM)	SRTM 90 m × 90 m resolution
Land use and land cover	National Remote Sensing Centre (NRSC) 100 m × 100 m resolution
Soil	Food and Agriculture Organization (FAO) gridded raster data 6500 m × 6500 m
Weather data	Precipitation of 0.5 degree Temperature of 1 degree Relative humidity, solar radiation, wind grid, weather data http://globalweather.tamu.edu/
Future climate conditions from the GCM	MRI-CGCM3 model http://pcmdi9.llnl.gov/

TABLE 1. Data used for the SWAT model.

based on the characteristics of current water supply and demand and the locations of the existing and planned thermal power plants.

Under the Water Supply Module, future water availability is projected for the four sub-basins using the Soil and Water Assessment Tool (SWAT), under future climate change conditions for the Intergovernmental Panel on Climate Change (IPCC) Representative Concentration Pathways (RCP) 4.5 and RCP 8.5 for the time period of 2020-2050 projected from a general circulation model (GCM), MRI-CGCM3 (Yukimoto et al., 2012). Major input data to the SWAT model including the Digital Elevation Model, land use and land cover, soil types, weather and future climate conditions from the GCM, etc., the relevant data sources of which are provided in Table 1 (for details, see Zhou et al., 2018).

The results from the SWAT model simulation on water supply and water availability are provided at the scale of hydrologic response unit (HRU) which is characterized by homogeneous land use, slope and soil type. To be consistent with the results from future water demand projections which are provided at the district level based on the statistics and other secondary information, the hydrological modelling results were then downscaled to the district level based on the following steps:

1. Identify the districts that are located within or across the borders of each HRU;
2. Calculate the area of each district and the areas located within different HRUs;
3. Use the water yield result of relevant HRU from the SWAT model as the representative value for the district area that is located within the HRU;
4. For water availability at the district level, multiply the water yield of the representative HRU by the corresponding area of the district and sum up for all relevant areas in the district.

Under the Water Demand Module, future water demand up to 2050 from four non-energy sectors—irrigation, livestock, domestic sector and industry sector—as well as environmental water, is estimated based on various methodologies taking into account population growth, income levels, economic development and activity expansion, etc. Adding up the sectoral water demand and the environmental water corresponds to the total non-energy water demand. The water demand from thermal power generation is estimated in the Energy Module.

Under the Energy Module, future water demand from thermal power generation (including both the existing capacity and the planned new capacity) is estimated. Information is collected on i) the location of the existing and the planned power plants; ii) the type of power generation technology (such as coal-fired, gas-fired, oil-fired, hydro and other renewables) and the cooling system (open loop, close loop and dry cooling, etc.) for each of the existing and planned installations; and iii) the total annual electricity generation of each installation. Water use intensity of different technologies, i.e. the combination of the power generation technologies and cooling systems, is largely unavailable for the Ganges basin in extant literature. To obtain first-hand data, field surveys of 15 selected power plants in India and the questionnaire surveys of other power plants were conducted. With these input data, water demand from each of the existing and planned installations can be estimated. Water demand at the district level can be estimated by summing up the water demand of existing and planned installations that are located in a specific district.

Under the module of Water-Energy Nexus Assessment, water supply-demand balance is assessed at the district level by subtracting the total water demand (outputs from the Water Demand Module and the Energy Module) from the total water availability (outputs from the Water Supply Module). The ratio of water supply-demand balance is calculated at the district level by dividing the water supply-demand balance by the total water availability. The ratios are further classified into three categories, i.e. water-stressed area with the ratio value ranging between (- , 0], moderate water-stressed area with the ratio value ranging between (0, 0.5] and water abundant area with the ratio value ranging between (0.5, +). The existing or the planned thermal power plants which are located in the water-stressed areas may face serious water shortage, which impacts on their operational stability. Water abundant areas can be considered as locations for the development of new energy projects in the future.

A free online tool was developed to enable spatial visualization of the data and the results in maps on water

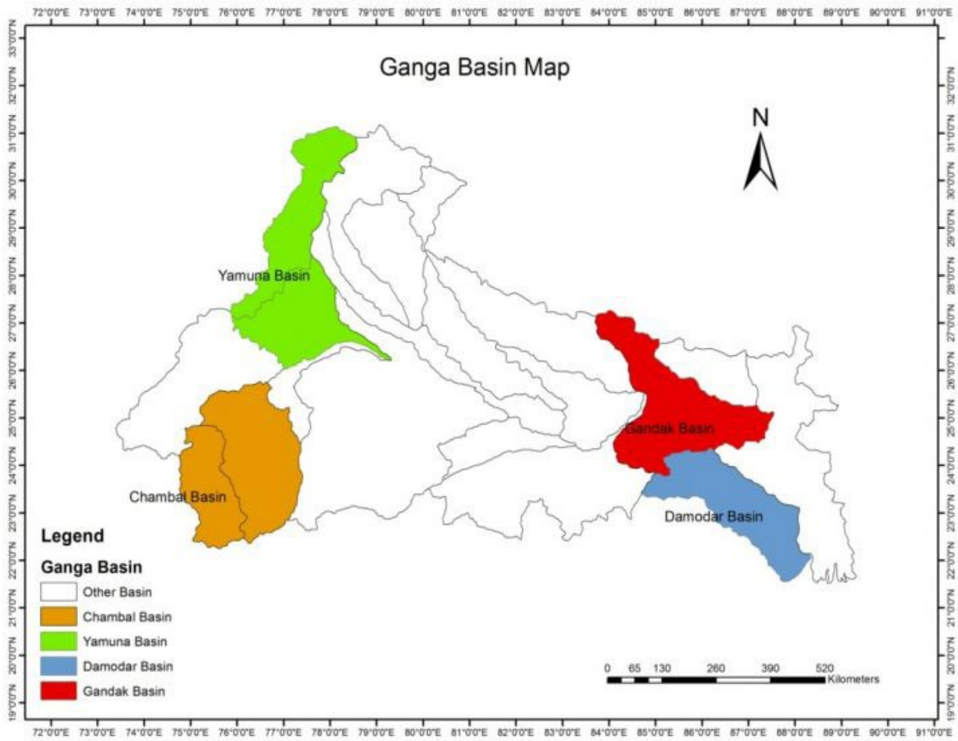

FIGURE 2. Location of Chambal, Yamuna, Gandak and Damodar sub-basins in the Ganges basin.

supply, water demand and water-energy nexus assessment at the district level for the four sub-basins in India (forthcoming at IGES website).

To better inform the policymakers and relevant stakeholders on the spatial distribution of water stress particularly from the long-term energy security perspective, stakeholder consultations were conducted to communicate with them the research purpose and methodologies, collect feedbacks on the concerns and special assessment needs and convey the research results and key messages.

3. RESULTS AND DISCUSSION

3.1 Water availability assessment for the four sub-basins

Future water yield changes compared with the historical period (1976–2005) in the Chambal, Damodar, Gandak and Yamuna sub-basins (see the location of the four sub-basins in the Ganges basin in Figure 2) under RCP 4.5 and RCP 8.5 at different time periods (2020s, 2030s and 2050s) are presented in Table 2. Water availability will not be evenly distributed around the year and will vary from season to season depending on the physical conditions such as precipitation, evapotranspiration and surface runoff, etc. The results show that water availability will increase in Damodar and Gandak in both dry and wet seasons, particularly in Gandak in the wet season in 2030s under RCP 4.5 and in the 2050s under RCP 8.5. However, it will decrease in Chambal in the dry season and Yamuna in both dry and wet seasons, particularly in the dry season in the 2050s under RCP 4.5 and in the wet season in the 2030s under RCP 8.5.

3.2 Water demand assessment for four sub-basins

Water demand from five sectors and the environmental water requirements in the four sub-basins for the base period 2010 and future periods (2030 and 2050) are presented in Figure 3. The results show that future water

Sub-basins	*Historical 1976–2005*		*Changes under RCP 4.5*						*Changes under RCP 8.5*					
			2020s		2030s		2050s		2020s		2030s		2050s	
	Wet	*Dry*	*Wet*	*Dry*	*Wet*	*Dry*	*Wet*	*Dry*	*Wet*	*Dry*	*Wet*	*Dry*	*Wet*	*Dry*
Chambal	396.1	25.2	61.3	-4.4	40.4	-5.3	61.8	-0.8	127.4	0.8	97.4	-1.8	200.6	6.2
Damodar	643.7	77.6	67.6	-0.2	30.5	11.2	210.3	16.5	94.8	2.9	81.4	13.7	246.6	9.9
Gandak	435.8	29.5	109.8	6.5	190.5	9.0	91.8	7.7	43.5	2.7	123.5	5.4	161.2	8.5
Yamuna	233.9	37.1	104.3	-6.6	42.4	6.5	84.4	-9.1	30.8	-11.5	-16.6	1.0	155.7	-7.0

TABLE 2. Seasonal water yield changes in four sub-basins for different time periods and climate scenarios (in mm). Note: Wet season: June-October; Dry season: November-May.

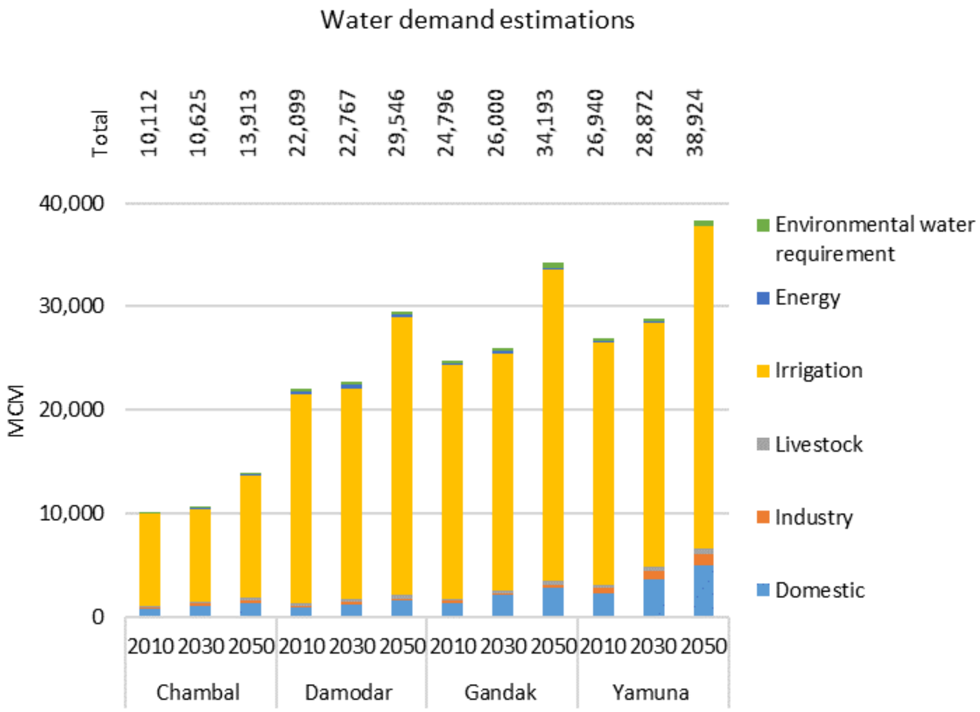

FIGURE 3. Sectoral water demand and future estimations in four sub-basins (in MCM).

demand will increase due to population growth, industrial development, increase in power generation and the expansion of irrigation. Out of the four sub-basins, Chambal will have the lowest water demand and Yamuna will have the highest. In all four sub-basins, irrigation water demand will dominate followed by domestic water demand and this trend will continue until 2050. In particular, Yamuna will have the largest irrigation water demand and the largest domestic water demand among the four sub-basins, followed by Gandak which will have the second largest water demand from both irrigation and domestic sectors. Energy water demand is the highest in Damodar followed by Gandak. Energy water demand will decrease in Chambal (from 66 million cubic meters, hereinafter referred to as MCM) in 2010 to 39 MCM in 2050) and Damodar (from 298 MCM in 2010 to 156 MCM in 2050) and will maintain the same level in Yamuna (102 MCM). However, it will greatly increase in Gandak (from 71 MCM in 2010 to 182 MCM in 2050).

3.3 Water stress assessment for four sub-basins

Water stress is assessed based on the ratios of supply-demand balance, defined as the difference between total water availability and total water demand divided by the total water availability. The results are shown in the succeeding Figures 4, 5, 6 and 7. Water-stressed areas with ratio values ranging between (-∞, 0] are indicated in red; moderate water-stressed areas with ratio values ranging between (0, 0.5] are indicated in orange; and water abundant areas with ratio values ranging between (0.5, +∞) are shown in yellow. Locations of existing and planned power plants are marked as green stars.

The results of the water stress assessment at the sub-basin level indicate that Chambal and Damodar will have water surplus in the future. Chambal will have the largest water surplus among the four sub-basins. Both Yamuna and Gandak, particularly Yamuna, will face severe water deficit in the future.

At the district level, in general there will be more districts which will face water stress in the future, particularly in 2050. The level of water stress varies among the sub-basins. In Chambal and Damodar, particularly in Chambal, most of the districts will have water surplus (regions marked in yellow or orange) which will be able to satisfy the water demand not only for existing and planned thermal power plants, but also for new installations in the future. From a temporal viewpoint, Chambal will have more districts with water surplus while Damodar will have more districts, particularly in the southern part, facing water stress (turning from orange into red) in 2050 compared with the levels in 2010. However, in Gandak and Yamuna, most of the districts will face severe water stress (regions marked in red) in the future. From a temporal viewpoint, most of the districts in Yamuna face water stress in both 2010 and 2050 and the changes will be minor. However, Gandak will have more districts facing water stress (turning from orange into red) in 2050 compared with the levels in 2010. The existing and planned thermal power plants

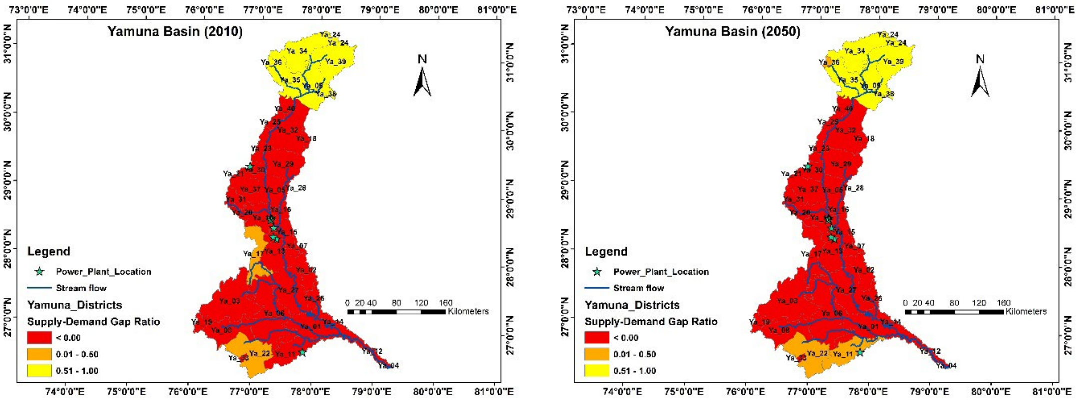

FIGURE 4. Sectoral water demand and future estimations in four sub-basins (in MCM).

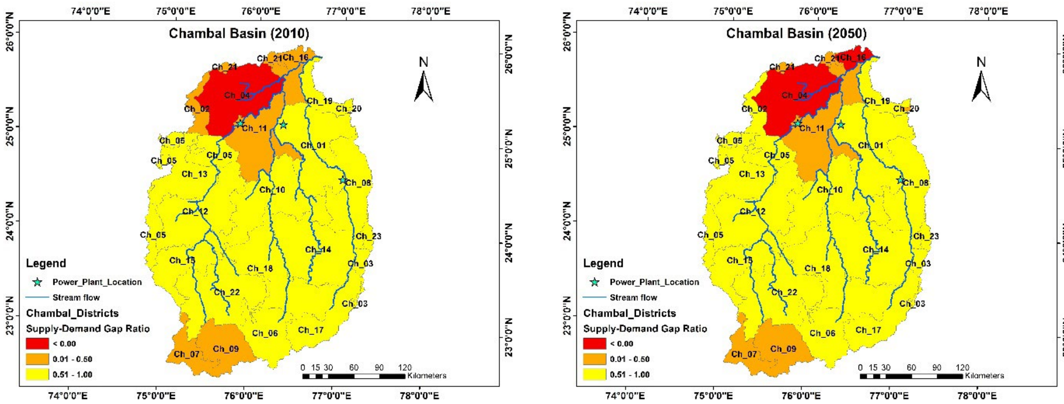

FIGURE 5. Water risk assessment for thermal power plants in Damodar.

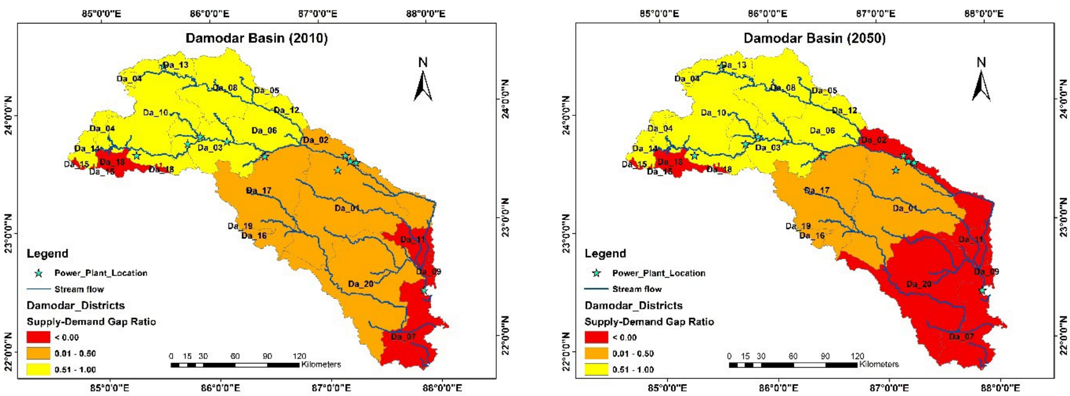

FIGURE 6. Water risk assessment for the thermal power plants in Gandak.

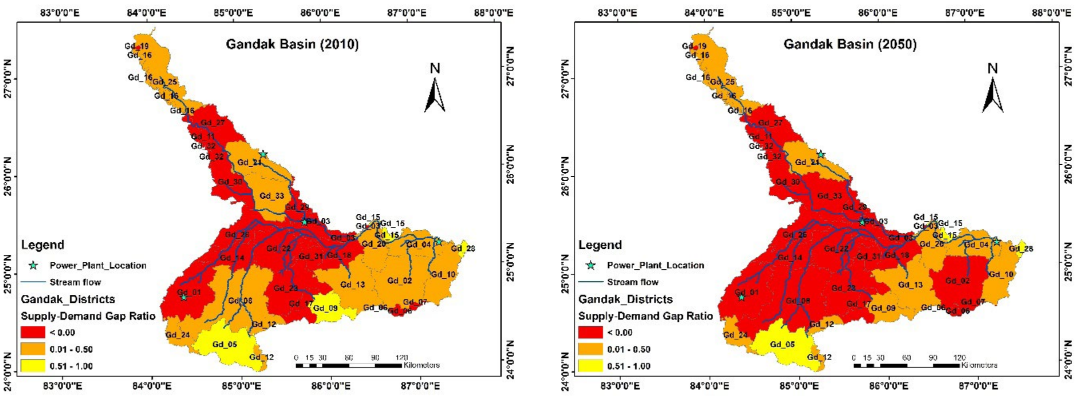

FIGURE 7. Water risk assessment for the thermal power plants in Yamuna.

located in the water-stressed areas will face high risks. Particularly in Gandak, there will be many planned thermal power installations whose operation will face severe water shortage.

The existing or planned thermal power plants which are located in water-stressed areas may face serious water shortage and their operation will be adversely influenced. Water abundant areas (e.g., Chambal) can be considered as locations for new energy projects in the future.

4. CONCLUSION

The potential water risks for future energy supply were assessed considering the long-term impacts from climate change based on an integrated approach combining various modelling techniques and approaches, including the hydrological model and water demand projections for major water users (agriculture, domestic, industrial, energy, and environmental water requirements), as well as power plant field surveys. To inform decision makers, relevant stakeholders and investors on the spatial distribution of water stress particularly from the perspective of long-term energy security, we developed a free online tool for spatial visualization of the results on water supply, water demand, water supply-demand gaps and water risks for existing and planned thermal power plants in India at the district level for four studied sub-basins: Chambal, Damodar, Gandak and Yamuna.

From the supply side, the analyses showed that the overall water availability will increase in the four sub-basins in the future. However, the water availability will vary among different seasons. The water availability will increase Damodar and Gandak in both the dry and wet seasons, but will decrease in Chambal and Yamuna particularly in the dry seasons. From the demand side, future water demand in the four sub-basins will increase steadily, dominated by irrigation and followed by domestic water use. Of the four sub-basins, Chambal will have the least water demand while Yamuna will have the largest water demand. Energy water demand will be the highest in Damodar followed by Gandak whose demand will increase greatly in the future. For water supply-demand balance, Chambal and Damodar will have water surplus, while Yamuna and Gandak will face severe water deficit in the future. At the district level, most of the districts in Chambal and Damodar will have water surplus, which can be considered as appropriate locations for building new thermal power plants. However, 18 out of 33 districts in Gandak and 30 out of 40 districts in Yamuna will face serious water stress in 2050. Consequently, 40% of existing and planned thermal power plants in Damodar and almost all in Gandak and Yamuna will face high water risks in the future. Considering the lifetime of 40 years or more, new thermal power installations constructed at the planned locations which are locked in the water-stressed areas will face severe water shortage in the future, which will greatly affect operational stability and thus endanger energy security in these sub-basins as well as in India. Relevant energy planning and water management organizations as well as investors need to factor-in the potential water risks for future thermal power generation and consider relocating the planned installations from water-stressed areas (particularly in Gandak) to alternative locations with water surplus (such as in Chambal). In addition, gradual transition to more water efficient options (high efficiency energy generation systems, dry cooling, renewable energy such as wind and solar) will reduce both water consumption and environmental impacts. Water conservation and enhancing water use efficiency from other major users, particularly from irrigation, the largest water consumer in the sub-basins, is also important in balancing water use by various users. Water rights and associated trading systems can be used as an economic incentive to help bring about more efficient water allocation and encourage water conservation and efficient use. However, the basic needs of the poor, particularly in rural areas, must be fully taken into account in related policymaking.

Due to the unavailability of published data, calibration and validation of the SWAT model was not fully performed by this study but cross-checked with other references. This is a major limitation of this study. Calibration and validation are critical factors influencing the reliability of the hydrological modelling results and need to be improved through future studies making use of observation data or other reference data from secondary sources. In addition, the present study can be further extended to cover all 19 sub-basins of the Ganges River by applying the district-level assessment approach developed for the India case study to provide a full picture of water risks for the energy security in the Ganges basin.

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Climate change adaptation through optimal stormwater capture measures

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ABSTRACT

Urban water management has become more challenging and expensive in the global change context. The major shortcomings of existing research on water management systems are the neglect of uncertainty in climate change, inadequate knowledge of infrastructural response sensitivity, the lack of holistic water management framework and limited consideration of local aspects in adaptation strategies formulation. The main goals of this research are to (1) analyse climate change impact on extreme precipitation patterns, and (2) conduct iterative stormwater simulation for alternative on-site stormwater capture measures for climate change adaptation and sustainable urban development. Impacts of climate change were investigated by considering precipitation projections of multiple GCMs (Global Climate Models) over Yato Watershed, Tokyo. Precipitation IDF curves of 2, 5, 10, 25, 50 and 100-year return periods for present and future climates revealed that, for all return periods and durations, the precipitation intensities are significantly greater for the future climate than the present climate. The HEC-HMS tool enabled simulation of flood hydrographs for current and future climate conditions. The simulated results indicated that there would be an increase of 11–20% in peak discharge at the Yato Watershed outlet at the end of this century. It was observed that Kinuta Park is in a strategic location which can be used to construct a storage facility of 180,163.14 m^3 for reducing flood events. The study proposes maintaining the stability of the water cycle of the urban catchment as an alternative for sustainable water management.

HIGHLIGHTS

» An overall increase of 6% to 25% is projected in extreme precipitation intensities over the study area.

» Increase in peak discharge by 11% to 20% due to increasing extreme rainfall precipitation events.

» Quantile mapping technique enabled a significant reduction in GCM precipitation bias.

» Use of multiple GCMs and RCPs are recommended due to significant uncertainty associated with climate projections.

INTRODUCTION

In recent years, stormwater management has become challenging and expensive because these events occur more frequently and are becoming more extreme. Many scientists believe that climate change and urbanization have caused these so-called extreme events. Rapid and unplanned urban expansion threatens sustainable development when the necessary infrastructure is not developed or when policies are not implemented. In other words, the absence of adaptation strategy increases the risk of hazards such as floods. Urban floods are frequently reported due to the significant rise in extreme precipitation intensity (Saraswat, Kumar, & Mishra, 2016; Herath, Penh, Okui, Imbe, & Kitagawa, 2012; Luo et al., 2015). Today the world is confronted with climate change, which poses unprecedented multidimensional challenges for all countries and communities in the Asia-Pacific region due to the uneven distribution of precipitation between wet and dry seasons (UNISDR, 2015). With an energized global water cycle, the future climate is expected to feature increased precipitation intensities and more dry days (IPCC, 2014; Yilmaz, Hossain, & Perera, 2014).

Thus, increased rain intensities and prolonged water scarcity periods are two of the most serious problems associated with climate change (Adusumalli & Arora, 2015). Water resources will be affected in both quantity and quality, and hence water, stormwater and wastewater infrastructure will face greater damage risk. The effect of climate change will manifest from difficulties in operations to disrupted services and increased cost of water and wastewater services. Governments and water managers will therefore have to re-examine development processes for municipal water services and adaptation strategies and incorporate climate change into infrastructure design, operation and maintenance. The expected climate change impacts involve an increase in precipitation intensities, direct runoff as well as quick rise in stream flow and depletion in groundwater table, which are similar to urbanization impacts on the water cycle. Similarly, due to the increase in impervious areas and construction of stormwater drainage networks that shorten the period of concentration and increase direct runoff, this results in a sharp rise in stream flow and depletion of groundwater table (Herath & Musiake, 1994). Hence, experiences and methods adopted for coping with water management in the context of urbanization can also be used for adaptation.

It is inappropriate to seek large scale investments for stormwater management, especially under the large degree of uncertainty associated with climate change. Therefore 'soft' measures such as infiltration trenches, landscaping and preservation of natural water bodies in reducing urban flood risks are imperative. Onsite measures are one of the soft measures that can be adopted readily under an uncertain future climate. For example, incorporating storage facilities into city planning can prolong the time of concentration together with infiltration facilities to infiltrate excess rainfall runoff from rooftops and paved areas to ultimately reduce the direct runoff volume (Herath et al., 2012). Such onsite facilities recover the pre-global change infiltration and retention functions as well as help revert the hydrological cycle to its original state. Pavement materials, drainage components as well as storage systems have been developed to improve efficiency and effectiveness to address urbanization through onsite measures. This research proposes adopting a similar kind of development for climate change in order to restore the local water cycle, and investigates the stability of the local water cycle as the target for sustainable urban stormwater management. This requires taking an integrated approach to stormwater management by managing the total hydrological cycle. The overall objective of this study is to review and analyse various on-site measures that can help restore the water cycle to the pre-climate change state, and reduce flooding due to future climate uncertainty.

Climate projections are used to understand the expected impact of climate change on different sectors of a country. Climate projections are synthetic time series of climate variables with the goal that such time series statistics will match real world data. The climate projections can be for past, current as well as future conditions. Global Climate Models (GCMs) simulate the response of greenhouse gas concentrations and provide estimates of climate variability such as temperature and precipitation (Mishra & Herath, 2011). The latest generation of state-of-the-art Earth System General Circulation Models (ES-GCMs) has recently been used to carry out simulations of a new set of scenarios for Coupled Model Intercomparison Project Phase 5 (CMIP5) (Taylor, Stouffer, & Meehl, 2012). The CMIP5 simulations include four future emission scenarios referred to as representative concentration pathways (RCPs): one mitigation scenario (RCP2.6), two medium stabilization scenarios (RCP4.5/RCP6) and one very high emission scenario (RCP8.5). GCM outputs are often not suitable for direct application to assess climate change impact at the local level due to their oversimplification of coarse resolution input information, resolving equations and other factors. To bridge the gaps between the scale of GCMs and local scales, and to account for inaccuracies in describing precipitation extremes, downscaling methods are commonly used in climate change studies. Dynamic downscaling and statistical downscaling are the two most common methods used in literature. Dynamic downscaling includes nesting of high-resolution Regional Climate Models (RCMs) with GCMs, which ensures consistency between climatological variables, yet are computationally demanding. On the other hand, statistical downscaling methods use statistical relationships between large-scale climate variables (predictors) and local-scale climate variables (predictant) and hence require less computation (Willems & Vrac, 2011).

Assessment of extreme precipitation events is an integral part of stormwater risk analysis and design. Design precipitation, the maximum amount of precipitation for a given duration and a return period, is often required for the design of different hydraulic structures. Frequency analysis is commonly used to estimate the design precipitation for a given duration and for a selected return period when there are adequate annual extreme precipitation intensity data records available. Results of the frequency analysis are commonly presented in the form of Intensity-Duration-Frequency (IDF) curves (Nhat, Tachikawa, Sayama, & Takara, 2007). In many cases (including this study), very little short duration extreme precipitation data was found, hence temporal downscaling was carried out. Different approaches have been used to detect temporal scaling properties of precipitation. Scaling theory is applied for deriving the short duration precipitation intensities from daily precipitation data. Menabde, Seed, and Pegram (1999) applied the simple-scaling theory to describe precipitation IDF in Australia and South Africa. Bara, Kohnova, Gaal, Szolgay, and Hlavcoval (2009) applied the simple scaling theory to the IDF characteristics of short duration precipitation in Slovakia. The analysis of scaling properties of extreme precipitation processes observed at a given site was based on the examination of scaling behaviour of the statistical moments of precipitation data over different durations using the simple scaling framework.

Computer-based modelling is utilized to assess and analyse the flood hazard and vulnerability, and also helps in comprehending the magnitude and frequency of the event (Mishra, 2017; Saraswat, Kumar, & Mishra, 2016). In recent years, two-dimensional models have mainly been employed to simulate urban storm-water flood problems. Tools such as HEC-HMS, SWMM, MIKE are widely used to model urban drainage systems (Elliott & Trowsdale, 2007), and such models provide good representations of physical phenomena. Geographic Information Systems (GIS) are commonly used to collect and manage the spatial data required as input for models (Heaney, Sample, & Wright, 2001). Through the modelling results, different adaptation measures can be selected to assess the effectiveness of reducing risk exposure. Hydrological changes due to urbanization have been extensively studied in the past (Weesakul, 2010; Suriya & Mudgal, 2010; UNISDR, 2012); however, very few studies cover the quantitative optimization of stormwater capture measures in urban areas due to climate change (Herath et al., 2012).

STUDY AREA

Urbanization in Tokyo caused changes in the water cycle due to the reduction of forests as well as conversion of paddy fields to new towns or residential areas, impacting the water retention capacity of the land surface (Nakao & Tanimoto, 1997). Consequently, surface runoff has been increasing progressively through urbanization. Tokyo Metropolitan Government has been widening rivers to accommodate excessive precipitation. In order to prepare for the possible additional precipitation under climate change, alternative measures such as infiltration pits and rainwater harvesting systems have to be implemented, which can also be beneficial to the water cycle. Tokyo presents typical characteristics of urban areas: low land, dense population, valuable assets, and intensive on-land and underground infrastructures. The city is one of the busiest zones in the world, highly urbanized and highly vulnerable to flood risk (Unno & Maeda, 2004). Moreover, lying in the humid subtropical climate zone, Tokyo experiences very intense precipitation and typhoons every year. Many flood disasters have occurred due to typhoons, heavy rains and storm surges. While progress in river improvements is ongoing, the risk of heavy rains exceeding the current protection level has risen in recent years, and Tokyo still experiences flood disasters frequently.

As a result, from the realization of the problems and challenges, various moves have begun toward resolving the problems related to urban flood risk. Infiltration and storage facilities have been installed in the Yato River catchment to increase the infiltration capacity of the area, to cut the peak discharge and maintain a good balance in the city's water cycle. Such facilities still offer high potential as a measure to reduce flood risk. This study investigated on-site measures to simulate and test adaptation strategies to reduce climate change-induced floods and water scarcity to cope with future climate uncertainty in the Yato Watershed. The Yato Watershed, situated in Setagaya Ward, Tokyo, Japan (Figure 1), with drainage area of approximately 3 km^2 is a tributary of the Tama River. The river flows southwards with a total length of 3.3 km and is urbanized. Yato River is a typical urban river with a concrete bank in the form of an open ladder-type ditch over most of the river length, except the section flowing through Kunita Park which is in the

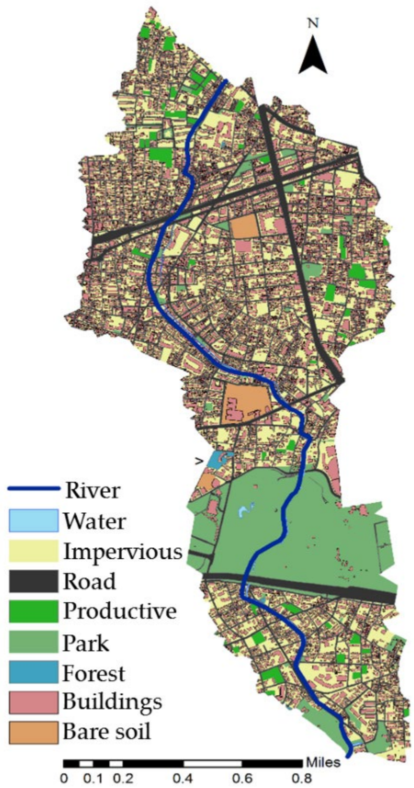

FIGURE 1. Yato Watershed and its various types of land use.

shape of a natural stream. The watercourse in some parts is "invisible" as it flows underground (under highways, or pedestrian concourses) in the form of a closed culvert. Land-use land-cover maps for the simulation period were reclassified based on 2006 and 2011 land-use maps. Land-use maps include eight categories listed in Figure 1. Removal of vegetation, increased imperviousness and drainage channels are characterized by high flow peaks and fast response to even minor precipitation events. There are four types of soil in Yato Watershed: Kanto loam, Alluvial lowland, Kazusa group, and Shimosa layer group (Penh, 2012). Most of the area is covered by Kanto loam, which consists of volcanic ash, a suitable type of soil for infiltration. Under the impact of climate change, precipitation intensity increases and the return period declines in the future (Herath et al., 2012).

METHODOLOGY

This study blends meteorological, hydrological, engineering and socioeconomic research to provide methodologies and a framework useful for strategic planning to address water management in urban areas under climate change and urbanization. The research combined climate change risk quantification, physical process simulation and decision making for water management planning and implementation in the urban watershed context. In this study, GCM precipitation output from GFDL-CM3 and MRI-CGCM3 with RCP8.5 emission scenario were employed to assess the impact of climate change on precipitation patterns over the Yato Watershed. These GCMs were selected for the study due to its easy accessibility and high temporal resolution (3-hour) for the analysis period. The RCP8.5 corresponds to the pathway with the highest radiative forcing or greenhouse gas emissions compared to the other RCPs. Moreover, the RCP8.5 scenario was selected to study the extreme precipitation events in the future as present emission scenarios are already either following or very close to the RCP8.5 (Sanford, Frumhoff, Luers, & Stanford, 2014). Observed precipitation data from 1976 to 2005 were compared with the corresponding GCM precipitation data for identifying the biases. Next, quantile-based bias correction was employed to correct the GCM precipitation data from 2071 to 2100 as the future climate for impact assessment. Furthermore, a simple scaling technique was applied to derive the short-duration precipitation intensities from available precipitation data. The scaling behaviour of observation precipitation intensities was examined, and it was revealed that the statistical properties of observation precipitation follow the assumption of simple scaling. The comparison of IDF curves for present and future climate indicated a significant increase in maximum precipitation intensities, which has major implications on planning and design of urban stormwater drainage systems. In order to understand the change in peak discharge at the outlet caused by increased extreme precipitation, HEC-HMS was utilized to simulate the rainfall-runoff model at the Yato catchment. Major steps involved in carrying out this study are described below (Figure 2).

1. GCM outputs were analysed and evaluated to establish the validity of the GCM simulations at the local context. GCM outputs underwent two inherent drawbacks, namely coarse resolution and biases in their frequencies/magnitudes which warrant that GCM output should not be used directly at the local scale. The drawbacks were minimized using quantile-quantile bias correction technique (statistical downscaling). In this technique, simulated changes in the daily frequency distribution of GCM precipitation are applied to observation precipitation (Mpelasoka & Chiew, 2009). This method consists of two steps: (1) truncating GCM precipitation data below a threshold value corresponding to non-exceedance probability of zero observational precipitation value; and (2) matching cumulative distribution function (CDF) of truncated GCM data series and observation data series by taking the inverse CDF of the GCM data with observational shape and scale parameters. The comparison (visual and relative error) of average monthly wet days and precipitation amount for raw and corrected GCM daily precipitation outputs with those of the observation data used to measure the performance of the downscaling A smaller error is expected in the case of corrected GCM.

2. Hydrological regime was analysed using HEC-HMS (Hydrologic Engineering Centre – Hydrologic Modelling System) developed by the US Army Corps of Engineers to establish catchment scale water cycle for the current and future HEC–HMS supports both lumped and distributed parameter modelling. The HEC–HMS model was calibrated and validated for isolated precipitation events. The event-based simulations employed the Natural Resource Conservation Service (NRCS) loss method to compute infiltration and unit hydrograph method to transform excess precipitation into a runoff. The NRCS method uses a curve number (CN) that depends on land-use, hydrological soil groups and antecedent soil moisture. Simulated river discharge with observed was compared, and the best fit was obtained by adjusting model parameter values. The stormwater modelling result was evaluated by visual inspection and using the Nash-Sutcliffe (NS) efficiency which indicates the degree of match between observed and simulated flows (Nash & Sutcliffe, 1970). Past studies have shown that these methods were successfully used to analyse goodness

of fit. The NS values can vary from 0 to 1, with 1 indicating a perfect fit of the data. Calibration of the model was carried out using data on 24-hour precipitation with 10-minute interval for 24th August 2009. In order to validate the calibrated model, another set of 24-hour precipitation data with 10-minute interval for 3rd December 2010 was used. First, the model was run with the model input values. This was followed by varying each input parameter within the prescribed range keeping the others constant and running the model.

3. Performance of on-site facilities and development of optimum adaptation strategies were analysed using HEC-HMS stormwater model coupled to onsite facility performance at the grid level. Combination of storage facilities and infiltration are proposed in developing a flood control plan to reduce the flood peak in future. Several simulations were carried out iteratively for on-site facility installations until the hydrologic cycle for pre- and post-climate change period were similar.

4. Previous reports on perception on alternative infiltration and storage facilities were reviewed to understand the local cultural values and perception as well as willingness of the locality to install the infiltration facilities to reduce urban flood risk and improve the urban water balance (Penh, 2012).

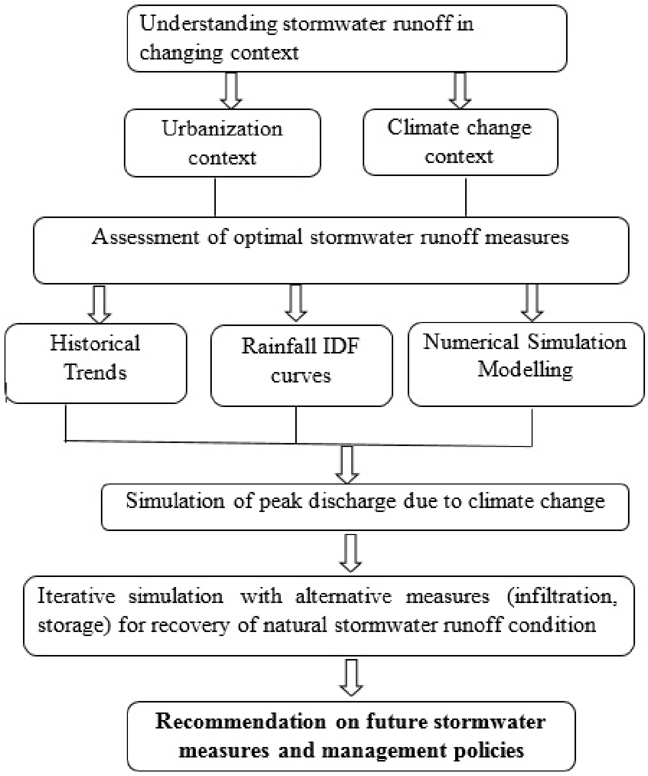

FIGURE 2. General approach for identifying optimal stormwater capture measures (however, this study omitted in-depth analysis of "regulatory policy scenarios", "economic instrumentation", "simulation of water cycle", "RS and GIS", and "land-use change" components).

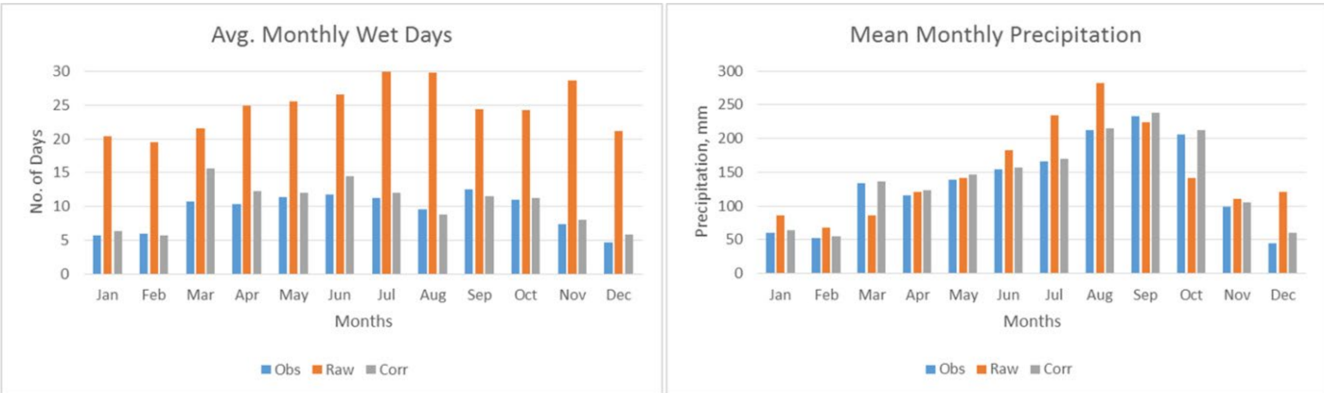

FIGURE 3. Comparison of observed and MRI-CGCM3.2 (RCP8.5) mean monthly wet days and precipitation amount from 1976–2005.

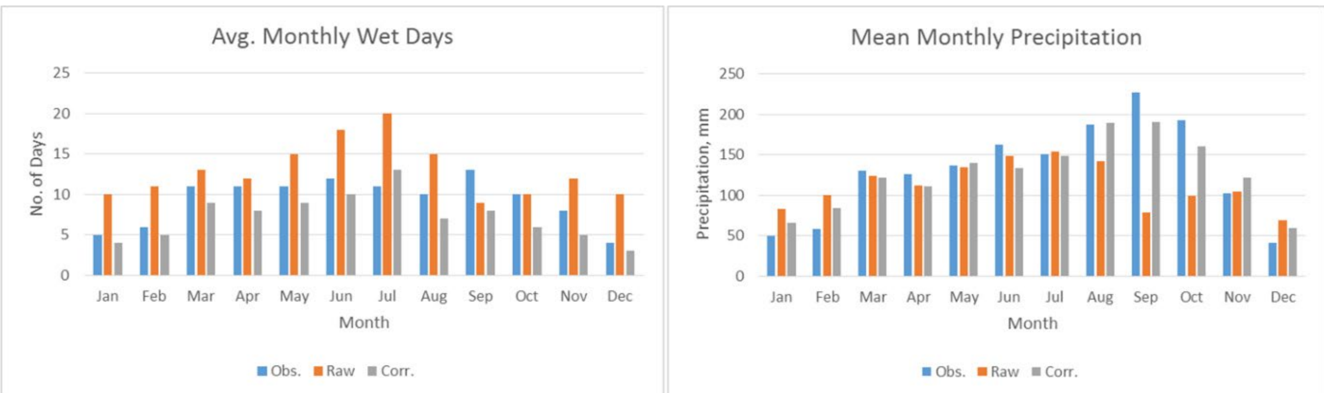

FIGURE 4. Comparison of observed and GGDL-CM3 (RCP8.5) mean monthly wet days and precipitation amount from 1976–2005.

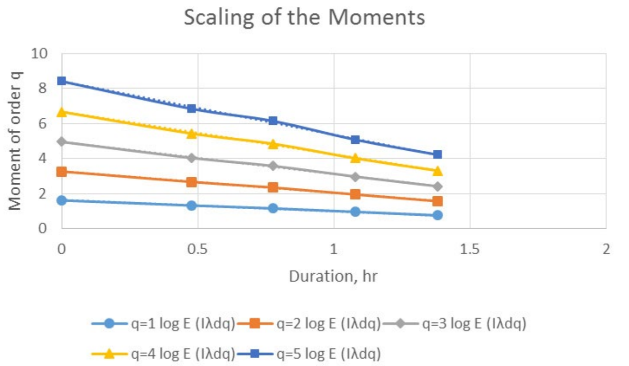

FIGURE 5. Scaling of the moments at Setagaya precipitation station.

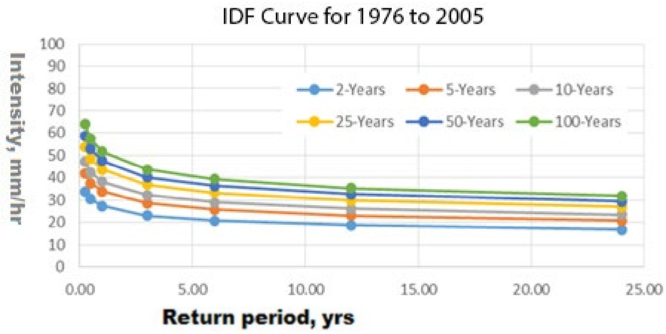

FIGURE 6. Present Climate Precipitation IDF curves for Yato Watershed using observation data.

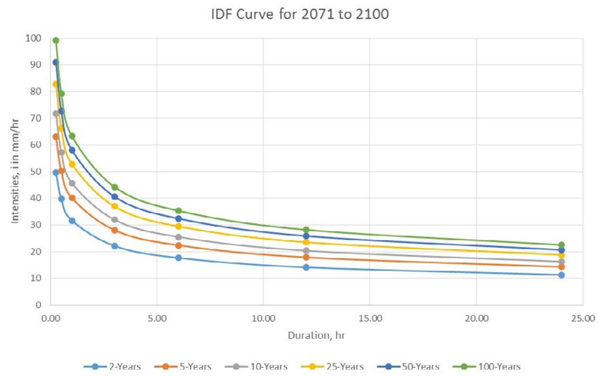

FIGURE 7. Future Climate Precipitation IDF curves for Yato Watershed using MRI-CGCM3.2.

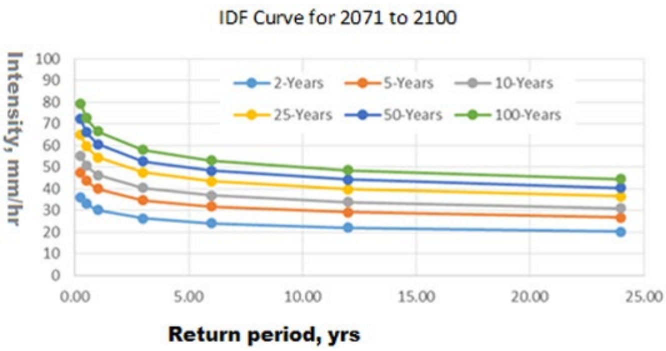

FIGURE 8. Future Climate Precipitation IDF for Yato Watershed using GFDL-CM3.

RESULTS AND DISCUSSION

Bias correction

This study utilized the quantile-quantile bias correction technique which reduces biases from the entire frequency distribution of a variable. The technique has shown to be very effective in removing biases from GCM outputs while retaining changes in precipitation frequency and variability (Mansoor, Mishra, & Herath, 2015; Mishra & Herath, 2014). In the beginning, GCM precipitation output of MRI-CGCM3.2 and GFDL-CM3, each for RCP8.5 scenario were evaluated with the observed precipitation data to obtain a better result. Two-parameter gamma distribution was used for frequency distribution analysis. Figures 3 and 4 show the comparison of monthly average wet days and precipitation amounts for the two GCMs. Biases in monthly wet days and precipitation amounts have been reduced with the use of a threshold. The observations showed that the proposed bias-correction technique could be reliably used for correcting biases in future GCM outputs with the use of present climate parameters. Such bias-corrected daily GCM precipitation data exhibit far better agreement with the observed precipitation than that of raw GCM.

Precipitation IDF curves

Precipitation Intensity Duration Frequency (IDF) curves for the Yato Watershed were produced to examine any significant deviation in extreme precipitation event pattern in the future due to climate change. Over 30 years of records (1976–2005) of precipitation data of the Yato Watershed were collected for confirming the simple scaling properties. Precipitation intensities of 1-, 3-, 6-, 12- and 24-hour durations were tested to investigate the scaling properties as sub-daily precipitation was unavailable. A log-log plot of the moments against their durations was examined for moment order q=1, 2, 3, 4 and 5. Figure 5 illustrates the qth moment of the precipitation intensities (mm/h) against different durations. With the application of the simple scale scaling model for precipitation intensities at the Setagaya precipitation station, the scale factor was estimated to be 0.6012.

Using the Gumbel distribution (Koutsoyiannis, 2004), the precipitation IDF for different duration (1-, 3-, 6-, 12- and 24-hrs) precipitation intensities and precipitation IDF curves for 2-, 5-, 10-, 25-, 50- and 100-year return periods for present (1976-2005) and future (2071-2100) climates (Figures 6–8) were estimated. From the IDF curves we can observe that, for all return periods and all durations, the precipitation intensities are significantly greater for the future climate than the present climate. The calculations revealed that there would be an average increase of 6% to 25% in extreme precipitation intensities. For smaller return periods, the increase (change) in extreme precipitation intensities was found to be smaller. Average increases of 6% and 25% were found for 2-year and 100-year return period values. These observations can have major implications for the design, operation and maintenance of stormwater infrastructures in the Yato Watershed.

Stormwater modelling

In this study, stormwater modelling was performed primarily to generate flood hydrographs with certain statistical return periods resulting from single design storm events with the same statistical return periods. The HEC-HMS tool was used to perform rainfall-runoff modelling based on a combination of the NRCS Curve Number model and the NRCS Unit Hydrograph model. The model calibration was carried out by adjusting the model parameters until simulated results matched historical

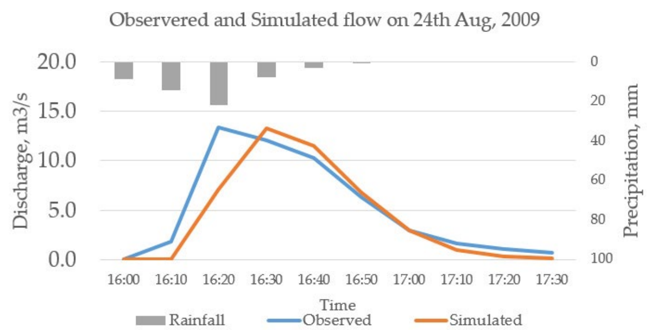

FIGURE 9. Comparison of observation and simulated discharge for model calibration.

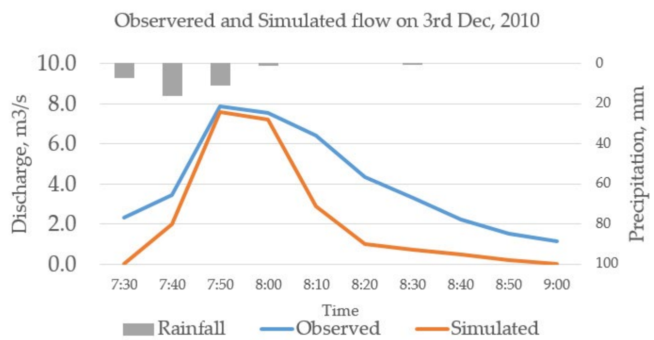

FIGURE 10. Comparison of observation and simulated discharge for model validation.

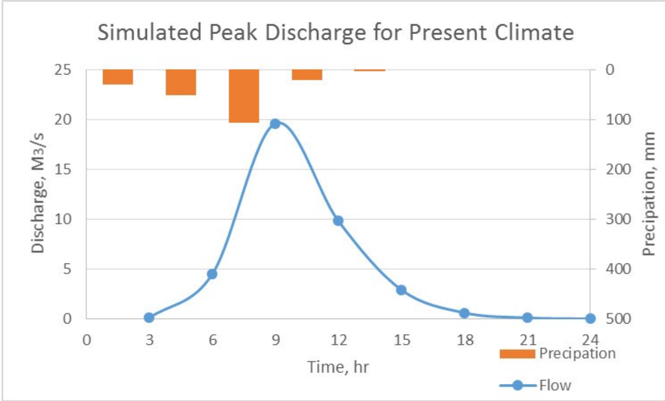

FIGURE 11. Peak discharge for present climate.

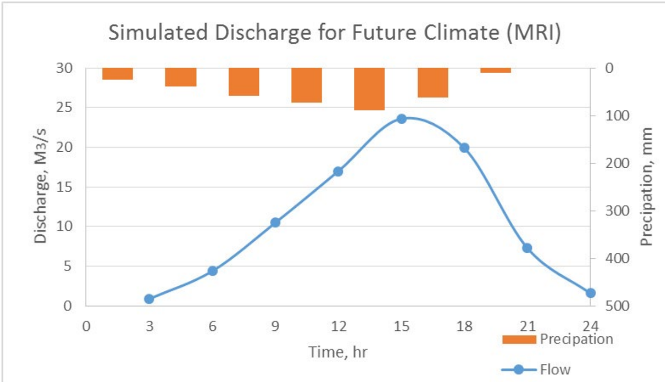

FIGURE 12. Peak discharge for future climate using MRI-CGCM3.2.

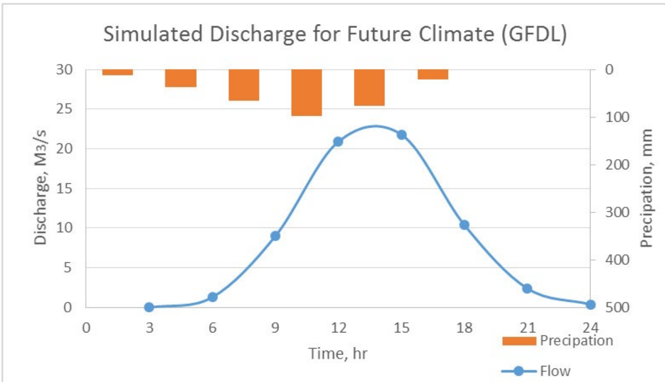

FIGURE 13. Peak discharge for future climate using GFDL-CM3.

data. The process was carried out manually by repeatedly adjusting parameters, computing and inspecting the goodness of fit between simulated and observed hydrographs. Watershed parameters were modified to produce the best fit between model and observation values. Validation results indicate that there is good agreement between the observed and simulated flows. The observed and simulated discharge hydrographs are presented in Figure 9 and Figure 10. The results show that the calibrated model is capable of capturing 24 hours of precipitation and producing satisfactory stream discharge. The NS efficiency values for calibration and validation were found to be 0.77 and 0.56. Usually, NS values greater than 0.5 are considered acceptable. Hence, the model was

Simulation	*Peak Discharge (m^3/s)*	*Precipitation Volume ($1000m^3$)*	*Loss Volume ($1000m^3$)*	*Discharged Volume ($1000m^3$)*
Present	19.6	754.2	347.6	406.6
MRI-CGCM3	23.6	1329.1	405.5	923.6
GFDL-CM3	21.8	1105.0	388.4	716.6

TABLE 1. Summary of 20-year daily maximum simulated flood for the present (1976-2005) and future (1971-2100) climate.

used to estimate discharge at Yato Watershed outlet for present and future precipitation.

Daily maximums form a 20-year return period were projected for present and future climate scenarios to understand the impacts of extreme precipitation events on flood discharge. Figs. 11-13 show flood hydrographs that the model predicted for the Yato Watershed outlet for a return period of 20 years. From Table 1, the present precipitation leads to a peak discharge of 19.6 m^3/s in the Yato River whereas MRI-CGCM3.2 and GFDL-CM3 give peak discharges of 23.6 m^3/s and 21.8 m^3/s respectively. The flood hydrographs indicated that there would be an increase of 11% to 20% in peak values at the outlet of Yato Watershed when considering climate change.

Developing alternative on-site measures

Infiltration facilities offer more benefits such as reducing surface inundation, requiring only small underground space, and improving the groundwater table in the sense of improving urban water balance. On the other hand, storage facilities are very effective in controlling river flood. Based on a previous study (Herath et al., 2012), the cost of infiltration facilities is more expensive than the cost of a storage facility at Yato Watershed under various design precipitation intensities. Further, the study shows that the total cost of the combined facilities will be more than constructing either storage facilities or infiltration facilities. Therefore, the combination of storage facilities and infiltration facilities is the best option economically. Thus, considering the flood control efficacy, economic outlay and environmentally-friendliness, a combination of infiltration and storage facilities should be considered. In developing a flood control plan to reduce flood peaks in the future, a combination of storage facilities and infiltration were taken into account. From the land-use planning perspective, Kinuta Park is in a good strategic location for building a storage facility. Volume calculations suggested that a storage facility (Location: 35° 37′ 51.5″N 139° 37′ 0.4″ E) with a maximum of 180,163.14 m^3 can be built in Kinuta Park. Table 2 gives a summary of simulations carried out with the proposed storage facility at Kinuta Park. Stormwater simulations revealed that the storage facility alone is inadequate for reducing the future peak discharge to the present level of peak discharge. Therefore, the average Curve Number (CN) of Yato Watershed has to be lowered by 1.15% to 6.65%. This translates as an expansion of the infiltration facilities in the area. The types of infiltration facilities that can be installed in the catchment depend on the land use, and residential areas, public facility areas, green areas, and roads are suitable.

CONCLUSION

The general characteristics of precipitation over the Yato Watershed, Tokyo have been studied, and a synthetic design storm pattern has been developed that accounts for climate change. Climate change considerations were reflected in the design precipitation pattern, which shows that intensity increases the most. The predicted amount of precipitation from the quantile mapping method and the number of wet days computed are notably close to the observations. Further, this method accurately captured extreme values of precipitation for all GCMs. Given there is large uncertainty in the projected precipitation intensity of these climate models, developing an ensemble model by incorporating all climate models, performing an uncertainty analysis, and creating probability-based IDF curves offers a solution to reduce this uncertainty. Comparison of IDF curves for present and future climates indicated a significant increase in maximum precipitation intensities, which has major implications for planning and design of urban stormwater drainage systems. Integration of runoff CN values offers a useful technique for identifying suitable infiltration measures (surface materials) and their locations during urban planning, in order to reduce urban floods and increase groundwater recharge. The results of this study are of significant practical importance for the design, operation, and maintenance of stormwater management infrastructures under a changing climate scenario. The results will also help local governments incorporate strategic decisions in response

Simulation	*Peak Discharge (m^3/s)*	*Precipitation Volume ($1000m^3$)*	*Loss Volume ($1000m^3$)*	*Discharged Volume ($1000m^3$)*	*Change in CN no.*
MRI-CGCM3	19.5	1329.1	832.6	496.5	1.15%
GFDL-CM3	19.6	1105.0	691.4	413.6	6.65%

TABLE 2. Summary of future stormwater simulations with proposed measures.

to climate change in a consistent framework and investigate technologies suited for water management from both short- and long-term perspectives.

Promotion of rainwater storage and infiltration facilities will contribute to a well balanced hydrological system as well as reduction in global warming impact. Countermeasures for urbanization or drainage and storage of excessive precipitation during the wet season can be introduced to cope with floods and simultaneously compensate for water scarcity during the dry season and restore the water cycle to its original state. Thus, the incremental flood and water scarcity problems brought about by climate change can be addressed.

Considering the substantial uncertainty associated with the climate change projections for different GCMs and RCPs, selection and use of GCMs and RCPs can be further explored. The key to any stormwater management practice is community acceptance, and various studies have shown that the more aware a community is of the advantages, maintenance and operation problems, the more willing they are to contribute in any form, thus it is vital to involve the community as an integral part of any new stormwater management policy. This study was initially intended as part of a broader-based socio-economic component study context, and was compiled based mainly on previous studies and reports.

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Simulating spatiotemporal changes in land-use functions in Guyuan, China, using an agent-based model dependent on multi-level stakeholder participation

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ABSTRACT

Seeking a more integrative understanding of the coupled human-environment system to tackle critical issues is currently a key concern for policymakers and the scientific community, especially in developing countries. This study developed an agent-based model (ABM) to simulate spatiotemporal changes of land use functions (LUFs) in the environmentally fragile region of Guyuan in western China to better understand local issues. We employed both the Framework of Participatory Impact Assessment (FoPIA) and a questionnaire survey to combine human factors with environmental data. We concluded that: (1) Our ABM well represented spatiotemporal LUF changes in Guyuan; and (2) Land abandonment is a critical problem in Guyuan. Thus, the promotion of land cultivation and the improvement of cultivated land-use efficiency is urgently needed. Our model has great potential for land-use policy scenario simulations and could benefit policymakers in recognizing land-use issues and recommending land management policies.

HIGHLIGHTS

- An agent-based model was developed to simulate land-use functions (LUFs).
- Multi-level stakeholders were involved in the assessment procedure and are reflected in the model.
- Agricultural land abandonment is a potentially critical land-use issue, and land reform and associative measures are urgently needed.

KEYWORDS

Agent-based modelling, China, Guyuan, Land-use functions, Stakeholders

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1. INTRODUCTION

Over the past five to six decades, ecosystems have witnessed rapid and extensive changes having been impacted by the rapidly growing demand for food, health and natural resources (Millennium Ecosystem Assessment, 2005; Kappas, Groß, & Kelleher, 2010). By 2011, such pressure caused a 61% increase in global land degradation, threatening sustainable land management at local, regional and global scales (Liniger, Mekdaschi, Moll, & Zander, 2017; Orr et al., 2017; FAO, 2011). The Sustainable Development Goals (SDGs) initiative published by the United Nations (UN) in 2016 highlights in seven of its 17 goals the importance of sustainable land use (United Nations, 2017). Seeking a more integrative understanding of coupled human-environment systems and cooperation between the scientific and decision-making communities to tackle critical problems associated with such systems is currently a key issue for policy and scientific communities, especially in developing countries.

Land-use functions (LUFs) refer to the goods and services provided by different land uses, and they summarize the most regionally relevant economic, environmental and societal issues (Pérez-Soba et al., 2008; Zhen et al., 2009). The LUF framework was originally developed to stress the need to evaluate land-use change impacts on regional sustainability in a manner that reflects economic, social and environmental dimensions (Pérez-Soba et al., 2008). It has been widely used to assess regional sustainable development under both a developed and developing context around the world (Wiggering, Müller, Werner, & Helming, 2003; König, 2013). For instance, König et al. (2010) conducted a policy-focused sustainability impact assessment induced by land-use changes in Yogyakarta City, Indonesia, by developing a set of nine key LUFs and associated indicators, including three social, three economic and three environmental sustainability criteria (König et al., 2010). Xie et al. (2010) identified 16 sub-functions within economic, social and environmental dimensions to assess the multifunctionalities of land use, and they found that land conversion policies significantly affect land-use patterns in China, reflected in a decrease in arable land, grassland and built-up areas and an increase in forestland area. The concept nowadays has been extended to support solution-oriented research and encourage policy development (Peng, Liu, Liu, Hu, & Wang, 2015; Wei, 2010).

However, regional policymakers often lack access to theoretical or rational impact assessment results that land-use policies have on local development, and this appears to be more critical in remote agricultural areas. Guyuan, in the Ningxia Hui Autonomous Region, China, is a remote and less-developed region comprised of complex landforms and fragile soil conditions. The Government of China has established a nationwide sloping land conversion program in this region since 2000, which has effectively helped to conserve local soil erosion, but it appears to have potentially caused agricultural land abandonment and food safety problems (Xue & Zhen, 2018). Land-use scenario assessments are needed for local policymakers to promote and adjust local land management methods and pursue land sustainability measures. Furthermore, regional sustainable land-use assessments have mainly focused on non-objective regional evaluations, but research on spatial visualization assessment results is limited. However, the visualization of regional sustainable statuses can help policymakers to obtain a more specific and direct understanding while being beneficial in recognizing land-use problems in which to take appropriate land management measures.

Land change modelling is used to explain and forecast both land and landscape conditions, providing spatial results of land-use changes. Such models play a key role in decision and policymaking on many different scales. Various models have been developed and can be grouped into six key categories (National Research Council, 2014), including machine learning and the statistical approach, the cellular approach, the sector-based economic approach, the spatial economic disaggregation approach, the agent-based approach, and hybrid approaches. Agent-based models (ABM) are useful in intervention design because they provide a means to explore interactions in land systems and can be used to assess possible policy effects or decisions *ex ante* (Valbuena, Verburg, Veldkamp, Bregt, & Ligtenberg, 2010; Bai, Yan, Pan, & Huang, 2015).

This study was conducted in Guyuan, an environmentally fragile region in western China that currently suffers from agricultural land abandonment issues. The Framework of Participatory Impact Assessment (FoPIA) and a questionnaire survey were used in this study to combine multi-level stakeholders into an assessment procession and develop an ABM to simulate spatiotemporal changes of LUFs in Guyuan, while also helping local policymakers in addressing land management challenges in the regional land system. Our research

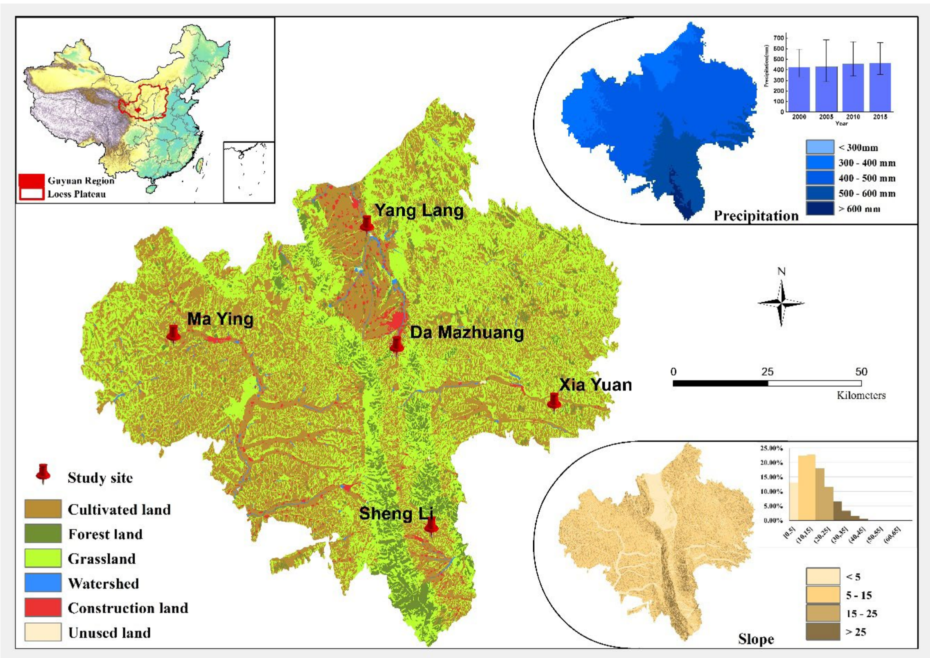

FIGURE 1. Location of Guyuan and its precipitation and slope conditions.

objectives were to:

1. Determine how to build an ABM to simulate land-use function changes in Guyuan; and
2. Reveal spatiotemporal changes in LUFs in Guyuan.

2. MATERIALS AND METHODS

2.1 Study Area

Guyuan, located in the hilly and gully region of the Loess Plateau, is an environmentally fragile and economically underdeveloped area (Figure 1). It has a semi-arid continental monsoon climate. Annual precipitation is limited and highly variable both spatially and temporally. Based on meteorological, land cover and land change data, mean annual rainfall ranged from 431.4 ± 197.9 mm in 2005 to 463.9 ± 150.8 mm in 2015 (Guyuan Bureau of Statistics, 2016a), which is insufficient to support rainfed farming. The main land-use types are cultivated land (44.7% of the total land-use area) and grassland (44.9% of the total land-use area). Approximately 41.6% of the total area has a slope greater than 15°, and 12.1% has a slope greater than 25°, which makes cultivation difficult and makes the fine-grained loess soil in the region highly vulnerable to erosion.

The major crops are winter wheat that are planted in rotation with summer maize and potatoes, which account for 48.0% of the total cultivated area. The agricultural population is 1.11 million, and these workers account for 74.4% of the total population. However, the disposable income of rural households is 7002.1 CNY, which was lower than the provincial average of 9119.0 CNY and the national average of 11 422.0 CNY in 2015 (Guyuan Bureau of Statistics, 2016b). The approximate conversion rate to USD in 2015 was approximately 6.4 CNY per USD (Xue & Zhen, 2018).

2.2 Description of Methodology Used

This study first employed the FoPIA to involve local government officers and experts. Through a series of workshops, we came to recognize LUFs and indicators in Guyuan City, identified relationships between LUFs and land-use types and assessed changes in LUFs over a period of 10 years under a scenario of a typical degree of development. Following this, we enlisted local farmers for our questionnaire survey to obtain the willingness and the drivers of the farmers' land-use strategy. Based on the data derived from the questionnaire, we defined agent behaviour, and based on the LUF data obtained from the FoPIA, we initiated the contextual design of the ABM. Finally, we established the LUF change simulation model for Guyuan in combination with multi-level

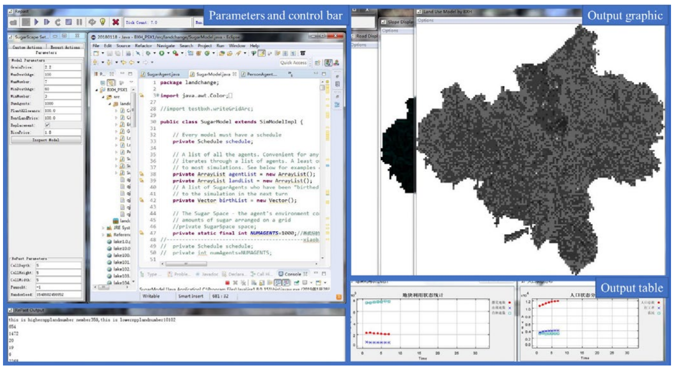

FIGURE 2. The interface of the compiled environment.

stakeholder data into the assessment procession, and based on this assessment data developed an ABM to simulate spatiotemporal LUF changes in Guyuan.

2.2.1 FoPIA for LUFs Assessment

The FoPIA was designed and adjusted based on Morris' research (Morris et al., 2011). It was conducted in three phases: (1) Preparation phase, (2) Participatory evaluation, and (3) Analysis of the results. In the first phase, we initiated the preparation workshop with transdisciplinary experts in September 2015, enlisting 10 policymakers (Wang & Zhen, 2017), and we communicated regional land-use problems, associative driving factors as well as land management and policy issues. The drafting of local LUFs and associated assessment indicators was prepared during the next phase. In the participatory evaluation phase, the second workshop was held in May 2017, enlisting 5 policymakers and 5 researchers. Data derived from this workshop comprised of 4 separate parts, namely, defining and weighing the LUFs and associative indicators (with scores from 0 to 5 representing no importance to extremely important), determining future scenario assessments (with impact scores from -3 to 3 representing the most negative impacts to most positive impacts), recognizing relationships between LUFs and land-use types (with a contribution rate from 0 to 100) and discussing land-use strategies. In the final analysis of the results phase, the result was discussed and shared with local experts and researchers and a subsequently constructive recommendation was provided. Detailed processes related to FoPIA can be found in the Supplementary Material and a study by Xue and Zhen (Xue & Zhen, 2018).

2.2.2 Questionnaire to Determine Agent Behaviour

The household questionnaire was designed in three parts: The first part was concerned with basic family data including gender, age as well as the primary occupation and level of education of household members. The second part was concerned with their attitude to land-use issues, namely, whether they had abandoned agricultural land and the reason that they did so (if applicable). The last part was concerned with the status of land abandonment and the experience with land management measures, such as rural land transfer programs, which have been recommended in FoPIA by experts. Sample households were randomly chosen in each village, and the final sample size (i.e., the number of households) was based on suggestions from village managers to ensure reliability and representativeness. Between May 2 and 9, 2017, we conducted the questionnaire survey in each village through a face to face interview, and 202 valid questionnaires were collected in total.

2.2.3 Agent-based Model for Spatiotemporal LUF Changes

The model was based on Bai's model (Bai et al., 2015), designed to simulate farmland changes. Our model is composed of four sub-models using four types of agents. The sub-models include an individual status transfer sub-model, a household classification sub-model, a spatial environment distribution sub-model and a household farmland land-use decision sub-model. Agents include individual agent, household agent, household group agent and the government agent. Figure 2 shows the interface of the ABM, developed using the Java language and the RePast simulation platform.

In this model, individual agents represent local residents, with basic characteristics including age and occupation. During model runtime, the individual status transfer sub-model was used to change each individual agent, and the structure of household agents, which consists of individuals, will also change. In the household classification sub-model, households are classified into subsidy-dependent, pure-farming, part-farming, non-farming and pure-outworking groups. Each group has different land-use strategies. Both characteristics and strategies were obtained from the questionnaire. The spatial environment distribution sub-model was designed to describe farmland quality and land abandonment or the transfer of land-use right, which rely on farmland quality. The household farmland land-use decision sub-model is the last sub-model to reflect the final condition of the land-use status and the coordinate distribution of LUFs.

We attempted to conduct the LUF simulations under the context of typical development practices, and we hypothesized that land-use efficiency and the abandonment of agricultural land would continue to follow current trends into the future. The spatial data resolution of the model was 1 km^2. The meteorological data as well as land-cover and land-change data were provided by the Data Center for Resources and Environmental Sciences, Chinese Academy of Sciences (http://www.resdc.cn/). The simulation years investigated were from 2015 to 2025.

Dimensions		*Land Use Functions (LUFs)*	*Weights*
Economic	ECO1	Residential or non-land-based activities	3.50
	ECO2	Infrastructure	3.67
	ECO3	Land-based production	4.33
Social	SOC1	Provision of work	2.50
	SOC2	Quality of life	3.17
	SOC3	Food security	4.50
Environmental	ENV1	Provision of abiotic resources	4.17
	ENV2	Provision of biotic resources	4.00
	ENV3	Maintenance of ecosystem processes	3.83

TABLE 1. Land-use functions and indicators in Guyuan City. Source: Framework for Participatory Impact Assessment (FoPIA) workshop, 2017.

3. RESULTS AND DISCUSSION

3.1 LUFs Weights

LUFs were defined and separated into three different dimensions, including the economic dimension, the social dimension and the environmental dimension, comprising of three LUFs and indicators in each dimension (Table 1). Detailed information on each LUF and indicator can be found in Supplementary Materials. The weights of LUFs, which reflect food security (SOC3; 4.50) and land-based production (ECO3; 4.33), remain the most fundamental issues for Guyuan, and farmers in this region are beginning to recognize the importance of the ecological environment. The high weights of ENV1 (the abiotic resource provision; 4.17) and ENV2 (the biotic resource provision; 4.00) reflect the effectiveness of the promotion and protection initiatives that have been conducted in the past several years (Xue & Zhen, 2018).

3.1 Matrix of LUFs and Land-use Types

The results from the contribution matrix (Figure 3) show that cultivated land in Guyuan has the greatest contribution to food security (87.86; the contribution table can be found in the Supplementary Material), land-based production (84.71) and provision of work (65.71) functions. Forests were predominately good in LUFs in the environmental dimension, including the provision of abiotic resources (77.86), the provision of biotic resources and the maintenance of ecosystem processes (81.43), and they also have an outstanding influence on the quality of life function (69.29). In addition, construction land has a significant and uniquely important

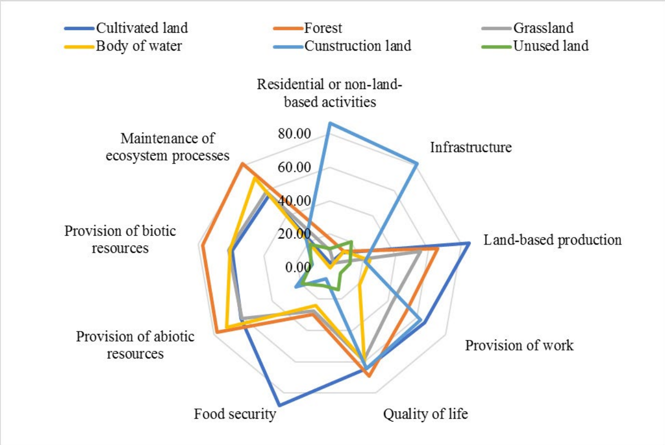

FIGURE 3. The matrix of LUFs and land-use types.

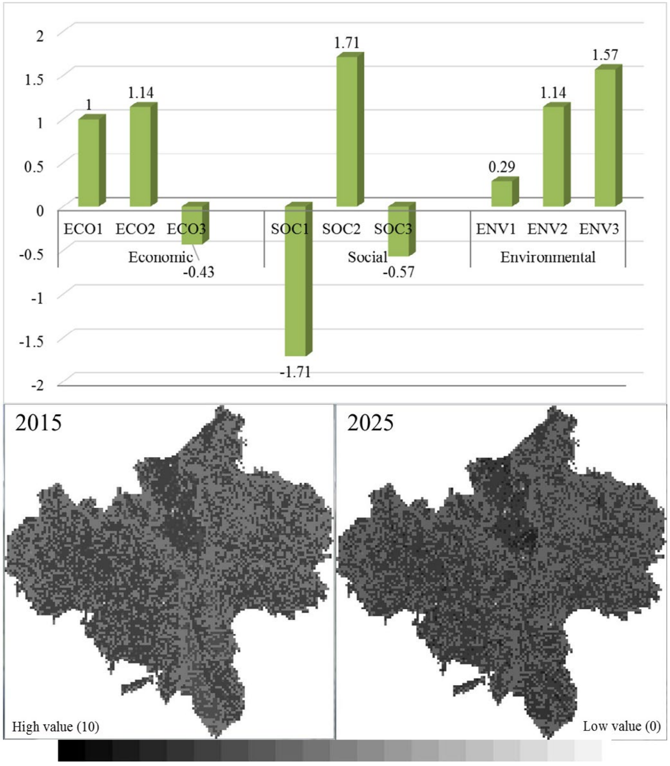

FIGURE 4. LUF assessment results over 10 years in Guyuan.

contribution to local residential or non-land-based activities and infrastructure (86.43), which benefits from its manufacturing features. Unused land offers little contribution to all LUFs, with an average contribution rate of 13.95.

3.2 Assessment Results of LUF Changes Over 10 Years

In summary, LUFs will have a slight improvement in 2025 according to the LUFs map in Figure 4. The most significant improvement will be in central Guyuan, where the primary land-use type is construction land. One reason for this is the expansion of the construction area and its contribution to the local economy. Another reason is that with urban and factory development, more work will be available for young people, which also plays a key role in social LUFs (SOC2: 1.71) according to FoPIA experts. Another important improvement is in the south section of the city, where the primary land-use type is forest. Since 2000, the sloping land conversion program (SLCP) has increased regional forest cover from 35% to 73% and has increased regional grassland cover from 12.8% to 22.2%, for a total increase of 3.11 × 10^5 ha throughout the whole Guyuan City. Trees and grass planted throughout the duration of this program will gradually mature and enhance the provision of biotic resources and the maintenance of ecosystem processes of LUFs [62]; thus, these enhancements will obviously improve the LUFs in the south section of the city.

In the northeast and western sections of the city, where the primary land-use type is cultivated land, areas with low LUF values even expended. The reason for this is that if Guyuan develops as expected, the low benefits and high costs for farmers on poor-quality land will strongly motivate less agricultural work, and some households will effectively choose to abandon their land. With less stress on agricultural work and an increase in land abandonment, the importance of the provision of the work function would weaken (SOC1; -1.71) and food security (SOC3; -0.57) would subsequently be threatened. Moreover, the ability of abandoned agricultural land to provide land-based production will also suffer (ECO3; -0.43). However, land abandonment will also permit natural ecosystem recovery, which will promote the maintenance of LUF ecosystem processes (Sulieman, 2013; Zhang, Liu, Xue, & Wang, 2015) in combination with the SCLP (ENV3; 1.57).

3.3 Challenges for Stakeholder Involvement in Model Design

The model designed for this study is a type of artificial-social model, which was constructed based on mechanisms and running rules in accordance with local facts. Individual agent in this model is the basic unit to reflect the interaction with farmland through agent behaviours; thus, empirical characterizations and parameterizations are necessary. However, it is a major challenge to refine and assess differential behaviour through empirical observation (Filatova, Verburg, Parker, & Stannard, 2013). Some studies only used census data to simplify their models (Gaube & Remesch, 2013); however, the practical and social meaning of such models are lost in terms of behavioural description. In our model, we combined the FoPIA and a questionnaire to obtain both microscopical contextual data from experts and government officer workshops and microscopic empirical characterization data from individuals during face to face interviews. Although this model cannot effectively simulate all factors related to the human-environmental system, being concerned with key land-use behaviour and issues, rules of agents and mechanisms that impact agents under different land-use decisions provide significant practical data. Therefore, our model can support policymaking processes in complex social-ecological systems.

4. CONCLUSIONS

First, food security and land-based production are the most fundamental issues for Guyuan, and local farmers are beginning to recognize the importance of the surrounding environment. Cultivated land dominates LUFs in the social dimension, and forests contributed most to LUFs in the environmental dimension. Second, we built an agent-based model for LUFs based on multi-level stakeholder methods. Simulations from this model showed a remarkable change in central Guyuan owing to the expansion of the construction area and its contribution to local economic and work provisions. On the other hand, cultivated land area, primarily in the east and west of Guyuan, showed an overall decrease owing to the trend in agricultural land abandonment. Third, our model can directly reveal potential land-use issues, which helps policymakers to design land management measures for regions that have unique and complex land-use conditions.

In Guyuan, land abandonment is a serious issue. Therefore, promoting the attraction to cultivate land is urgently needed in this region to improve cultivated land-use efficiency. Considering the positive effects that SLCP has had on Guyuan City, it would be feasible to promote this program into border areas, and the development of a forest economy is also an alternative choice for efficient rural land-use practices.

Results from this study have certain limitations. On the one hand, given that the simulation resolution of this model is 1 km^2, small plots in Guyuan were not considered. On the other hand, located in a hilly and gully loess region, land-use plots, particularly cultivated plots, are historically small and discrete in this region. During the next phase of development, we intend to employ a higher spatial resolution in our model to further observe and analyze regional land-use issues and potential land management methods. ABMs on a village scale or at a level that can distinguish between land forms should be constructed to make good use of empirical stakeholder data and obtain more targeted policy recommendations.

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SUPPLEMENTARY MATERIAL

The supplementary material is available on the web version of this article (https://doi.org/10.30852/sb.2019.705).

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Appraising slow onset hazards for loss and damage: Case studies in Southeast Asia

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ABSTRACT

Slow onset processes were investigated in five pilot areas in Southeast Asia, i.e., Kampong Speu Province (Cambodia), Selangor State (Malaysia), Thatdama Kyun Village (Myanmar), Kanan Watershed (Philippines), and Quang Ngai Province (Vietnam). Pilot areas with low-lying coasts are exposed to floods, saline intrusion and sea-level rise while some are also affected by storms and typhoons. Floodplains are exposed to floods and river bank erosion while highlands are affected by flash floods, mudslides, landslides and forest degradation. Dry conditions and high temperatures are not confined to a specific geomorphological setting. The assessment of L+D is a challenge as many impacts are not directly attributed to anthropogenic climate change. However, where science has clearly linked global warming and sea-level rise to anthropogenic causes, and human influence in a particular area is minimal, L+D assessments are relevant to policy platforms such as the United Nations Framework Convention on Climate Change (UNFCCC). The land use planning system is a potential entry point for integrating DRR, CCA and L+D.

KEYWORDS

Climate change adaptation, Climate hazards, Disaster risk reduction, Loss and damage, Slow onset hazards, Southeast Asia

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HIGHLIGHTS

- Characteristics and issues on slow onset processes are context and area specific.
- Site features, capacity, resources and technology influence limits to adaptation.
- Detection and attribution to climate change is a major challenge for assessing L+D.
- The land use planning system facilitates integration of DRR, CCA and L+D.
- Integration is easier at the local level compared to a country-wide basis.

INTRODUCTION

The world is already seeing the consequences of 1°C of global warming through more extreme weather, rising sea-level and diminishing Arctic sea ice, among other changes (IPCC, 2018). A changing climate leads to changes in the frequency, intensity, spatial extent, duration and timing of extreme weather and climate events (IPCC, 2014). Extreme events may also trigger associated or cascading hazards depending on its nature, intensity, extent and locality. All types of fast and slow onset hazards are expected to increase as the climate changes. Ten key risks associated with fast and slow onset hazards have been identified for Asia, where a majority of these have direct impact on society in terms of health, well-being and safety (Hijioka et al., 2014). If global warming exceeds 1.5°C, tropical Southeast Asia is projected to experience a range of fast and slow onset hazards that will impact economic growth (IPCC, 2018).

Scientifically robust research is increasingly critical to document and report on loss and damage (L+D) due to climate impacts, particularly for Southeast Asia. It is also relevant to the Katowice Climate Package adopted in COP 24 in December 2018 (the Rule Book for the Paris Agreement), which gives prominence to L+D in the upcoming global stock take.

Risk can be perceived as resulting from the interaction of climate hazards with vulnerability and exposure determined by socio-economic factors (IPCC, 2014). This understanding of risk facilitates the notion that the impacts of climate variability and change can be prevented; as they occur only in the intersection of hazard, vulnerability and exposure. The concept is important as it encourages focus on vulnerable groups and serves to drive adaptation efforts, particularly within national processes (van Aalst et al., 2018). It also promotes understanding that vulnerability and exposure cannot be totally removed, hence enabling the discourse on residual risks. However, there are limitations associated with this risk framework. The dynamic nature of risk, particularly the way it changes over time is not captured well. Furthermore, aspects related to capacity and underlying reasons for the inability of vulnerable groups to reduce climate-related risks or cope with impacts is not recognized.

The research project on "Integrating Climate Change Adaptation, Disaster Risk Reduction and Loss and Damage to Address Emerging Challenges due to Slow Onset Processes" brought together distinct groups of biophysical and socio-economic scientists. Key objectives included identification of characteristics, priorities and emerging issues related to slow onset processes in low-lying coastal areas, floodplains and highlands that impact the livelihood and well-being of the communities therein and assessment of the limits to adaptation based on "best available science", as well as approaches that integrate climate change adaptation (CCA) and disaster risk reduction (DRR). Other objectives include the development of methodologies to evaluate L+D associated with adverse and cascading impacts of climate change drawing on lessons from disaster risk management, and discerning natural and anthropogenic causes of climate change. Ultimately, policy and planning strategies are recommended to integrate CCA, DRR and L+D in development plans in line with existing governance systems (APN, 2019).

In order to fulfill the project objectives, local level pilots were conducted in five countries in Southeast Asia (Cambodia, Malaysia, Myanmar, Philippines and Viet Nam) by teams of researchers from multidisciplinary backgrounds, working closely with their respective policy and decision-makers and local communities. Researchers from Japan were also involved to facilitate transfer of knowledge and build capacity. Given the broad objectives of the project, this paper briefly describes the various slow onset processes and their features, which have been identified in each of the pilot areas. The challenge of managing hazards associated with these processes within each pilot is also highlighted. This is followed by a discussion on the limitation of the approach used in this project for loss and damage assessments, with respect to its relevance to ongoing discussions in policy platforms, specifically the United Nations Framework Convention on Climate Change (UNFCCC).

METHODOLOGY

Local level pilots were implemented in five countries, i.e., Kampong Speu Province (Cambodia), Selangor State (Malaysia), Thatdama Kyun Village (Myanmar), Kanan Watershed (Philippines) and Quang Ngai Province (Viet Nam). The assessment was conducted using the best available science from atmospheric, geological, chemical and social sciences, among others. Participatory appraisals were used to identify and rank local level hazards and processes. Questionnaire surveys and interviews were also carried out to supplement information related to L+D. Dialogues between researchers and policymakers of multi-disciplinary backgrounds were conducted on a periodic basis, to delineate effective options to integrate DRR and CCA in development plans. The risk framing approach was confined to specific geographic settings in this project. The spatial context was taken into account when demarcating zones with existing and future susceptibility to hazards, which was useful to delineate exposed elements and vulnerable communities. This area-based risk framing was used to investigate a range of fast and slow onset hazards in each pilot. This enabled risk to be perceived as a continuum, where DRR measures target short-term risks and CCA addresses long-term threats. This is also in line with the key message of IPCC (2014), which states that "the first step towards adaptation to future climate change is reducing vulnerability and exposure to present climate variability and associated extremes".

RESULTS AND DISCUSSION

Among the projected impacts for Southeast Asia under global warming of 1.5°C include increases in the number of extreme hot days and heavy rains, which contribute to higher risks of floods, flash-floods and landslides as well as net reductions in yields and nutritional value of rice (IPCC, 2018). In addition, an increase is expected in populations that are both exposed and susceptible to

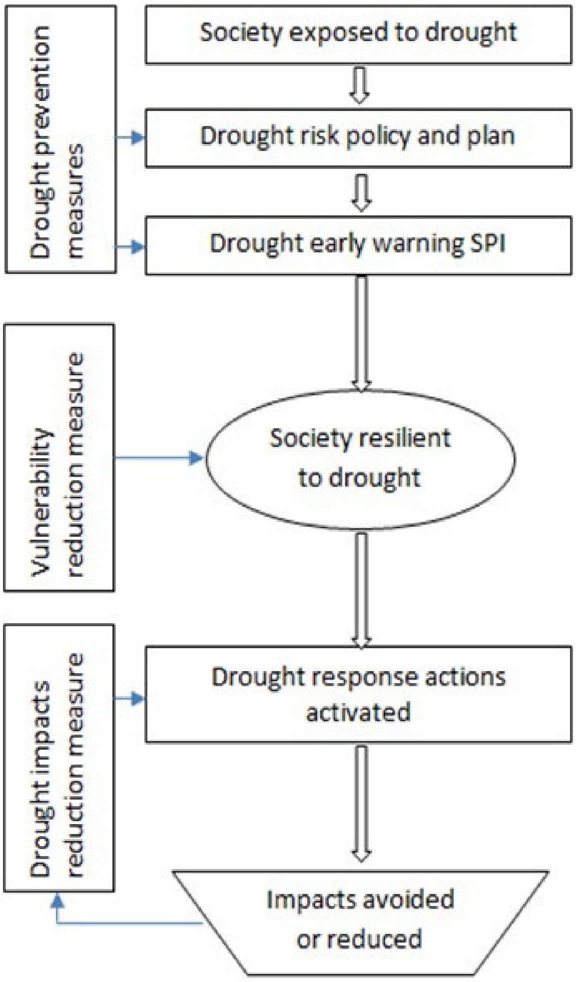

FIGURE 1. The drought risk management framework proposed for Cambodia mainstreams the involvement of exposed communities (Chhinh et al., 2019).

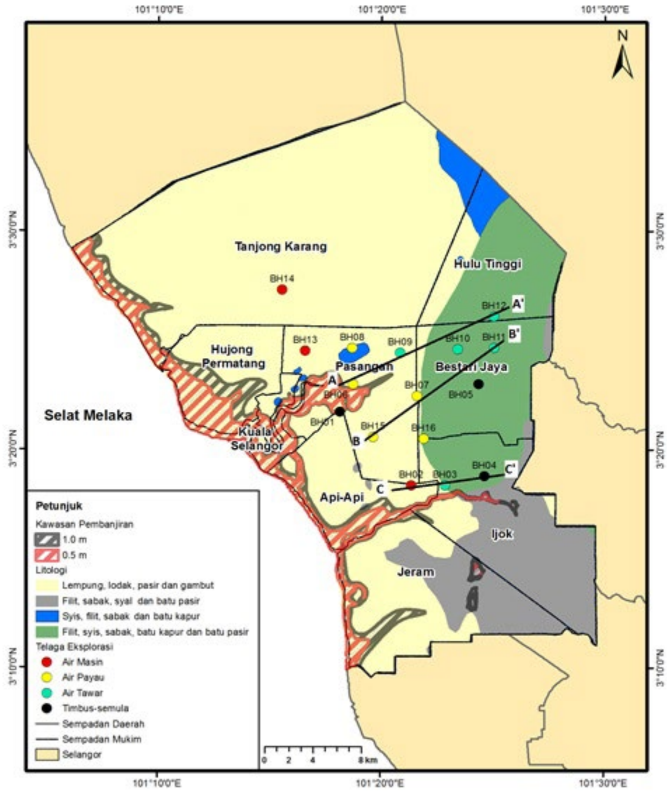

FIGURE 2. Coastal inundation susceptibility maps for two conditions, sea-level rise of 0.5 m (hatched in red) and 1.0 m (hatched in black), were used in conjunction with subsurface information from boreholes (colour coded circles) to determine the current quality of groundwater and its projected impacts (Umi et al., 2018).

poverty, particularly those dependent on agriculture and coastal livelihood. As the sea level rises, low-lying coasts in Southeast Asia are expected to be affected, bringing new issues on environment and socio-economic aspects to the region, including those related to migration and security. Decision-makers have to be made aware of impending threats albeit with appropriate information on uncertainty (Doyle, Johnston, Smith, & Paton, 2019).

Slow Onset Processes in the Pilot Areas

The Kampong Speu Province in Cambodia is located primarily within the catchment of the Prek Thnot River, with forests in the eastern highlands and agriculture in the western lowlands. Hazards common in the area are floods, drought and heatwaves. The slow onset characteristics of drought makes it difficult to detect as an emerging threat (Chhinh & Millington, 2015). Drought requires effective water management within the affected community, who would be the first to experience the hazard. The response of the authorities at the national and local levels to drought has been relatively slow compared to the actions taken to address floods. This indicates that it is important to build the capacity of the local community so that they can respond effectively while waiting for external support (Figure 1). Rainfall monitoring and forecasting, as well as effective irrigation systems, are major challenges for this agrarian community (Chhinh, 2014). This is compounded by disconnects between planning at the national and local levels, weak institutional arrangements and capacity, as well as poor engagement of all stakeholders, particularly the local community.

The Selangor State in Malaysia comprises a western coastal region that gets progressively more rugged to the east, where the highlands straddle part of the Titiwangsa Range. Kuala Selangor, the area that was studied in detail, is located in the coastal lowlands and is exposed to hazards such as coastal inundation, floods and saline intrusion due to sea-level rise (Umi, Yaakub, Suratman, & Pereira, 2016). Agriculture areas in Kuala Selangor are susceptible to impacts of coastal inundation and saline intrusion, giving rise to future implications on food security as this is an important rice-production area (Figure 2). Saline intrusion is expected to affect sub-surface aquifers. Groundwater is affected in

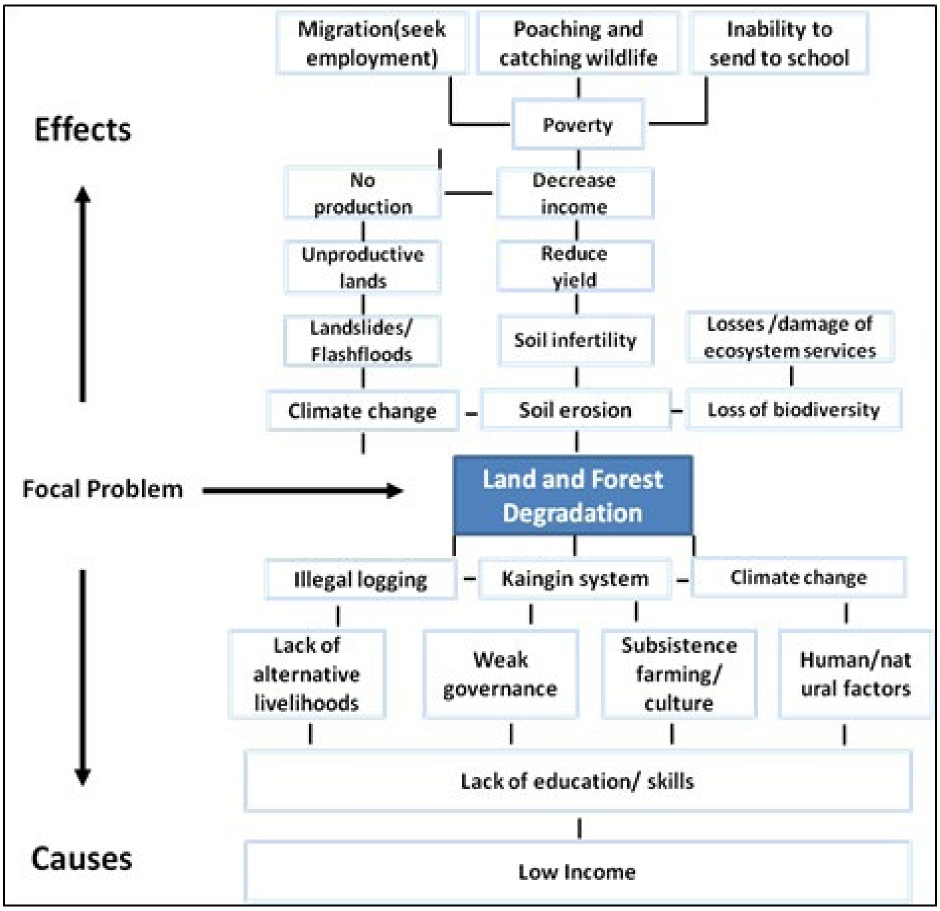

FIGURE 3. Local level focus group discussion resulted in the cause and effect diagram of land and forest degradation in the Kanan Watershed, General Nakar, Phillippines (Pulhin et al., 2019).

terms of both quality and quantity of reducing reserves for industrial, agricultural and domestic use (Umi, Lim, & Pereira, 2018). An emerging hazard that has been detected in the Selangor State is the cascading effects of landfills and open dumps that are exposed to floods and landslides (Yahaya, Lim, Taha, & Pereira, 2016). The rapid expansion of urban areas has brought residential zones closer to landfills and abandoned open dumps. Future disaster events may expose such population and make them vulnerable to emerging hazards. Preliminary assessment conducted on landfills and open dumps in Selangor reveals that six out of 20 landfill sites in the state are highly exposed to the 100-year flood, while two sites are exposed to slope failure (including mass waste movement). The exposed sites are currently without any protection measures making populated areas in the vicinity vulnerable to hazards and their cascading impacts. An integrated framework has been recommended in Kuala Selangor, building on existing policies such as the Integrated Coastal Zone Management (ICZM) and Environmental Impact Assessment (EIA). The integrated framework incorporates comprehensive and iterative adaptation, taking into account the natural state, projected conditions, potential impacts both at the surface and subsurface, deployment of science, technology and innovation, economic cost benefit analysis to identify suitable adaption options as well as continuous monitoring and evaluation, in conjunction with the local community, among others (Umi, Lim, & Pereira, 2018).

The Thatdama Kyun Village in Myanmar is a landmass with changing morphology at the confluence of the Ayeyarwady and Pathein Rivers. The area is exposed to hazards such as flooding, river bank erosion, extreme temperature and irregular rainfall (SEEDS, 2019). The island setting of the village makes it prone to flooding and river bank erosion, which has damaged agriculture land, depleted livestock, reduced household income, affected food security, displaced village population and caused other social impacts. Heatwaves and an increasing number of hot days have caused health problems to the villagers. Vector and water borne diseases, as well as scarcity of drinking water, are also health issues of concern. While households receive weather-related information such as river level, wind speed and flood warnings from television and radio, the lack of electricity is a barrier to receive timely information on disasters. The lack of awareness has made it difficult for villagers to deal with the changes in climate and increased frequency of disasters. This is compounded by inherent vulnerability due to poor nutrition, health services and access to education. Enhanced capacity and technical information, as well as strengthened institutional frameworks, are critical to enable these villagers to manage the impacts of climate change (MoNRE, 2017).

The Kanan Watershed in the Philippines is a forestland drained by the Agos River with some 35 tributaries, stretching from the Sierra Madre Mountain to the Pacific Ocean. The area is exposed to flash floods, mudslides and landslides exacerbated by strong typhoons (Gaillard, Liamzon & Villanueva, 2007). Flood waters that contaminate the local supply of drinking water resulting in increased cases of waterborne-diseases. Intense rainfall contributes to river siltation while increased temperatures dry up irrigation channels and other sources of water. Households in this area are vulnerable to land and forest degradation associated with climate change (Figure 3). Proactive interventions to raise awareness on the importance of the watershed and improvement of farming systems are important. Land and forest degradation has created cascading effects on infrastructure, agriculture, forestry and coastal sectors, among others (Social Action Center, 2014). This includes reduction in crop harvest by 30%, reduced fish catch from rivers, loss of soil fertility due to soil erosion leading to low crop yields, damaged river canals and planted crops, decrease in water flow due to a month-long intense heat and loss of livelihood sources. Such events have contributed to economic and non-economic L+D in the area. Government and civil society organizations are providing assistance and support to communities in adapting to climate change and managing disasters (Local Government of General Nakar, DENR Region IV-A, & the Haribon Foundation, no date). However, transformational adaptation (Warner et al., 2019) that addresses socio-economic and governance barriers are needed for present and future adaptation to be more effective.

The Quang Ngai Province in Viet Nam is a coastal province with diverse terrain with multiple fast and slow onset hazards. These include typhoons, tropical depressions, floods, flash floods, landslides, monsoons, thunderstorms, tornados, lightning, droughts, forest fires, saltwater intrusion and sea-level rise (Huynh, 2015). The management of drought is challenging and requires improvements in early warning and irrigation systems. Prolonged drought, in combination with high temperatures, creates a high risk of forest fires that destroy the environment on a large scale and seriously affects the microclimate (IMHEN & UNDP, 2015). Sea-level rise and saltwater intrusion, which are typical slow onset processes, have been classified as low risk in the Province. The Ly Son Island is particularly sensitive to disasters and is most vulnerable to climate change (MoNRE, 2012). A vulnerability index developed at the national level based on parameters such as exposures, sensitivity and adaptive capacity was used to rank each district in Quang Ngai Province. This is to enable comparison between districts so that appropriate measures can be identified to build resilience to disasters and climate change. The priority for Quang Ngai Province is to increase resilience of the natural environment (Huynh, 2015). Loss and damage due to natural disasters is high in the Province.

Challenges for Loss and Damage Assessment

There are many approaches to assess L+D. These include accounting for economic and non-economic losses, and use of social media and crowdsourcing as well as and pre-defined economic costs to reduce assessment time during a disaster (Eckhardt, Leiras, & Thome, 2019). However, the assessment of L+D for slow-onset hazards remains a challenge. When deployed at the local level, the area-based risk framing approach does not differentiate impacts caused by natural or human induced climate change. In the UNFCCC platform, climate change is defined as change attributed to anthropogenic causes. This makes L+D evaluation challenging in the pilot areas, where there is a paucity of data linking impacts to human-induced climate change. However, science has clearly linked global warming and sea-level rise to anthropogenic causes (IPCC (2014)). Drawing on this relationship, could heatwaves in Kampong Speu Province (Cambodia), Thatdama Kyun Village (Myanmar) and Quang Ngai Province (Viet Nam) be attributed to climate change? Forest fires in both these areas could not be directly attributed to climate change as the study could not differentiate human contribution from natural alteration. Similarly, could the expected impacts of global sea-level rise in Kuala Selangor (Malaysia), which includes coastal inundation and saline intrusion in a region with minimal groundwater extraction, be attributed to climate change? Where direct linkage has been proven in global conditions, as in the case of heatwaves and sea-level rise, and minimal human contribution is observed at the local level, L+D assessments could and should be considered legitimate in the UNFCCC platform. In such areas, it is also possible to use historical socio-economic information to conduct a prospective L+D evaluation. This can be done using multiple scenarios, including the worst case situation, where adaptation is absent.

CONCLUSION

The characteristics, priorities and emerging issues related to slow onset processes are context specific and area dependent. The local level pilot areas are exposed to multiple climate driven fast and slow onset hazards such as flood, landsides, drought, saline intrusion and forest degradation. Pilot areas with low-lying coastal areas are exposed to floods, saline intrusion and sea-level rise while some are also affected by storms and typhoons. Pilot areas in the floodplains are exposed to hazards such as floods and river bank erosion while the highland areas are affected by flash floods, mudslides, landslides and forest degradation. Some hazards are found to be independent of setting. These include dry conditions and high temperatures that trigger forest fires as well as landfills and open dumps that could become the source of emerging hazards.

Limits to adaptation are dependent upon the natural setting of an area, social capacity, resources and availability of technology. The area-based risk framing approach was useful to assess both fast and slow onset hazards in a specific area over a continuous time-frame.

The short term requires DRR while the long term calls for CCA, when it is within natural limits. In Myanmar, the island setting of the Thatdama Kyun Village at the confluence of two rivers made it prone to flooding and river bank erosion. The loss of agriculture land, livelihood opportunity, health and other social issues have caused great hardship to the villagers and some have migrated away from the area. In Kuala Selangor, Malaysia, areas in the agriculture-rich lowlands will be exposed to slow onset coastal inundation, and saline intrusion is expected to affect sub-surface aquifers, giving rise to future food security issues. Some areas may have to be abandoned in the future, and it is important that the community is informed of this hazard and that resources are allocated for long term adaptation efforts. Increasing temperatures and heatwaves are already reported in the Kampong Speu Province (Cambodia), Thatdama Kyun Village (Myanmar) and Quang Ngai Province (Viet Nam). This hazard contributes to forest fires and impacts human health, and the situation is expected to worsen in Southeast Asia as global warming increases to 1.5°C. The Governments of the region need to make comprehensive, coordinated efforts via ASEAN, the UNFCCC and other platforms to limit global warming below 1.5°C. Resources should also be deployed in the region to adapt to a 1.5°C world.

The issue of detection and attribution to climate change is a major challenge in the assessment of L+D for both fast and slow-onset hazards. The area-based risk framing approach used in this study assumes that all impacts are linked to anthropogenic climate change, which is not necessarily the case. There is limited evidence that any one single fast onset event is due to anthropogenic climate change. This makes L+D assessments of such events a challenge, to be relevant to the UNFCCC platform. In the case of heatwaves and sea-level rise, where minimal human contribution is observed at the local level and direct links are proven in global conditions, L+D assessments could provide significant contribution to the discourse at the UNFCCC platform. More scientific work is required from multi-disciplinary teams to develop a robust L+D methodology that incorporates detection and attribution to climate change, which is appropriate to the UNFCCC platform. A critical review of all research projects supported by APN and their ensuing publications, to delineate information on detection and attribution to climate change, would serve as an excellent foundation to advance L+D assessment in the region.

Policy and planning strategies that integrate CCA, DRR and L+D are easier to deploy for specific local areas compared to a country-wide basis. The integration is also easier in small areas compared to large tracts of land, with a higher number of interacting hazards. The risk framing approach used in this study, which links DRR and CCA, can be expanded for a specific local area to include L+D. Historical L+D information is useful to provide insights for developing prospective L+D scenarios, both for DRR (near term) and CCA (long term). On a conceptual level, the three elements of DRR, CCA and L+D can be incorporated into land use planning and development management policies. The integrated framework should take into account fast and slow onset hazards and be suited to existing governance systems. Important aspects include natural state of the local area, projected conditions, potential impacts both at the surface and subsurface, deployment of science, technology and innovation, suitability of adaption options including transformative adaptation, as well as continuous monitoring and evaluation in conjunction with all stakeholders, especially the local community.

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Developing an economic, environmental and agronomic case for the increased use of organic amendments in South Asia

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ABSTRACT

Aggressive fertilizer subsidies throughout South Asia have led to a rapid increase in the use of synthetic nitrogen fertilizers such as urea at the farm level. While this has been successful in increasing yields, significant yield gaps remain between potential and actual farm yields, while unbalanced or over application of fertilizers potentially damages soil and environmental health. This project examined organic amendment (OA) application in India and Sri Lanka on productivity, soil properties and greenhouse gas emissions. In India, poultry, farm-yard manure and vermi-compost were applied to a paddy rice crop, and the potential benefits followed through to a post-rice chickpea crop. In Sri Lanka, we tested the optimal combination of synthetic nitrogen fertilizer rates when using municipal-waste compost in a multi-year maize-soybean rotation. Results at both trial sites saw an increase in crop yields under OA application; in particular chickpea yields from farm-yard manure and after repeated application of municipal-waste compost. However, all OA treatments increased emissions of the greenhouse gases nitrous oxide and methane due to additional nitrogen or carbon availability. Furthermore, the low nutrient content and relatively high cost of the OA's, particularly the composts, made them uneconomical as nutrient sources compared to conventional fertilizers.

KEYWORDS

Composts, Fertilizers, Greenhouse gases, Manures, Nitrogen use efficiency, Organic amendments

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HIGHLIGHTS

- OA increased maize yields by 21% or fertilizer savings of USD 48 ha^{-1} in urea costs.
- OA increased yields in post-rice chickpeas by up to 1200 kg ha^{-1} but also increased greenhouse gases by up to 30%.
- Input costs per Mg of grain produced were up to 25 times higher using compost.

1. INTRODUCTION

South Asia is home to a growing population of over 1.6 billion people, and it is estimated the region will have to double its food production between 2010 and 2050 to match increased demand. To achieve this, both India and Sri Lanka have accorded high priority to the use of fertilizers for achieving self-sufficiency and have implemented substantial subsidy programs, particularly on urea nitrogen (N) fertilizer. Synthetic N fertilizer input onto farms has increased 8-fold over the last century, including a doubling in South Asia since 1990 (Lu & Tian, 2017). At the same time, N use efficiencies (NUE) in the South Asia region, i.e., the amount of applied N fertilizer that is converted into harvested products, has dropped below 35% (Luis, Gilles, Bruna, Juliette, & Josette, 2014), primarily due to excessive application rates linked to heavy fertilizer subsidies. This combination of increasing N inputs and low NUE is the primary driver for increased losses of reactive N contributing to a number of environmental problems such as increased emissions of the potent greenhouse gas nitrous oxide (N_2O) (Bouwman, Boumans, & Batjes, 2002).

In this context, considering the vast amounts of organic residues produced in India and Sri Lanka, organic soil amendments (OAs), particularly in the form of composts, have been touted as an effective means of replacing or supplementing part of crop synthetic fertilizer requirements with a cheap source of nutrients, while increasing soil productivity and "health", and reducing the environmental costs associated with industrial N fixation (Ceotto, 2005). While benefits of increased nutrient stocks following OA application are relatively easy to quantify, and plant nutrient availability less so, OAs have primarily been promoted as a means to maintain or increase "soil health", the intuitive but hard to quantify confluence of optimal soil physical, chemical and biological properties often linked to soil organic matter. Valuing these additional benefits is made even more difficult by the long-term application time frame required to see these benefits (De Rosa et al., 2017), with quantification through longitudinal studies rare.

While many studies have demonstrated the benefits of applying OAs including enhancing both physical and chemical soil properties (Leroy et al., 2008; Quilty & Cattle, 2011) and soil carbon sequestration (De Rosa et al., 2017), few have critically examined the agronomic, environmental and economic benefits compared directly to equivalent inputs of synthetic fertilizers. Disentangling the additional nutrient benefits from other perceived soil health benefits in these studies is not always possible, making direct comparisons with synthetic fertilizer difficult. The high cost and low nutritional value of some OA products, combined with uncertainty around their capacity to match plant nutrient demand, ensures the use of OA in farming systems is substantially more complicated than conventional synthetic fertilizer. As such, there is a tendency for farmers to either over apply to match a single nutrient requirement (usually phosphorous) leading to the over application of N, or to apply simply as a "feel good" factor with no clear idea of the return on investment. Adding to this, various local and state governments have implemented schemes promoting activities such as composting, both as a means of reducing the cost of processing municipal wastes, but to also minimize reliance and costs of imported synthetic fertilizer (Bandara, 2008; de LW Samarasinha, Bandara, & Karunarathna, 2015). For instance, the Sri Lankan governments "Mahinda Chinthana" policy aims to reduce imports of synthetic fertilizers by up to 15% (MADAS, 2007). These products are promoted to farmers at a substantial premium, costing up to USD 130 Mg^{-1}. In Europe and North America, incentives and application rates for OA use largely stem from the need for waste disposal or legislation, driving down the price or encouraging their use. In South Asia however, as with other tropical regions, these drivers from the waste management side are mostly missing, with use focusing solely on improving production, and competing against heavily subsidized synthetic nutrient fertilizers. Low mechanization and increasing local labour costs in these regions are further driving up costs. Ultimately the sustained uptake of OA in tropical agricultural systems depends on improved transparency around the cost-benefits of OA compared to synthetic fertilizer.

This project examined the impact of two different scenarios of organic amendment use in India and Sri Lanka on productivity, soil properties and greenhouse gas emissions. At the Indian site, three different OAs (poultry manure, farmyard manure and vermi-compost) were applied to a paddy rice crop, and the potential nutritional and soil quality benefits followed through to a post-rice chickpea crop. In Sri Lanka, we tested the optimal combination of synthetic nitrogen fertilizer rates when using municipal-waste compost in a multi-year maize-soybean rotation. Agronomic, economic and environmental outcomes were compared.

2. METHODOLOGY

The trial at Matara, Sri Lanka, comprised a municipal-waste compost by fertilizer rate experiment in a maize-soybean cropping rotation for 2.5 years from October 2015 to February 2018. Matara sits in the tropical rainforest climatic zone of the Southern province of Sri Lanka, with an average annual precipitation of 2338 mm and mean annual temperature of 29.8 °C. The soil at the site is a marginally acidic (pH 6.6) Orthic Acrisols (FAO, 1998), comprising of 41% clay and 28% sand (0-20 cm), and is characterized by low-activity clays, low nutrient availability and low base saturation.

The trial had eight treatments in a factorial experiment of two compost rates, zero (0C) and 15 t ha^{-1} (+C) on dry weight, and four N rates; Zero N (0N), Low N (LN-70 kg N ha^{-1}), Medium N (MN-150 kg N ha^{-1}) and High N (HN-200 kg N ha^{-1}). The N application rate MN was designed to represent a regular farming practice in the region (150 kg N ha^{-1} for maize and 70 kg N ha^{-1} for soybean) as recommended by the Department of Agriculture, Sri Lanka. Experimental plots were laid out in a randomized design with four replicate blocks. Compost, produced locally from municipal solid waste in Matara, Sri Lanka, was applied twice (15 t ha^{-1} per application ~ 105 kg N ha^{-1}) as dry weight basis at the beginning of each crop in the rotation before planting and incorporated into a depth of 20 cm. Agronomic management followed the local farmer practice in the region. The composition of the compost is shown in Table 1.

In India, kharif (wet season) rice was transplanted into the paddy soil (35% clay, 0.45% C) on 26 July 2017, and harvested on the 24 October. The 6 m x 6 m plots were individually bunded to prevent water and nutrient movement between plots and treatments were randomized within three blocks. Organic amendments selected for the study represented the more common types available in the area and a wide range of nutrient qualities to ensure the study is as relevant as possible to local farmers. OA treatments were applied immediately prior to planting on 26 July 2017 at the higher end of local farmer practice to maximize treatment differences while ensuring economic feasibility. Irrigation was maintained at 2 cm throughout the rice-growing period with the last irrigation applied one month prior to harvest. Treatments were as follows:

T_1 – Farmer practice (Recommended Dose of Fertilizer 120-60-40 kg NPK ha^{-1})

T_2 – 25% of RDF through Vermi-compost + 75% RDF from urea

T_3 – 25% of RDF through Farmyard manure + 75% RDF from urea

T_4 – 25% of RDF through Poultry manure + 75% RDF from urea

The chickpea fallow crop was planted shortly after rice harvest on 26 October 2017 to capitalize on any residual soil moisture and late kharif rainfall, and was harvested on 24 January 2018. No additional fertilizer was applied. Seeds were directly drilled by hand as per standard farmer practice for the respective crops.

The effects of OA application and different rates of N-fertilizer applications on yield and cumulative GHGs were tested using two-way analysis of variance (ANOVA), and pairwise differences, with an alpha (α) level of 0.05, identified by the lsmeans package (Lenth, 2016) using the Tukey multiple-comparison test.

3. RESULTS AND DISCUSSION

3.1 Crop yields

In Sri Lanka, maize grain yield showed a strong response to N fertilizer rate at the lower application rates, increasing by over 65% from the 0N to the LN treatment (Figure 1). Additional N application in the MN and HN further increased yields though at a slower rate, with yields plateauing and no significant difference being observed between the MN and HN rates. A similar pattern was observed in the stover and total AGB, though stover yields continued to increase even at the higher N rates. Following three years of application, compost addition significantly increased maize yields at the higher N rates, with the greatest response seen in the MN treatment, which increased total above-ground biomass, grain yield and total N uptake by 21%, 14.5% and 31%, respectively. Yields from the medium N application rate with the addition of 15 t of compost (MN+C, 150 kg N ha^{-1}) were significantly higher ($P<0.05$) than the high N (200 kg N ha^{-1}) rate, which received fertilizer only.

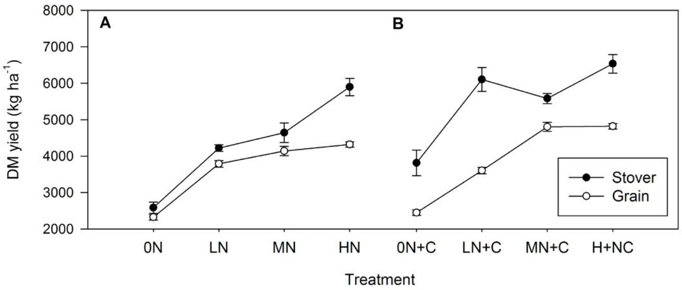

FIGURE 1. Grain and stover yield for the 0N, LN (70 kg N ha^{-1}), MN (150 kg N ha^{-1}) and HN (200 kg N ha^{-1}) treatments without (A) and with (B) compost addition (+C) for maize (October 2017 to February 2018) following 3 years of compost application crop at Matara, Sri Lanka.

At the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT) based in India, there was no significant difference between stover yields in the kharif rice crop, though a 13% and 17% yield penalty ($P<0.05$) from farmer practice (FP) associated with the Vermi-compost (VC) and Poultry manure (PM), respectively was observed in the grain yield (data not shown). Farmyard manure (FYM) had no impact (negative or positive) on either rice grain or stover production. By contrast, there was a striking increase in the fallow chickpea grain yields in all OA treatments compared to the FP (which failed to set seed), with yields in the PM, VC and FYM increasing by a factor of 5, 10 and 19, respectively (Figure 2), equating to a yield increase of 1,268 kg ha^{-1} in the FYM, 634 kg ha^{-1} VC, and 286 kg ha^{-1} for the PM.

3.2 Greenhouse gases

	Application rate (Mg ha^{-1})	*Total C (%)*	*Total N (%)*	*Total N applied (kg ha^{-1})*	*Total P applied (kg ha^{-1})*	*Total K applied (kg ha^{-1})*	*Price (USD Mg^{-1})*
Municipal-waste compost	15	19.2	0.7	105	–	–	$110
Vermi-compost	5	10.1	1.1	55	17.0	51.3	$70
Farmyard manure	5	24.3	2.6	130	32.8	114.2	$40
Poultry manure	1.5	19.0	3.2	6.0	90	45.1	$48

TABLE 1. Major compost and manure nutrient parameters for the applied OAs in the trials at Matara, Sri Lanka and ICRISAT, India.

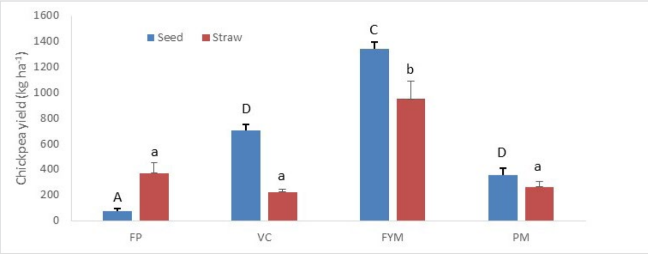

FIGURE 2. Chickpea seed and straw yields for the farmers' practice (FP), Vermi-compost (VC), Farmyard manure (FYM) and Poultry manure (PM) treatments at ICRISAT, India. Letters indicate significant differences between treatments (uppercase = seed, lowercase = straw, P<0.05).

In both studies, the application of organic amendments increased GHG emissions compared to the fertilizer-only farmer practice. In the maize-soy rotation in Sri Lanka, there was an overall effect of N rate on annual N_2O emissions, which increased significantly with the increasing N fertilizer rate. The application of compost significantly (P<0.05) increased average annual N_2O emissions by 39% in year 1 and 77% in year 2 at the highest N fertilizer rate, and 73% in the MN rate in year 2 (P=0.063). Similar increases were observed in maize in the third year of the experiment (Figure 3). The application of compost increased CO_2 emissions only marginally, increasing emissions by 23% though no significant differences were observed due to high spatial error.

In rice in India, CH_4 was by far the most important GHG contributor, accounting for >95% of global warming potential (GWP: N_2O + CH_4 expressed in CO_2-equivalents) in the farmers' practice treatment. A similar effect was seen across the OA treatments, except the PM, where the high N_2O emissions, combined with lower CH_4 fluxes, increased the contribution of N_2O to total GWP to over 50%. Overall, total GWP was lowest in the FP with 135 kg CO_2-eq ha-1 followed closely by PM, increasing to almost 200 kg CO_2-eq ha^{-1} in the FYM and VC due to higher CH_4 emissions.

3.3 Economic value of organic amendment application

In Sri Lanka, using a conservative local price of USD 0.28 per kg of urea, the reduction associated with reducing N inputs from the HN rate to the MN rate while achieving comparable yields represents an annual saving of ~USD 48 per hectare. Alternatively, compost also increased grain yields at the highest N rate by 0.5 Mg ha^{-1}, equivalent to USD 114 at local prices, with more value in the stover depending on local markets. The retail price of municipal-waste compost in Sri Lanka has been reported as being between USD 55-140 Mg^{-1}. At the application rate of 15 Mg per crop (30 Mg per year) this corresponds to a per hectare price of USD 1,650 per year, far in excess of the potential savings associated

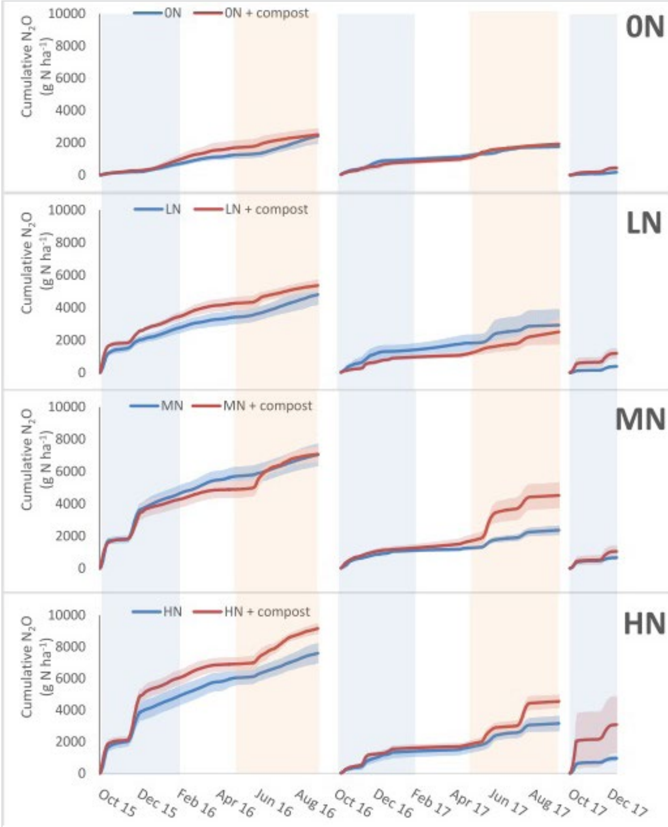

FIGURE 3. Cumulative N2O fluxes (g N ha^{-1}) for four N rates 0N, LN, MN, HN with compost and no compost during a 2.5-year crop rotation from October 2015 to February 2018 at Matara, Sri Lanka.

with lower urea application or increased yields. At USD 0.29 per kg urea, the value of N applied in the compost is only USD 126 ha^{-1}, and even accounting for other macronutrients (P and K) can only replace (assuming 100% availability over time) USD 363 (or USD 12.10 Mg^{-1}) worth of bagged fertilizer, well short of the USD 1,650 application cost. This is reflected in the input cost per unit of grain and stover produced in maize 3 (Figure 4), which increases from USD 11-29 Mg^{-1} (grain) for urea as N rate increases and marginal returns diminish, compared to USD 703-377 Mg^{-1} for the compost.

Local prices (Hyderabad, India) for the VC, PM and FYM in India are USD 70, 40 and 48 per Mg. In terms of relative value of the macro nutrients added, the PM represented greatest nutrient load at USD 46.33 Mg^{-1} (USD 3.2, 30.8 and 10.3 for N, P and K respectively), followed by FYM at USD 20.30 Mg^{-1} (USD 4.2, 8.2 and 7.9) and VC at USD 9.60 (1.8, 4.3 and 3.5). The significant yield increase in the chickpea resulted in the marginal cost to produce 1 kg of chickpea of USD 0.19 for FYM, 0.21 for PM and 0.55 for VC. The FYM and PM also contain substantial carbon (24% and 19% respectively) which may provide additional long-term benefits that are difficult to quantify, while the VC appeared to have a substantial mineral (soil) component with only 10% carbon.

At a local commodity price of USD 0.87 per kg of

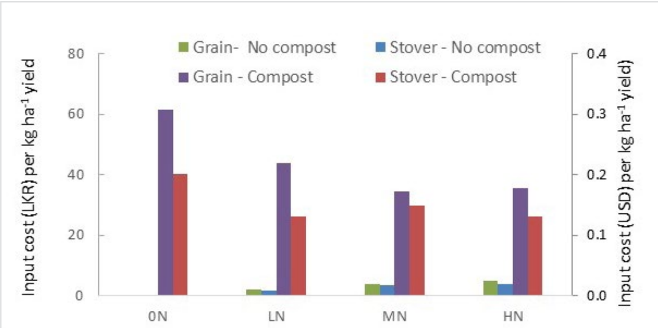

FIGURE 4. Nitrogen input costs in USD per unit of grain or stover produced for the maize 3 crop using urea only or municipal-waste compost combined with urea at different application rates. Urea was priced at USD 0.28 kg^{-1} and compost at USD 0.06 kg^{-1}.

chickpea, the return on investment (accounting for fertilizer costs only) for 1 kg of OA was USD 4.60 for FYM, 4.10 and 1.60 for VC. Some of this additional benefit would have been offset in the rice where the 25% reduction in urea application only reduced costs by USD 10.60 ha^{-1}. However, without a urea only comparison in the chickpea it is not possible to compare these returns to synthetic fertilizer costs.

4. CONCLUSIONS

In both Sri Lanka and India, significant increases in yields could be demonstrated with both the medium (2.5 years) and short (1 year) term application of organic amendments. However, the high relative cost of OA's compared to synthetic bagged fertilizers requires substantial additional benefits above the value of the nutrients alone to make their use economical. This effect is exacerbated by fertilizer subsidies, which skewer economic benefits even further away from organic amendment use. Additionally, the use of these products in all cases increased GHG emissions through the application of additional N, or through higher carbon inputs, which can stimulate both the production of N_2O through denitrification, and CH_4 through methanogenesis in low carbon soils. As such, for environmental gains to be realized, their use has to be coupled with either reduced use of urea or ammonium-based fertilizers, thus saving GHGs consumed in the production process, with decreased emission intensities (kg GHG emitted per kg of yield produced) or through increased carbon sequestration in soils. Longitudinal studies are required to demonstrate the long-term, cumulative soil benefits of repeated OA application across a range of management and amendment types, combined with full nutrient and GHG life-cycle assessment of waste streams to ensure pollution swapping does not occur.

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Vulnerability of urban waters to emerging contaminants in India and Sri Lanka: Resilience framework and strategy

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ABSTRACT

Vulnerability and resilience of urban waters, under the shifting paradigm of climate change and urbanization, needs to be evaluated from both quantitative and qualitative perspectives. We evaluated the vulnerability of urban waters of Guwahati, the largest city in Northeastern India, and Colombo, the coastal National Capital Territory of Sri Lanka, by analyzing the concurrence of Pharmaceuticals and Personal Care Products (PPCPs), enteric virus, antibiotic resistant bacteria (ARB), metal, faecal contamination and antibiotic resistance genes (ARGs), as well as long-term changes in precipitation and temperature. *Escherichia coli* (*E. coli*) ranged from 10-27 cfu ml^{-1} in the Kelani river, and from below detection limit to 49 cfu ml^{-1} in the Brahmaputra. *E. coli* strains isolated from the water were evaluated for resistance to the antibiotics norfloxacin, ciprofloxacin, levofloxacin, kanamycin monosulphate, tetracycline and sulfamethoxazole. In both countries, most of the isolates were resistant to multiple drugs and the resistance was greater for older generation antibiotics. The Brahmaputra River showed greater resistance to all of the antibiotics than the Kelani and Gin rivers. Antibiotic resistance genes gyrA, tetW, sul1 and ampC were detected in the Kelani River, while aac-(6')-1b-cr, gyrA, tetW, sul1, ampC and blaTEM were detected in the Brahmaputra River. Antibiotic resistance appears to be not correlated with the prevalence of PPCPs and *E. coli*, but with anthropogenic pollution and lifestyle. CSIRO and MIROC models predict more than a 1.2 °C increase in average yearly temperature, whereas average yearly precipitation is likely to remain the same, with some abnormalities in high and low extremes. A resilient framework is needed that ensures participation of every stakeholder by defining specific roles in the implementation process.

KEYWORDS

Climate change, Emerging contaminant, Resilience, Urban waters, Vulnerability

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HIGHLIGHTS

» Urban drains make surface waters vulnerable to emerging contaminants.

» Antibiotic resistance correlated with metal contamination rather than *E. coli* prevalence.

» Sri Lankan waters exhibit greater resistance after treatment than Indian waters.

» Resistance to fluoroquinolones is an alarming concern in India.

» A framework is proposed for the development of a resilient system by 2030.

» Scientists, engineers, planners, policymakers and residents need to collaborate.

1. INTRODUCTION

Assessing the vulnerability of urban waters is a significant and complicated task in planning water resilience. The decision-making process needs to consider aspects of health, the environment, economy, socio-culture and technical function within a planning framework. This framework must include interactions among users, organizations, and policymakers. Development of viable strategies for management of water resources involves the very important step of gaining a robust understanding of the status of water pollution (both established and emerging contaminants), people awareness, land use patterns, and likely changes in the future. Other considerations are the contamination threat to groundwater recharge and how to reduce nonpoint pollutant load in urban surface waters (Kumar, Rao, Kumar, &

Ramanathan, 2011; Kumar et al., 2013). Urbanization results in severe environmental deterioration (Honda et al., 2016; Kumar et al., 2019) because countermeasures, which need policymaker approval, are not able to keep pace with the change (Bausch & Schwarz, 2014; Hsu, Shih, Hung, & Lowry, 2015). Advancements have been made, but the difficulty lies in the application of existing information to solve this complex problem.

In Sri Lanka, the National Policy on Rain Water Harvesting was officially implemented in 2005. As India is facing water management problems in many regions, it should make rainwater harvesting mandatory under municipal and urban council jurisdiction within a prescribed period. The National Water Policy (NWP) [2002] mandates each state to formulate a water policy in consonance with local conditions. According to NWP, urban society is the most significant generator of wastewater. Specific targets need to be set for recycling and reuse in which sewage is seen as a resource. Planners must firmly project their viewpoints on the utility of water for both urban development and the sustainability of a region.

In many developing countries like India and Sri Lanka, there is no clear policy on reclaimed water usage. Unfortunately, such policies mainly remain on paper and are not successfully implemented due to a severe lack of awareness and active participation of all stakeholders. In diverse countries like India and Sri Lanka, the percentage of economically challenged stakeholders is too high, and safe water and food security are becoming critical issues. The governments need to be informed about the practicality of water policies. A relevant scientific assessment is needed, and social challenges understood to increase awareness and develop comprehensive guidelines and incentives. The approach must minimize discrimination based on caste, creed and affiliations. Coordination among agencies is required for safe and sustainable water supplies.

Climate change affects global precipitation patterns, which can lead to habitat problems. Hence, approaches are needed that can at least mitigate the effect of climate change. Managing water resources using an integrated approach is critical to minimize adverse social, economic and environmental impacts while meeting the increasing demand for safe water. IPCC (2014) stated, "water and its availability and quality will be the main pressures on and issues for societies and the environment under climate change". When we plan for future water supplies, the global picture becomes less important than the effect of climate change on safe water availability and sustainability in a specific region.

The occurrences of multi-drug resistant microbes, pathogenic viruses, metals, and Pharmaceuticals and Personal Care Products (PPCPs) in urban waters have become the crux of urban sustainability issues. However, vulnerability due to their concurrences, source apportionment, and identification of better indicators needs to be better understood. Sri Lanka witnessed a 36% increase in PPCPs use between 2000 and 2010 (Kühn et al., 2005). It is estimated that between 2010 and 2030, global consumption of antimicrobials will increase by 67% (63,151 to 105,596 tons) (Ferreira da Silva, Vaz-Moreira, Gonzalez-Pajuelo, Nunes, & Manaia, 2007). The accelerated consumption of antibiotics has influenced microbial ecology (Jiang et al., 2013), demonstrated by the detection of antibiotic resistant bacteria (ARB) and antibiotic resistance genes (ARG) in municipal solid waste leachate, sludge (Jiang et al., 2013), sediments (Klein et al., 2018), wastewater (Van Boeckel et al., 2015), surface water (GARP, 2011), drinking water and groundwater (Kümmerer, 2009), perhaps the most serious concern is the release of ARGs from urban Waste Water Treatment Plants (WWTPs). However, studies on ARB and ARGs in developing countries are very limited and there is none from Sri Lanka.

The present study focuses on vulnerability assessment of urban waters in Guwahati, the largest city in Northeastern India, and Colombo, the coastal National Capital Territory of Sri Lanka, through analyzing the concurrence of PPCPs, enteric viruses, antibiotic resistant bacteria, metals, faecal contamination, and ARGs. Guwahati, selected among cities under the Smart Cities Mission by the government of India has witnessed rapid and unplanned growth of urban land use owing to migration for jobs, facilities, business opportunities, and education leading to a population of about 968,549 (2011 census) within a limited geographical space (~328 km^2). The state capital, i.e. Guwahati is thus facing a severe freshwater availability issue owing to heavy dependency on groundwater exhibiting unprecedented depletion and deterioration in the last two decades. On the other hand, Colombo, the commercial capital and metropolitan city of Sri Lanka with a population of 5.6 million, is a popular tourist destination and financial centre of the island. It has one of the largest artificial harbours in the world and handles the majority of Sri Lanka's foreign trade. Many industries are situated on the city's periphery (Mahagamage, Chinthaka, & Manage, 2016). Such setup greatly enhances the vulnerability of urban waters.

The overarching goal is to propose a way to achieve sustainability of water resource management by understanding the processes governing water storage and supply. This requires analysis of urban spread, changes in land use and land cover, as the developing countries modernize infrastructure to meet the demands of employment and essential amenities for residents. The present work estimates health risk based on an understanding of

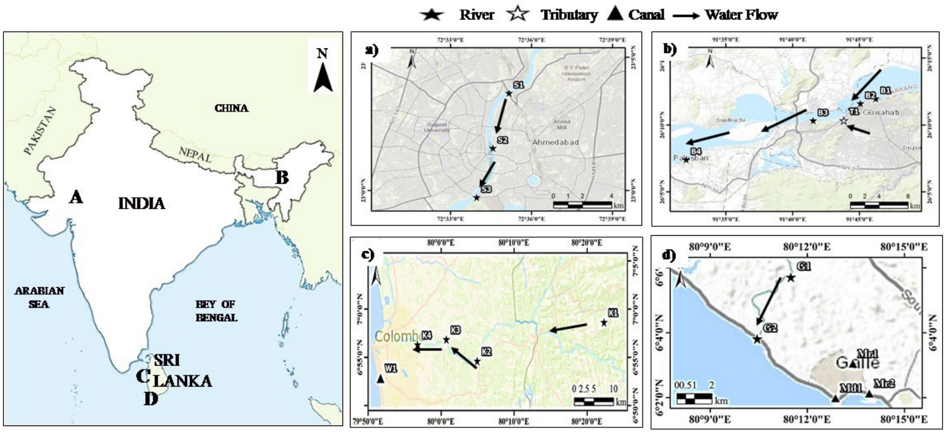

FIGURE 1. Locations of surface water sampling in: (a) Ahmedabad and (b) Guwahati in India; (c) Colombo and (d) Galle in Sri Lanka. Samples include the Sabarmati River (S1-S3), Brahmaputra River (B1-B4), Bharalu Tributary (T1), Gin River (G1-G2), Moda Ela (Md1), Moragoda Ela Canal (Mr1-Mr2), Kelani River (K1-K4), and Wellawaththa Canal (W1).

the vulnerability of the water supply system from various conventional biological and chemical pollutants, with particular emphasis on intestinal enterococci and heavy metals. The study also estimates the prevalence of ARB, ARGs and multidrug resistance (MDR) in the WWTPs of Western and Southern Sri Lanka compared to the Indian scenario. A new resilience strategy and framework is proposed for a safe water supply system that is more adaptive to changes in population and climate.

2. METHODOLOGY

2.1 Sampling

2.1.1 Surface waters in India

The Brahmaputra River is a perennial transboundary tropical river that crosses four countries (India, China, Bangladesh and Bhutan) and is fourth largest in the world in average discharge at its mouth (Pervez & Henebry, 2015). The Brahmaputra experiences annual floods from June to September. The Bharalu is a tributary of the Brahmaputra that traverses the dense urban sprawl and is now restricted to serving as unlined urban drainage. Pollutants flowing through Guwahati enter the Bharalu tributary and the Brahmaputra River. The flow rate of the Brahmaputra River is about 10-15 times faster than the Kelani River in Sri Lanka.

2.1.2 Surface waters in Sri Lanka

The Kelani River is the fourth longest river (144 km) in Sri Lanka that flows to the west coast through Colombo city. The basin receives an annual average rainfall of approximately 2,400 mm with a major contribution from the southwest monsoon period (May–September). The basin area is approximately 2,230 km^2. The Kelani river has been identified as the most polluted river due to its flow through areas with high population densities (Herath & Amaresekera, 2007; Liyanage & Yamada, 2017). It is a drinking water source for approximately 80% of Colombo municipals. The upper basin is primarily covered with thick vegetation, including tea, rubber, grass and forest, whereas the lower basin is heavily urbanized. Various industries are located along the riverbanks. Colombo's drinking water is threatened due to industrial and domestic discharge, particularly as some of the pollutants are difficult to remove by available treatment processes (Herath & Amaresekera, 2007).

The Gin River is a major river in the Southern Province of Sri Lanka, which fulfils the water requirement of the community of Galle municipality. The river becomes polluted by affected tributaries and the urbanized environment. The Moda Ela facilitates sewer transmission in Galle city. It starts in Mahamodara Lake and flows into the sea near the Galle Railway Station. Most of the sewers and drains in Galle city are connected to the Moda Ela. Even though residents do not consume its water, the surrounding area is frequently flooded during heavy rainfall. The Moragoda Ela is a canal that flows through an urbanized area of Galle district. The water is highly contaminated due to illegal littering.

2.2 Analyses

Surface water locations in India and Sri Lanka (Fig. 1) were selected based on the preliminary survey of *in situ* parameters (Hanna 981A) like pH, Total Dissolved Solids (TDS), Oxidation-Reduction Potential (ORP), Electrical conductivity (EC), Dissolved Oxygen (DO), Temperature and Salinity strategic sampling locations in each city were selected. In general, the rivers were sampled before, during and after entering in the urban areas. Locations with confluence points of major drains were also sampled. Sampling locations are shown for the Sabarmati River (S1-S3) (Fig. 1a), Brahmaputra River (B1-B4) and Bharalu tributary (T1) (Fig. 1b), Kelani River (K1-K4), Wellawatta Canal (W1) (Fig. 1c), Gin River (G1, G2) Moda Ela (Md1) and Moragoda Ela (Mr1, Mr2) (Fig. 1d). Metals were analysed by ICPMS (PerkinElmer's NexION® 2000). To ensure quality control, blanks were prepared for the dilution buffer, monitor kit, and media.

2.2.1 Isolation of E. Coli

Strains of *E. coli* were isolated and separated from water samples using a membrane filtration method. *E. coli* colonies were identified by staining. The number of *E. coli* colonies per mL of water sample (cfu ml^{-1}) was obtained by counting dark blue colonies and other coliforms by counting pink to red colonies. The total coliform count is the sum of *E. coli* and other coliforms.

2.2.2 Antibiotic susceptibility

The isolated *E. coli* colonies were evaluated for resistance to fluoroquinolones [norfloxacin (NFX), ciprofloxacin (CIP), levofloxacin (LVX)], aminoglycosides [kanamycin monosulphate (KM)], tetracyclines [tetracycline (TC)], and sulfonamides [sulfamethoxazole (ST)] using the KB disk diffusion method (Honda et al., 2016). The diameter of growth inhibition of *E. coli* colonies on the plates was used to estimate the level of resistance.

2.2.3 Screening for antibiotic resistance genes (ARGs)

Two litres of water were collected in sterile plastic pouch bags at each sampling site and kept cold during transport to the laboratory. Upon arrival, samples were filtered through polycarbonate membrane filters. The filters were then soaked with 500 µL of 2X DNA/RNA shield (ZymoResearch, USA) for DNA preservation. The DNA was extracted using the FastDNA™ spin kit for soil following the kit protocol (MP Biomedicals, LLC, Ohio, USA). The quantity and purity of the extracts were measured by the absorbance method (Eppendorf, Germany). DNA samples had absorbance ratios of λ260/λ280 ≥ 1.78. Antibiotic resistance genes were amplified by polymerase chain reaction (PCR). The PCR was performed in a thermal cycler (BioRad 2720) for 30 cycles. Six classes of ARGs were selected based on antibiotic mechanisms using specific primers.

2.2.4 Climate models

Two models were selected from among 61 climate change prediction models provided by the Coupled Model Inter-comparison Project, Phase 5 (CMIP5) through the Data Integration and Analysis System (DIAS). Reproducibility of each model was evaluated with regards to the average precipitation for May to October of the 1979-2005 wet seasons (10N-30N, 70E-100E). CSIRO and MIROC5 were selected as climate change prediction models by comparing correlation coefficients for the GPCP data. The used output of the models is based on the representative concentration pathways scenario at a radiative forcing of 6 W/m^2. This condition is considered the global warming effect with atmospheric CO_2 increase. Model output data were extracted for 1981 to 2000 through the DIAS server. The 24×36 grids output of all precipitation in the target area (24N-30N, 88E-97E) was extracted with 0.25-degree resolution. Also, the past reproduction data of air temperature (24×36 grids) was extracted with a 0.25-degree resolution, but we could extract the air temperature (6×9 grids) for the future with a coarse resolution of 1 degree.

2.2.5 Statistical analyses

SPSS 21 (IBM) was used to carry out principal component analysis (PCA) and hierarchical cluster analysis (HCA) after normalization by obtaining z-scores for each parameter. Varimax rotation, an orthogonal mode of rotation, was used to generate non-related principal components. Results were represented in a 3-dimension PCA diagram. Cluster analyses were conducted using the Ward method to show proximity among analysed parameters.

3. RESULTS AND DISCUSSION

3.1 Prevalence of *E. Coli*, antibiotic resistant bacteria (ARB) and antibiotic resistance genes (ARGs)

The prevalence of *E. coli* ranged from 10-27 cfu ml^{-1} in the Kelani River, 24,267-76,600 cfu in the Sabarmati and from below detection to 49 cfu ml^{-1} in the Brahmaputra River. Most *E. coli* isolates were resistant to multiple antibiotics, and the resistance percentage was higher for older generation antibiotics like tetracycline and sulfamethoxazole. The Brahmaputra River showed higher resistance to all antibiotics than the Sabarmati, Kelani and Gin rivers. However, resilience was also highest in the Brahmaputra River owing to its dilution capacity and processes like sedimentation, adsorption, photodegradation and microbial-mediated activities (Fig. 2). Two sites of the Brahmaputra River within Guwahati city exhibited near 100% resistance to all antibiotics except tetracycline, which is a severe environmental health concern.

The antibiotic resistance genes gyrA, tetW, sul1 and ampC were detected in the Kelani River, while aac-(6')-1b-cr, gyrA, tetW, sul1, ampC and blaTEM were found in the Brahmaputra River. ARGs dfr1, blaCTX, qnrS, vanA, parC, qnrB and blaSHV were not detected in any Kelani or Brahmaputra samples. The trend in metal concentrations was Cr>Ni>Mn>Zn>Cu>Pb>Co>Cd in the Kelani and Brahmaputra Rivers and Cr>Ni>Mn>Cu>Pb>Co>As>Cd>Zn in the Sabarmati River. Overall, both Brahmaputra and Kelani rivers showed vulnerability while passing through an urban area as well as resilience through dilution of metals, faecal pollution, ARB, and ARGs.

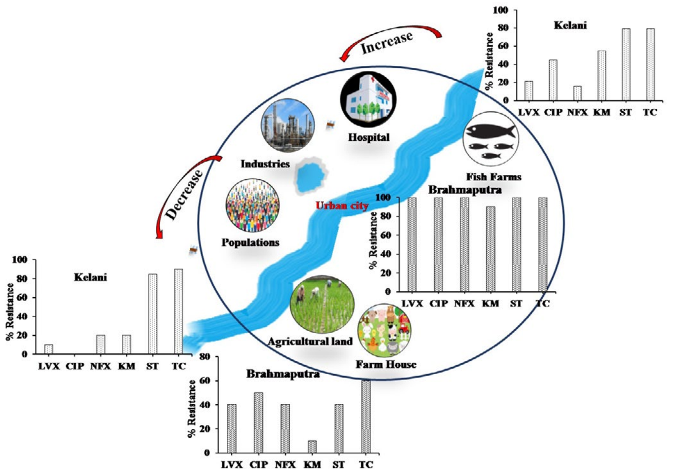

FIGURE 2. Prevalence of antibiotic resistant bacteria upstream to downstream along with urban areas of the Brahmaputra (India) and Kelani (Sri Lanka) rivers.

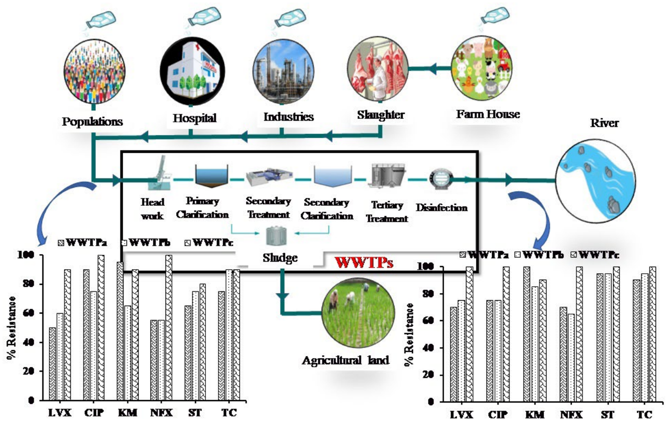

FIGURE 3. Prevalence of antibiotic resistant bacteria in the influent and effluent of the wastewater of India and Sri Lanka.

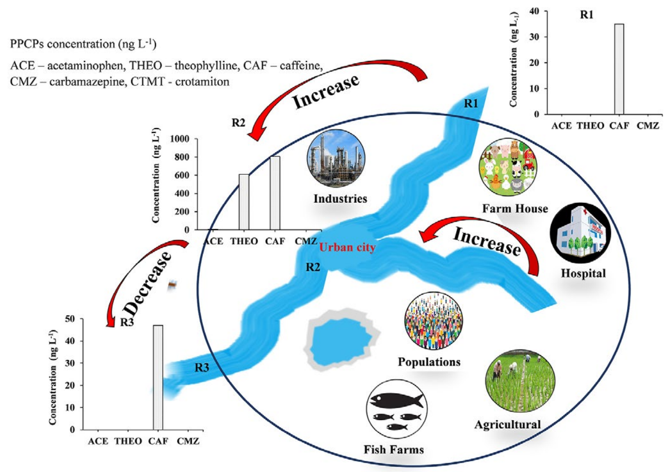

FIGURE 4. Influence of urbanization on PPCPs concentration in the river flowing through Guwahati city.

3.2 Prevalence of ARB and ARGs in Sri Lankan wastewater with reference to India

Although wastewater treatment resulted in greater than a 1.06 log reduction in *E. coli* at all WWTPs, the percentage of *E. coli* resistant to most of the antibiotics increased from influent to effluent. ARB, ARGs and multidrug resistance, were more prevalent in hospital WWTP owing to higher antibiotic concentrations used and excreted by patients. WWTPs in Sri Lanka showed more ARB than India, with consistent increases after treatment, but were less resistant to fluoroquinolones. In both countries, almost all sampling points contained *E. coli* strains with multidrug resistance, which increased after treatment (Fig. 3), and was strongly correlated with fluoroquinolones in every WWTP. Fluoroquinolone resistant genes (*aac-(6')-1b-cr, qnrB, qnrS*), β-lactams (*ampC*), and sulphonamides (*sul1*) were detected in municipal WWTPs with additional genes for *parC* in the hospital wastewater of Sri Lanka, implying much higher resistance to fluoroquinolones, especially ciprofloxacin.

Multivariate analysis suggests effluent showed higher loadings and association for ARB and multidrug resistance where pH change and longer interaction with metals during the treatment processes seem to have profound effects.

3.3 Occurrences of PPCPs and viruses

Samples from the Brahmaputra (n=4), urban drains (n=3), and the Ramsar site Dipor Bil (n=1) exhibited an order of prevalence for PPCPs as: caffeine > acetaminophen > theophylline > carbamazepine > crotamiton and for enteric viruses as PMMoV > aichi > hepatitis A > norovirus GII > norovirus GI (Fig. 4). PMMoV was an effective indicator of faecal pollution due to its prevalence, specificity and ease of detection. The prevalence of PPCPs among samples was similar to faecal bacteria and viruses (Kumar et al., 2019). PPCP concentrations were high in drain samples and very low in lake and river water. PPCPs are directly associated with raw sewage and thus were not detected in the upstream or downstream of the Brahmaputra, owing to self-purification of the river. PMMoV was the only virus detected in all river samples. Cost-effective technologies are needed to reduce levels of resistant genes in drinking water systems. Research on the bacterial strains in biofilms within water network systems is critical to understand and manage selection pressure stemming from treatment methods that enhance resistance.

3.4 Associations among conventional and emerging water quality parameters

PCA loading (Fig. 5a) and HCA clustering (Fig. 5b) suggest associations of faecal contamination (coliform) with electrical conductivity (EC), carbamapzine

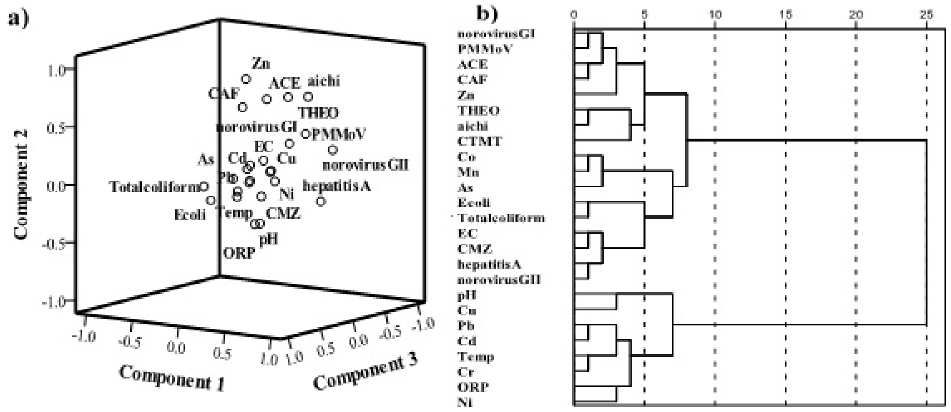

FIGURE 5. Associations among conventional and emerging water quality parameters shown by (a) principal component analyses and (b) hierarchical cluster analyses.

concentration, and hepatitis and norovirus count. Norovirus and PMMoV were associated with caffeine, acetaminophen and Zn. The pH, ORP and metal concentration likely control these associations. It further implies that people seem to be suffering more from temperature and monsoon-driven diseases like intestinal infection and cholera as well as the common cold and flu. Emerging contamination has no direct correlation with conventional parameters like pH, ORP or metals, as emerging contaminants are present in very trace quantities that probably do not affect these parameters. It further suggests that vulnerability of the water system cannot be assessed based on traditional water quality parameters and must include new indicators such as PMMoV, caffeine, carbamapzine and acetaminophen. Estimation of both labile and conservative PPCPs are equally important. It is time to adopt a holistic approach to the evaluation of vulnerability and resilience of water systems as well as to revise the ambient water quality guidelines by including new age parameters.

3.5 Climate trends and scenarios in the Brahmaputra watershed

Disruption of river flows and the fate of contaminants can reduce dissolved oxygen levels and changes in chemical reaction kinetics, enhance potential for toxic algal blooms, and may cause the migration and extinction of aquatic animals. These are some of the impacts of climate change on temperature and rainfall. Thus, understanding and predicting climate change impacts are of utmost importance to take necessary measures. Temperature and precipitation in the Brahmaputra region were reproduced by CSIRO–Mk3.6 and MIROC5 (Fig. 6). Average precipitation predicted by both models for present and future scenarios was similar (1200-1300 mm), but the magnitude of extreme events (floods and droughts) was different. Maximum and minimum precipitation predicted by the CSIRO model were 2000 mm and 800 mm, respectively, whereas by the MIROC model, these values were 2000 mm and 750 mm (Fig. 6). Yearly

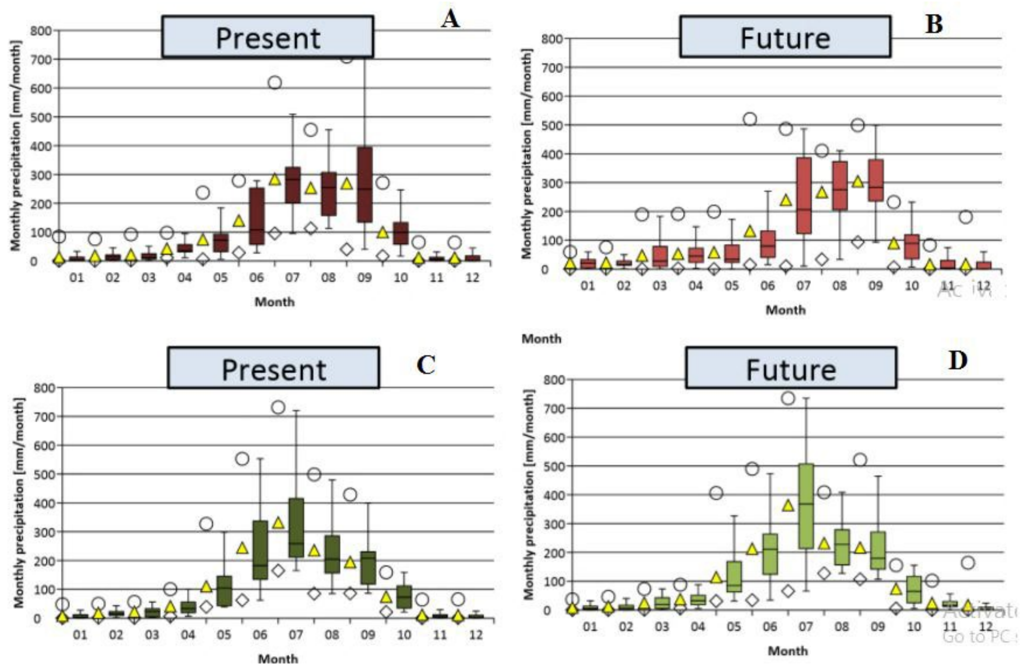

FIGURE 6. Present (1981-2000; A and C) and future (2045-2065; B and D) monthly precipitation predicted by the CSIRO and MIROC models.

variation in precipitation is not much, but there are quite a few monthly variations. The CSIRO model predicted a decrease in maximum monthly precipitation and number of rainfall months. With the MIROC model, the maximum monthly precipitation for both present and future years is more or less the same and the number of rainfall months remain the same.

There has been an increase in temperature of approximately 1.5°C over the past 50-60 years. Both models showed an increase in yearly temperature relative to the temperature of past years. However, temperatures predicted by the CSIRO model were comparatively higher than by the MIROC model. Monthly temperature prediction also showed the same pattern with both models. The CSIRO model indicates that temperature may rise as high as 38°C while the high is 32°C with the MIROC model. Overall, the temperature is predicted to increase, with maximums and minimums for current and future years of 29°C and 30°C, and 27°C and 28.8°C, respectively. Temperature and precipitation predictions by MIROC may be more accurate than CSIRO based on root mean square errors of 3.3 (MIROC5) and 4 (CSIRO).

The most pertinent question is how the scenario of projected population growth and land-use change will impact water quality vulnerability, treatment resilience, and cope with changes due to climate change. Importantly, how will all of this impact the livelihood of people residing in these areas? Some likely changes may be reflected in terms of inundation and more sewer overflow contaminating water resources. Further, as photodegradation is a significant pathway of PPCPs degradation and bacterial growth diminishes at lower temperatures, it is likely that with increasing temperatures owing to climate change there will be an associated increase in bacterial growth and breakdown of PPCPs, implying some future influence on the resistant capability of microbes.

3.6 Resilience strategy and framework for both watersheds

To prepare a resilience strategy and framework, the previous master plan for Guwahati city and people's perceptions were evaluated. A sample of 110 households (414 people) was surveyed for public perception and awareness of environmental pollution and water use.

3.7 People's perception

This survey aimed to assess the quality of life conditions and perceptions of present environment pollution and satisfaction with its management (Fig. 6 a to d). Overall, people were well aware of water supply limitations and had faith in the public health department in that, without the proper treatment, they would not supply water to the population. People were informed about household filters that can help avail safe potable water, but awareness of emerging contaminants was much less.

Only 11% of people suggested that disinfectant should be used for water treatment. Illiterate or less educated people had an inadequate understanding of health risk caused by environmental and/or water quality problems. However, most people preferred groundwater for drinking purposes rather than tap water. Perception and awareness regarding various indirect issues including biomass burning and lifestyles not perceived by the public as being directly linked to water management,

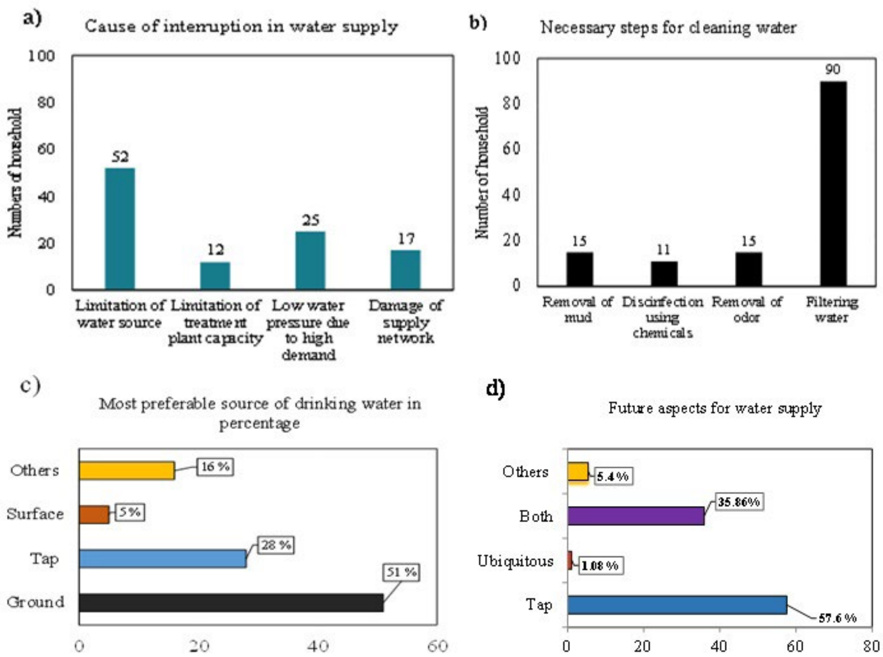

FIGURE 7. Awareness, perceptions, responses and willingness of the people of Guwahati city.

Years	Milestone	Strategy: Target 1	Target 2: Diffuse source pollution		Target 2: Solid waste	Target 3		Stakeholders
2018		1 Appoint the Kelani River Management Committee. (less than 1 month)						1: Government, factory, citizen, researcher.
2020	**Milestone1:** Investigate the current situation and establish policies.	2- Target 1: Sampling and analyzing. Identity the pollution, the source pollution and quantity. (1year) 2- Target 2: --Obtain the census of each type of householder. (1year) --Solid Waste Separation: food waste, paper, glass, plastic, metal, electronic waste, and others. (1year) 2- Target 3: Investigate the quantity of water usage. (year)						2- Target 1: researcher, factory. 2- Target 2: government 2- Target 3: researcher
		3 Monitoring system for WWTP/ river/ leakage/solid waste/ sand mining. 3 Target2-Categorize factories based on pollutant types and load, then warn the bad factories. (1yea r) (according to Water quality standards for effluent I river)						3: government 3-target 2: government, researcher.
2024	**Milestone 2:** --Complete construction in industrial zones and Section2. --Water quality: 30% pollutant is decreased. --Water quantity: the river level rise 20%.	**Target 1** --Design and build water waste treatment plant and sewer network. --Determine the monitoring methods; work out the payment scheme according to the pollutant load.	**Target 2** Type 1 Design and construct housing schemes for unauthorized household. Type 2+Section 2 (the area between water intake and Kaduwela) Build sewer network and WWTP.	Type 3 --Check the tank of type3 household when we do the census. --Ask to repair the tank. Recheck and re-repair every 5 years.	**Collection and transportation system:** Build facility; employ staff and trucks; place bins. Section2	**Target 3** 1 (5years) Establishment of rainwater harvest system (5 years to make sure every house uses the system) ○ Build permeable pavement Section2	(10 years) Education 1. Teach subjects on environmental protection from primary school 2. Organize workshops for the workers and citizens. 3. Make posters and paintings about environmental protection. 4. Develop water saving system for people. 5.Plan recreational areas/park and protected wetland along the river.	2- target1: researcher factory, 2: committee; employee, staff. 2-target2: government 2- target3: researcher
2028	**Milestone 3** --Complete construction in Section 3. --Water quality: 80% pollution is decreased. --Water quality: The river level rise 30%	--Monitoring the water quality of treatment plant. --Shutdown the factories whose effluents doesn't reach the standard.	Type 1&2+Section3 (the area between water intake and Colombo). Built sewer network and WWTP.		Section3	Section3		
2030	**Milestone 4:** --Complete contraction in Section1. --Water quality: 100% pollutant is decrease d. --Water quantity: the river level rise 40%.		Type 2 & Section1 (the areas between Kaduwela and Hawella) Built sewer network and WWTP.		Section1	Section1		

TABLE 1. Timeline, milestones and strategies for urban water management.

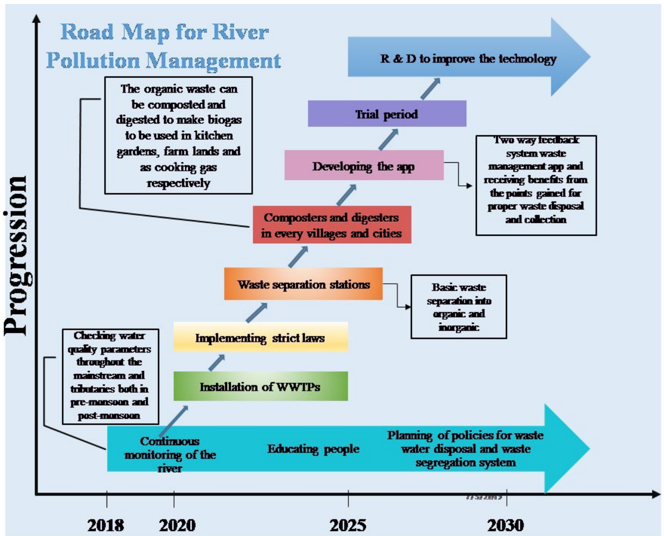

FIGURE 8. Roadmap for progression of Sustainable River Management.

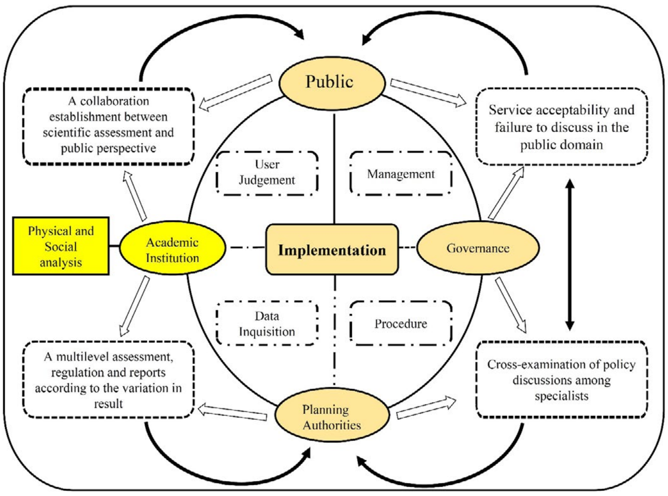

FIGURE 9. A framework for the participation of all stakeholders in planning and their roles in the implementation process (Kumari, 2019).

needs to be positively instilled in a meaningful manner for which a roadmap is required (Kumar et al., 2019).

3.8 Roadmap 3030: Vision for future decision-makers

Table 1 is divided into four major sections with demarcation of actions. Some key actions recommended for sustainable management of rivers are:

- Continuous monitoring of the river and tributaries for pollution load, as on-going assessments are required for management.
- Educate people to segregate waste at the source and provide incentive and/or recognition, at least initially. Include this in the education syllabus for children and allocate resources to help the public understand its importance.
- Provide proper waste collection systems, as no one wants to segregate waste if it is later mixed and their efforts wasted.
- Develop strict rules and policies for industrial wastewater discharge backed with robust local community effecting monitoring and implementation.
- Building WWTPs should be the responsibility of each institution and ward. Decentralized management is essential.
- Proper guidelines for permissible limits in discharge water should be developed and implemented.
- Provide tax incentives for incinerators or composters for effective waste management.
- Develop SMS (solid waste management system)

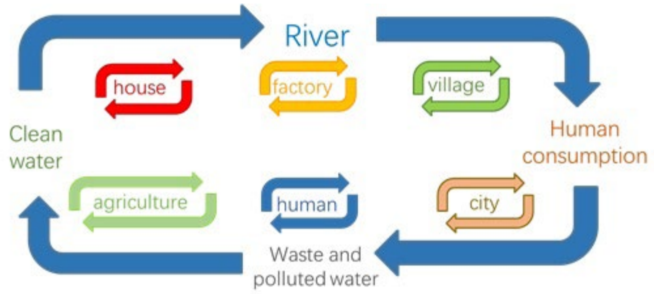

FIGURE 10. A depiction of "Limited Resources and Unlimited Loops".

application/app to report waste mismanagement, lodge complaints and receive feedback. Education can be included with instruction on simple techniques.

» Use waste materials in constructing roads and pavements and apply new technologies (e.g. construction of green buildings and soil-less farming).
» Increased navigation, inland water transportation and river tourism would lead to the cleaning of the river by dredging.

4. CONCLUSION

A multi-disciplinary approach requires the participation of scientific experts, engineers and architects, designers, planners, researchers and social scientists (Fig. 9) (Kumari, 2019). Local communities also need to be involved to ensure everyone has a voice. Guwahati and Colombo have many common problems and thus similar needs. Both cities need to enhance voluntarily public participation by frequently organizing authoritial events. Such events should firstly address social aspects and establish committees with varied expertise. Furthermore, everyone involved must understand that water resources are limited, and depend on the efficient functioning of "unlimited loops" (Fig. 10). Thus, assessment of emerging contaminants along with hydrological parameters may lead to the development of a resilience strategy and actionable framework for environmental safety and sustainability.

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Addressing non-economic loss and damage associated with climatic events: Cases of Japan and Bangladesh

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ABSTRACT

Non-economic loss and damage (NELD) could constitute a major proportion of the total loss and damage caused by any climate-related disasters. Despite this, most NELD has not been well measured and reported in most post-disaster reports and databases and has often not been given the attention it deserves in most disaster risk assessments and risk reduction interventions. Issues include a lack of proper recognition among the stakeholders engaged in disaster risk reduction and climate change adaptation of the value that society attaches to NELD, and a lack of simple methods to identify, prioritize and measure NELD. Keeping these barriers in view, this research aimed to develop an assessment framework to identify and prioritize NELD in key vulnerable sectors and make policy recommendations for addressing NELD. In this paper, results from case studies conducted in Japan and Bangladesh, two of the five project countries, are presented for a better understanding on this subject. The analytic hierarchy process (AHP) was used to identify and prioritize key NELD caused by climate-related disasters and to identify important risk reduction practices that could address NELD. The findings show that mental health disorders can be one common and important NELD in both Bangladesh and Japan despite their contrasting developmental situations. Inaccessible sanitation and waterborne diseases were Bangladesh-specific NELD, while poor risk governance and risk communication between local governments and communities were Japan-specific NELD.

KEYWORDS

Climate change adaptation, Climate-related disasters, Community, Disaster risk reduction, Loss and damage, Mental health, Non-economic loss and damage

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HIGHLIGHTS

- This paper identified non-economic loss and damage (NELD) such as loss of health, and loss of social, cultural, and environmental assets as important for achieving long-term and sustainable risk reduction. The disaster impact assessments and post-disaster needs assessments (PDNAs) that are being conducted must include NELD in order to inform the follow-up risk reduction interventions.
- The paper identified that NELD has not been well considered in disaster risk reduction and climate change adaptation interventions and that NELD is difficult to adequately understand, identify and estimate due to the complex pathways through which various different types of NELD manifest.
- This paper demonstrated the application of an analytic hierarchy process (AHP) for identifying and prioritizing key types of NELD and risk reduction solutions for addressing NELD caused by climate-related disasters.
- The paper highlighted that issues such as mental health disorders can be a common type of NELD in Bangladesh and Japan. There is a need to strengthen the existing risk reduction measures addressing mental health issues, and interventions should be evaluated for their ability to address NELD.

1. INTRODUCTION

Loss and damage (L&D) caused by climate-related disasters is one of the most crucial challenges in the context of climate change. In particular, non-economic loss and damage (NELD), such as loss of human functions, social and cultural assets, and environmental assets, has not been well considered in climate change adaptation (CCA) and disaster risk reduction (DRR)-related decision-making. Recognizing the importance of this issue, the sixteenth session of the Conference of the Parties (COP16) under the United Nations Framework Convention on Climate Change (UNFCCC) suggested the necessity to address L&D, and COP19 established the Warsaw International Mechanism (WIM) to tackle L&D (Decision 2/CP.19) in 2013, which was further strengthened by the Paris Agreement in 2015. The WIM highlights NELD as a key area of its work with a five-year rolling work plan, and its Executive Committee established an expert group on NELD to enhance data on and knowledge of NELD (UNFCCC, 2017). Further, the recently concluded COP24 in Katowice, Poland emphasized the need to address loss and damage in global stock-take rules and transparency rules.

Despite these efforts, the countermeasures to address NELD are still lacking at the national level because of limited understanding on the subject and limited means to identify, measure and estimate, as well as mitigate NELD (UNFCCC, 2013; UNFCCC, 2014; UNFCCC, 2017). NELD has also not been sufficiently reported in most post-disaster reports and databases (Swiss Re, 2013; Chiba, Shaw, & Prabhakar, 2017). The low attention paid to NELD can result in significant underestimation of actual disaster losses, leading to insufficient and sub-optimal investments in recovery, suboptimal DRR and CCA decision-making, and a decrease in community resilience to climatic disasters (IPCC, 2014; Morrissey & Oliver-Smith, 2013; Chiba, Prabhakar, Islam, & Akber, 2018).

Keeping the above background in view, this research aimed to understand NELD caused by recent past major climate-related disasters and develop an assessment framework to identify and prioritize NELD. This paper, in particular, provides a comparative analysis of key NELD in Bangladesh and Japan (Chiba & Prabhakar, 2017; Chiba et al., 2018). The findings will contribute to enhanced understanding and data collection of key NELD under the UNFCCC process and at the national and local levels.

2. METHODOLOGY

This study involved country-level expert consultations, participatory approaches such as community-level focus group discussion (FGDs), questionnaire surveys, and the analytic hierarchy process (AHP) to identify and prioritize key NELD caused by climate-related disasters in two study locations in Bangladesh and Japan. The process helped to identify important issues in NELD, and important risk reduction practices that could address NELD from the perspective of the affected local communities and local government officials (Chiba & Prabhakar, 2017; Chiba et al., 2018). The study in two countries helped to obtain an understanding of contrasts and commonalities in NELD under two different developmental situations that are elaborated in this paper.

2.1 AHP-based approach

The study applied community-based participatory approach with the analytic hierarchy process (AHP) to examine key types of NELD caused by climate-related disasters in Bangladesh and Japan (Chiba & Prabhakar, 2017; Chiba et al., 2018). The AHP is a multi-criteria decision-making tool that can be used to solve complex decision problems (Saaty, 1990). It has been widely applied to group decision-making, as well as questionnaire surveys, in many disciplines; and is based on a multi-level hierarchical structure consisting of the goal, criteria, sub-criteria (i.e., indicators), and alternatives (i.e. practices). It uses a set of pairwise comparisons to derive the weights of importance for each element at each level, using a scale of absolute judgements that represents how much more one element dominates the other.

In this study, elements of AHP analysis for NELD consisted of decision criteria, indicators and alternatives (i.e. risk reduction practices) for addressing NELD (Chiba & Prabhakar, 2017; Chiba et al., 2018). The AHP elements were identified, evaluated and prioritized by following sequential steps: literature review; expert and community consultations; and questionnaire surveys. Comprehensive literature review in the context of DRR

	Bangladesh	*Japan*
Number of respondents from local communities	247	175
Number of respondents from local government officials	26	22
Who undertook fieldwork	NELD expert	NELD expert
When it was undertaken	November – December 2016	October – November 2016
Language used	Bengali	Japanese

TABLE 1. Questionnaire surveys in Bangladesh and Japan (Source: Chiba & Prabhakar, 2017; Chiba et al., 2018).

and CCA was conducted to understand NELD, expert consultations assessed the suitability of proposed NELD-related elements identified from the literature in each country context, and community consultations through focus group discussions then narrowed the scope of NELD-related elements and identified key NELD-related elements from the affected community perspective. Subsequently, structured questionnaire surveys helped prioritize key NELD-related elements from a broader sample of affected local communities and local government officials (Table 1). The questionnaires consisted of key criteria, indicators and practices examined by expert and community consultations.

2.2 Study location

2.2.1 Bangladesh: Koyra Upazila, Khulna

Koyra Upazila in the Khulna district of Bangladesh was selected as the study location for several reasons, including serious L&D from Cyclone Aila in 2009, and the rich social, cultural and environmental assets that were exposed to the cyclone (Chiba et al., 2018). Koyra has a total population of 193,931, with 50.9% female population and a population density of 861 per sq. km, growing at a rate of 1.7% per annum (Bangladesh Bureau of Statistics [BBS], 2011). The majority of households depend on agriculture, fishing, forestry and labour for their livelihoods. The annual rainfall ranges from 1,500 mm to 2,000 mm, with about 70% of the total rainfall in the monsoon season.

Cyclone Aila in 2009 is one of the most severe disasters that Bangladesh has suffered during recent years, followed by Cyclone Sidr which happened in 2007 (Chiba et al., 2018). It affected an estimated 3.90 million people in 11 coastal districts in Bangladesh. The cyclone severely affected Koyra killing 57 people (United Nations Development Programme [UNDP], 2009). Approximately 300,000 people were affected, and thousands of houses were completely (49,000) or partially (27,000) destroyed. Significant L&D, especially in the farming and fishing sectors, were reported due to inundation of paddy fields, shrimp farms (fish ponds), and sweet fish ponds with saline water. About 40,000 people had migrated from Koyra by October 2009 (European Commission Humanitarian Aid [ECHO], 2009).

2.2.2 Japan: Nachikatsuura Town, Wakayama

Nachikatsuura Town, Wakayama Prefecture in Japan, was chosen as the study site for several reasons such as the severity of L&D from Typhoon Talas, the 12th typhoon of the season in 2011, as well as the vulnerability of the rural small municipality with limited capacity and social, cultural and environmental assets that were exposed to NELD (Chiba & Prabhakar, 2017). Nachikatsuura is located in the southeast part of Wakayama on the Kii Peninsula, bordering the Pacific Ocean, and has 88% of the total area under forests (Ministry of Agriculture, Forestry and Fisheries [MAFF], 2015). It is also a tourist destination with UNESCO-designated World Heritage Sites, including Kumano Nachi Taisha Grand Shrine and Nachi Falls. The town lies in a warm-temperate zone, has an average annual precipitation of more than 2,000 mm, with the highest recorded rainfall of 4,000 mm in 2011 (Nachikatsuura Town, 2013). On average, the town is hit by 3.2 typhoons every year (Japan Meteorological Agency [JMA], 2017). It has a total population of 15,946 (male: 7,405; female: 8,541) with a household count of 8,046 as of February 2017 (Nachikatsuura Town, 2017). With 39% of the population above 65 years, a large proportion of whom are single; this town is ranked 9th in Wakayama in terms of proportion of aged population (Wakayama Prefecture, 2016).

Typhoon Talas in 2011 is one of the most severe disasters that Nachikatsuura has suffered during recent years, with the highest casualties in Wakayama Prefecture (Chiba & Prabhakar, 2017). The main causes of damage were debris flow and river flooding from the heavy rainfall that accompanied the typhoon. As a result, 2,410 households were affected, 29 people died (including one missing), 14,458 people were evacuated (91% of the town

Rank	*Criteria*	*Indicators*	*Practices*
Community members			
1	Compliance with societal value	Inaccessible sanitation	DRR policy and planning
2	Relevance to DRR/CCA policy and planning	Waterborne diseases	DRR policy and planning
3	Measurability and verifiability	Mental health disorder	Disaster compensation
Government officials			
1	Compliance with societal value	Waterborne diseases	Disaster compensation
2	Relevance to DRR/CCA policy and planning	Inaccessible sanitation	Cyclone shelter policy
3	Measurability and verifiability	Schools discontinued	Cyclone shelter policy

TABLE 2. List of NELD-related elements prioritized by community members and government officials in Koyra (Source: Chiba, 2018).

Rank	Criteria	Indicators	Practices
Community members			
1	Compliance with societal value	Less collaboration between local government and community	Emergency shelters
2	Relevance to DRR/CCA policy and planning	Less community participation in decision-making	DRR policy and planning
3	Measurability and verifiability	Mental health disorder	Disaster compensation
Government officials			
1	Compliance with societal value	Mental health disorder	DRR policy and planning
2	Relevance to DRR/CCA policy and planning	Less collaboration between local government and community	Emergency shelters
3	Measurability and verifiability	Chronic diseases	Disaster compensation

TABLE 3. List of NELD-related elements prioritized by community members and government officials in Nachikatsuura (Source: Chiba & Prabhakar, 2017).

population), 103 houses were completely destroyed, and 17 public facilities were affected. The economic damage totalled JPY2,283 million (Nachikatsuura Town, 2013).

3. RESULTS AND DISCUSSION

3.1 Bangladesh

3.1.1 Community perspective

Table 2 shows the overall results of NELD-related elements prioritized through questionnaire surveys to community members in Koyra. "Compliance with societal value" was a principal criterion for decision-making. The community members put more emphasis on water and sanitation indicators including "inaccessible sanitation" and "waterborne diseases", and a health-related indicator of "mental health disorder". They, in turn, determined the "DRR policy and planning" as the most effective risk reduction practice to address NELD.

3.1.2 Local government perspective

As shown in Table 2, "Relevance to DRR/CCA policy and planning" was considered the most important criterion by local government officers for identifying appropriate indicators and practices. The government officers also identified "waterborne diseases", "inaccessible sanitation," and "school discontinued" as important indicators for assessing the effectiveness of interventions and that "DRR policy and planning" as the most effective practice to address NELD.

3.2 Japan

3.2.1 Community perspective

Table 3 presents the overall results of NELD-related elements prioritized through questionnaire surveys to community members in Nachikatsuura. Similar to the case of Bangladesh, "compliance with societal values" appears to be the dominant criterion for decision-making, and community members prioritized local governance indicators such as "less collaboration of local government with local communities", "less participation of community in decision-making", and "mental health disorder" as important indicators for identifying effective practices for addressing NELD. The community members prioritized "emergency shelters" to secure safe locations for local communities to be the most effective risk reduction practice to address NELD. The focus on emergency shelters indicates the short-term nature of the NELD impacts, which was not the case in Bangladesh, where long-term impacts of NELD appeared to have dominated decision-making.

3.2.2 Local government perspective

Similar to the community perspective, "compliance with societal value" was considered most important by local government officials. The indicators of "mental health disorder", "less collaboration of local government with local communities" and "chronic diseases" were the three most prioritized indicators and, in contrast to the community perspective, "DRR policy and planning" was the most effective risk reduction practice to address NELD, indicating the long-term view taken by government officials.

3.3 NELD and development nexus

Comparing results between Bangladesh and Japan may provide some insights into the association between the developmental state of the country and opinions of respondents in terms of NELD indicators and practices. The results indicate that both Bangladesh and Japan placed high importance for addressing the issue of mental health disorder (Table 4). Different characteristics of these countries in terms of NELD could also be

NELD		*Bangladesh: Koyra*		*Japan: Nachikatsuura*	
Impact area	*Indicators*	*Community*	*Gov't*	*Community*	*Gov't*
Health	Mental health disorder	•		•	•
	Chronic diseases				•
Water & sanitation	Inaccessible sanitation	•	•		
	Waterborne diseases	•	•		
Education	Schools discontinued		•		
Local governance	Less collaboration			•	•
	Less participation			•	

TABLE 4. Comparison of top three NELD in this study (Note: Gov't = Local government officials, • = prioritized. Source: Authors).

found. In the case of Bangladesh, issues such as inaccessible sanitation, and waterborne diseases took precedence in discussions with community members and government officials. This is in line with the significant challenge that developing countries, in particular, are facing after cyclones due to the breakdown of water and sanitation systems and the dearth of safe drinking water (Haque et al., 2012). On the other hand, Japan's case has highlighted challenges in local risk governance raising the need for close coordination and communication with community associations, voluntary organizations, and volunteer groups, and for establishing communication channels to seek opinions and consensus-building with communities.

4. CONCLUSION

The study intended to understand NELD caused by recent past major climate-related disasters and developed a methodological framework to identify and prioritize NELD and important practices to address NELD. The cases of Bangladesh and Japan were presented. The AHP was applied to identify and prioritize key types of NELD caused by climate-related disasters and to find important risk reduction practices that could address NELD.

For Koyra, from the community perspective, the study identified "compliance with societal value" as an important criterion, "inaccessible sanitation", "waterborne diseases" and "mental health disorder" as important indicators, and "DRR policy and planning" as an important risk reduction practice. On the other hand, for Nachikatsuura, the study specified "compliance with societal value", "less collaboration of local government with local communities", "less participation of the community in decision-making", "mental health disorder", and "emergency shelter" as essential NELD elements. The results indicate that both Bangladesh and Japan placed high importance on addressing the issue of mental health disorder. Bangladesh identified serious issues of inaccessible sanitation and waterborne diseases, while Japan highlighted challenges in local risk governance in terms of communication between local government and communities. There is a need for these prioritized NELD to be incorporated into the post-disaster needs assessments (PDNAs), and post-disaster impact assessments conducted in both countries. Local governments in both countries have damage assessment formats that are filled in during disasters, and that ensure the prioritized NELD are incorporated into these formats for regular data collection and use for risk reduction decision making. The findings will lead to enhancing the UNFCCC process in terms of NELD-related data and knowledge.

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Opportunities and challenges of compliance to safe building codes: Bangladesh and Nepal

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ABSTRACT

This paper discusses the opportunities and challenges of compliance to safe building codes in Bangladesh and Nepal for increased disaster resilience. Recent disasters in both countries highlight that non-compliance to building codes is one of the significant causes of building-related disasters. Increased institutional and community awareness of the importance of safe building codes presents an opportunity to explore barriers and enablers to compliance. Building codes do exist in the two countries, but compliance is generally absent or limited, especially in the widespread informal building sector, which has restricted access to codes and little financial capacity to comply. The research undertaken is significant for two reasons: (1) disaster resilience is of high concern nationally in both Bangladesh and Nepal, where safe buildings are required to protect human lives and assets; and (2) the UN Sustainable Development Goals and Sendai Framework for Disaster Risk Reduction, among others, emphasize the importance of building codes. The project was formulated with the aim of identifying pathways for facilitating voluntary compliance to safe building codes for disaster resilience in Bangladesh and Nepal. The research methodology included two main components: a comprehensive literature review to identify potential solutions and gaps in terms of disaster resilience; and semi-structured interviews, including focus group discussions with stakeholders around challenges and opportunities for facilitating voluntary compliance to safe building codes. The findings were analyzed to understand how building codes might be more widely adopted to enable disaster resilience. A key output of the research is a training handbook on safe construction relevant to the informal sector and produced in local languages of the two case study countries.

HIGHLIGHTS

- Shared understanding on evidence-based knowledge as a critical component in the commitment to local action.
- Institutional and community awareness of the importance of compliance with and barriers to enforcement of codes.
- Fostering communities of collaborative practice.
- Development of local and international dissemination networks.

1. INTRODUCTION

1.1 The case for exploring building codes compliance

In low-income countries, such as those in South Asia, building code frameworks are generally inadequate, reflecting the situation in the case study countries discussed here—Bangladesh and Nepal—where the bulk of buildings are constructed informally without adherence to building codes. Rough estimates indicate that over 80% of housing in these countries are built using informal construction (United Nations Human Settlement Programme [UN-HABITAT], 2010; World Bank, 2007). Even in the small proportion of formal sector housing, adherence to building codes is generally

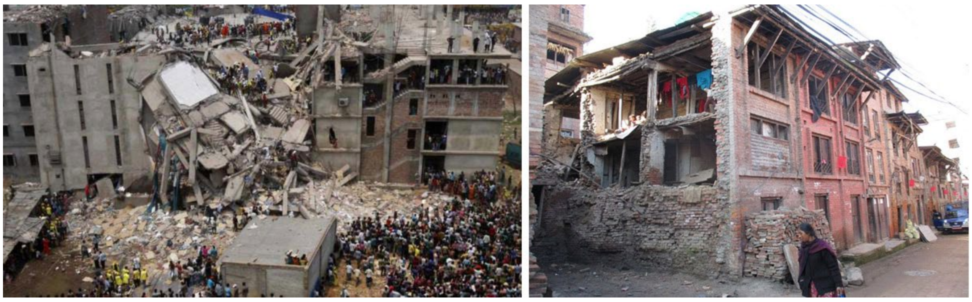

FIGURE 1. Recent disasters such as the Rana Plaza Garment Factory collapse in Bangladesh (left) (courtesy of Daily Star) and the 2015 Earthquake in Nepal that devastated many buildings (right) have raised local interest in building codes.

lacking or limited at best. Unlike developed countries, building codes are not integrated in building and planning regulations. Both Bangladesh and Nepal have building codes (Department of Urban Development and Building Construction [DUDBC], 2005; Housing and Building Research Institute [HBRI], 2015), but enforcement and compliance face significant challenges.

Affordability is a key constraint for the vast bulk of the population that builds informally. The codes provide good practice guidelines often based on developed country models and can thus be onerous and difficult to implement in the local socio-economic context. The codes also include guidelines for making buildings resilient to disasters, termed as "safe building codes". If these codes are followed to even a minimum, a level of disaster resilience can be achieved. To support this process, a "grey" document or guidance/training handbook, locally contextualized and achievable within the socio-economic constraints of developing countries, was developed as a key output of the project (Ahmed et al., 2018).

Both Bangladesh and Nepal face disaster risks from various types of hazards including earthquakes, floods, windstorms and landslides. Both countries are also severely threatened by climate change with increasing magnitude and frequency of hazards as indicated in the Global Climate Risk Index 2019 (Sarkar, 2018). These disasters exact a severe toll on buildings. Recent devastating disasters in Bangladesh and Nepal have spurred significant institutional and community interest and activity on disaster resilient construction and safe building codes (see Figure 1). Rising interest indicates there might be an opportunity for voluntary adoption of safe building codes and, therefore, providing a relevant and opportune time to undertake research on this issue.

The research problem presented is complex, multi-faceted and deeply entrenched in socio-economic, political and cultural conditions that have taken root over a long period of time. Addressing all of these complex issues would require a social transformation of a profound nature, and at this point in time, perhaps only the small beginnings of such transformation are evident from the increase in institutional interest in building codes after the 2015 earthquake in Nepal and the Rana Plaza building collapse in Bangladesh. The research conducted, therefore, does not intend to provide quick-fix or simple solutions, but rather identifies a plausible trajectory of social transformation that may realize a greater and more widespread voluntary compliance of safe building codes in the long term.

1.2 Rationale for research context

Within the Asia-Pacific region, South Asia has very low economic and human development; after Sub-Saharan Africa, it is the least developed region in the world (United Nations Development Programme [UNDP], 2015; World Bank, 2016). The region is also highly vulnerable to disasters (Gaiha, Hill, & Thapa, 2012). A quarter of the world's population lives in South Asia (World Bank, 2016) and it is one of the most densely populated regions in the world. The impacts of disasters in the smaller South Asian countries are pronounced and recovery difficult because of their lower socio-economic status compared to the largest South Asian country, India (Sarma, 2015). The context of this research project is focused on two of the smaller South Asian countries, namely Bangladesh and Nepal, but can offer relevant lessons to the wider region. Transfer of lessons and cross-learning can be achieved between these countries due to the similarity in socio-economic conditions. Bangladesh and Nepal are disaster hotspots and recent events have instigated an interest in safe building codes, therefore allowing cross-learning between nations to achieve disaster resilience.

2. METHODOLOGY

The research methodology followed an exploratory approach, where ideas emerged from the data in an inductive vein. A set of research questions, linked with the aim and objectives, guided the research methodology, and comprised a combination of literature review and field investigations.

2.1 Research questions

In response to the research problem identified above, the following key exploratory research question was formulated: how can compliance to voluntary safe building codes be facilitated in the current contexts of Bangladesh and Nepal for increased disaster resilience?

To seek answers, the following set of sub-questions were posed:

» What are the strengths and weaknesses in terms of disaster resilience of building codes globally, and specifically in the project countries?
» What knowledge and insights can be gained from institutional and community stakeholders in the project countries on opportunities and challenges for facilitating compliance to safe building codes?
» What practice-and-policy guidelines are required to facilitate voluntary compliance and implementation of safe building codes?

2.2 Aim and objectives

The aim and objectives of the project are in line with the research question and sub-questions, and define the framework of activities:

Aim:

» To identify pathways for facilitating voluntary compliance to safe building codes for disaster resilience in Bangladesh and Nepal.

Objectives:

» Review global and local literature in the project countries including building codes and regulations to identify potential opportunities and gaps in terms of disaster resilience;
» Engage in consultations with key stakeholders at institutional and community levels to understand challenges and opportunities for facilitating voluntary compliance to safe building codes;
» Produce practice-and-policy guidelines for facilitating voluntary compliance and implementation of safe building codes extending to informal sector buildings;
» Involve early career researchers in the project countries to meet the project objectives and thereby build local research capacity; and
» Explore the possibilities of forming networks and cross-learning between the project countries and wider regional and international knowledge dissemination.

2.3 Methodological approach

To answer the research questions and sub-questions, a qualitative exploratory methodology was adopted as it assists in developing as complete an account of the phenomenon under investigation as possible (Quinlan, 2011). The intent of the research is well-aligned with this approach in that it explores subjective experiences of specialist practitioners to understand the phenomenon.

The methodology comprised two components. The first involved a comprehensive literature review. Both academic and grey literature were reviewed to identify potential solutions and gaps in terms of disaster resilience. The second involved semi-structured interviews and focus group discussions to identify challenges and opportunities for facilitating voluntary compliance with safe building codes.

3. RESULTS AND DISCUSSION

3.1 Overview of the global literature review

The results of the literature review show that the outcome of many disaster events can be traced to societal decisions in relation to land-use planning (development location) and building systems (construction techniques). Conversely, building and planning regulations are considered a powerful tool for increasing community resilience and reducing risk to disaster events (Bernicat, 2015; World Bank, 2015). Along with the UN, prominent international development agencies such as the World Bank, United States Agency for International Development (USAID) and Japan International Cooperation Agency (JICA) are attempting to address the global priority of resilient buildings and are promoting the uptake, compliance and implementation of safe building codes (JICA, 2016; USAID, 2016; World Bank, 2015). As the World Bank's Global Facility for Disaster Risk Reduction (GFDRR) (2016) aptly states: "Building code compliance saves lives" (p. 2), an indication of its intent to promote building code compliance. Although building codes and regulations are often used simultaneously, they are significantly different in meaning and scope. The broader term "building regulations" used in developed countries often refers to both land-use planning and building codes (World Bank, 2015). However, in many developed countries such as Australia, there is a division between building codes and regulations, where building codes relate to technical building provisions or construction requirements (Australian Building Codes Board [ABCB], 2018) and regulations concentrating on administrative processes such as building and planning permits (e.g. New South Wales Environmental Planning and Assessment Act, 1979). What is important, though, is that the integration of building codes and regulations has been advantageous in minimizing the impact of disasters. Their importance as a mechanism to protect life and build community resilience has become the focus of countries more recently (United Nations Economic and Social Commission for Asia and the Pacific [UNESCAP], 2012). Japan, for example, maintains some of the world's strictest codes, although it has taken more than seven decades and a series of disasters for the country to have reached this level (Glanz, & Onishi, 2011).

The situation is vastly different for many developing countries where building codes are often not mandatory (Thiruppugazh, 2008). Bangladesh has a National Building Code, yet it has been explained that "the Building Code is not an independent legislation or act, rather it is a national level approved document" (HBRI & Bangladesh Standard Testing Institute [BSTI], 2006, p. iv). In addition, in developing countries, it is widely reported that enforcement and compliance of codes face serious barriers, including ineffective governance and corruption (GFDRR, 2014), adding further complexity and resulting in greater vulnerability to disasters.

Building codes may be prescriptive- or performance-based. While prescriptive regulations are generally inflexible, performance-based codes provide more flexible approaches. This flexibility allows for the development of alternative solutions to suit individual building requirements, i.e., achieving the same regulatory goal, but from a different perspective (Cote & Grant, 1988; Gann, Wang, & Hawkins, 1998). This approach was considered relevant in this project because of the limitations of the regulatory framework in the case study countries.

The brief literature review highlighted systemic irregularities, lack of legitimacy and procedural justice as key issues impeding compliance in developing countries, and not necessarily the absence of codes. Furthermore, attention is drawn to the need for more contextualized codes that address issues associated with the more traditional means of construction in rural areas and urban informal settlements. Safety in the built environment is a priority for governments and the essential purpose of building codes and regulations. However, codes are of no use if there is a low level of compliance, hence the examination of the various subjects that relate to building codes and compliance with a brief comparison of practices in developed countries and developing countries was undertaken in this project.

3.2 Findings from the case studies

Empirical investigations were conducted in parallel in the two case study countries, Bangladesh and Nepal, as well as reviews of local literature and building codes. A wide range of stakeholders were consulted from academia and industry, as well as at the low-income community level through masons. The key findings from the case study investigations are summarized below.

3.2.1 Bangladesh

Bangladesh, a small country, hosts a large population where the capital city, Dhaka, accommodates close to 20 million people. The investigations focused largely on Dhaka because of its national prominence. Due to the large population, the city has been growing in a very irregular form and has urbanized in a very haphazard manner. Building construction at present, and in the past, is not given due attention particularly with regard to the existing building regulations and codes (see Figure 2). Therefore, over 90% of buildings that have already been constructed in the city are highly vulnerable to earthquakes and other hazards. The city has experienced several large building collapses where many people have died, many of which were not due to natural hazard events, but rather because of deficient construction that did not follow building codes. Given this situation, it is extremely important for the city, and the whole country, to identify effective mechanisms to promote the implementation of building codes. Those who deal with the Bangladesh National Building Code (BNBC) (e.g. engineers) should be trained at the university level through incorporating it into the curriculum; at the moment, the codes are not dealt with in sufficient detail in the curriculum. In addition, workers in the building construction industry can be trained through various ways such as providing incentives or rewards, and implementation of the BNBC can be promoted through such training.

In Bangladesh, cities like Dhaka experience widespread violation of building codes. A large number of buildings that have already been constructed in Dhaka in a haphazard manner are at risk of collapse during earthquakes and other hazards; according to a survey of a national daily newspaper, about 78,000 buildings out of 326,000 in Dhaka have been identified as vulnerable to disasters (Sarker, 2009). Therefore, there remains a need for the city to identify mechanisms on how to effectively comply with building codes. In this case, continuous assessment of opportunities and challenges can assist in direct action. Future research can include assessing

FIGURE 2. In rapidly urbanizing Dhaka, little attention is given to building codes.

different stakeholders' opinions at a larger scale that also encompasses all city communities so that they can freely share their ideas and experiences. In addition, taking examples from countries where building codes are successfully implemented and research activities to explore mechanisms to promote such application of codes can be initiated.

3.2.2 Nepal

The investigations in Nepal were undertaken in three municipalities and focused on earthquakes because most of the building codes relate to this hazard after the massive earthquake in 2015. It was found that there are significant activities by the municipal authorities including public awareness campaigns, different levels of training such as mason training, dissemination of the National Building Code (NBC) by megaphones and media channels, and weekly household owner counselling for building permit applications. At the state level, guidelines, construction specifications, pamphlets and prototype designs have been developed, together with training on safe building construction for engineers, sub-engineers, assistant sub-engineers and masons. However, the NBC has focused more on new or modern technology, such as reinforced concrete. The highly dense traditional settlements have specific construction characteristics which the NBC has not been able to take into consideration in its work.

One of the biggest challenges is the lack of awareness of homeowners regarding safety, the NBC and its compliance (see Figure 3). In the older parts of cities such as in Kathmandu, buildings had been constructed a long time ago following traditional styles when building codes did not exist in Nepal and often stand on small lots, and implementation of the NBC in these areas is difficult. Large stocks of old buildings exist, which were not built according to building codes and where retrofitting is challenging; provision of transport accessibility in these densely built areas with small lot sizes as required by current codes would be impossible without demolition of buildings. Construction is often not undertaken under the supervision of skilled built environment professionals (engineers and architects) due to economic constraints. Many such professionals lack sufficient design knowledge, especially in city centres where structures such as high-rise buildings are being constructed. At the government level, there is inadequate institutional capacity and political interference. Thus, the study recommends capacity development, raising awareness of different stakeholders, solutions for retrofitting existing buildings, and incentive mechanisms. Further studies are needed to find ways to formalize and standardize safe construction using traditional technology (i.e. for informal settlements).

FIGURE 3. In rapidly urbanizing cities of Nepal, such as in the Kathmandu valley, buildings are constructed with no awareness of building codes.

3.3 Discussion of key results

The discussion of the key results of the research is structured along the main research question and sub-questions, drawn from the literature review and case studies, and summarized below.

3.3.1 Response to sub-question 1: Strengths and weaknesses of building codes

- Building regulations vs building codes: A key weakness in developing countries, including the case study countries, is the lack of distinction between building regulations and building codes. Building codes and regulations are often used simultaneously, but their scope and meaning vary.
- Integration of building regulations and building codes: The level of differentiation and integration between regulations and codes varies widely, both in developed and developing countries, making compliance and enforcement complex for achieving disaster resilience.
- Mounting emphasis to act: In many developing countries, building codes exist but implementation is often not mandatory. However, after recent disasters in the case study countries, there is a stronger emphasis on the implementation of codes.
- Need for greater intervention: Despite the mounting emphasis on many existing challenges in terms of capacity, compliance and enforcement, there is little knowledge of them even among built environment professionals.

3.3.2 Response to sub-question 2: Knowledge and insights from stakeholders

Challenges:

- Large informal sector: As mentioned in the

FIGURE 4. In both Bangladesh (left) and Nepal (right) there is a variety of informal construction from brick-and-concrete buildings to buildings made of traditional and less durable materials.

Introduction, section 1.1., a vast bulk of buildings in both these countries are built informally. In Nepal, there is an attempt to contextualize building codes for small buildings and those built with traditional materials using a "Mandatory Rule of Thumb" approach, but there is no such effort in Bangladesh (see Figure 4).

» Lack of awareness and knowledge: Although building codes exist in both countries, there is a widespread lack of awareness and knowledge on how to understand and apply the codes. Codes are often understood as increasing resilience only to earthquakes, and not the wider range of hazards that impact these countries.

» Lack of capacity: There is a need for capacity building at all stakeholder levels from formally trained built environment professionals to informal sector construction workers.

» Perception of extra cost: Building codes are widely perceived as costly and hence avoided, without any serious cost-benefit analysis presented by professionals or demanded by building owners.

» Corruption: Building codes are by and large ignored, if known at all, and building approvals are often received through bribery. Often such corrupt acts are facilitated through political connections; political patronage and bribery are some of the key corruption instruments.

Opportunities:

» Institutional initiatives: In Bangladesh, there is a building resilience program supported by the World Bank. Similarly, in Nepal, there is strong international support and the government has mandated the implementation of building codes, which provides an opportunity for promoting compliance.

» Educational initiatives: There are some initiatives to include education on building codes at the tertiary level such as at the Bangladesh University of Engineering and Technology (BUET) and the Institute of Engineering, Tribhuvan University, Nepal.

» Awareness and capacity building: There are quite a few initiatives in Nepal such as the "Earthquake Safety Day" and training of masons. While Bangladesh is lagging behind, there is an opportunity for the country to learn from these initiatives.

3.3.3 Response to sub-question 3: Practice-and-policy guidelines for voluntary compliance

» Increasing awareness: There is scope for a much more concerted and extensive effort to raise awareness. Policies could be implemented through public, private and civil society partnerships.

» Professional bodies reinforcing codes in education: Policies should be targeted for capacity building at the tertiary level education of built environment professionals to the training of construction workers. The "Grey Building Handbook" produced in this project can serve as a training manual for informal sector builders (Ahmed et al., 2018).

» Financial incentives for compliance: A range of policy instruments including financial incentives, "reward-and-punishment", and regulatory code of professional practice could move forward the agenda for building code compliance.

» Formation of new authorities/institutions: There is the need for a specific authority for implementation and enforcement of building codes.

» More integrated and targeted guides: There is scope here for the integration of codes and regulations, as well as building codes dealing with a wider range of hazards.

3.3.4 Responses to the main research question

Various approaches were suggested in the interviews and literature to catalyze voluntary compliance such as incentives, tax benefits, reduced insurance premiums and reverse mortgages, inclusion in educational curricula and school buildings, contextualized approaches according to country, sector-wide training that includes construction workers and informal builders, and perhaps most importantly, raising awareness. A mixture of such strategies in varying extents in the formal and informal sectors as discussed below can be an effective way forward in addressing the main research question.

Formal sector

In Bangladesh and Nepal, there are already initiatives for implementing building codes and regulations in the formal sector although gaps exist in the coverage and reports of violation and corruption. Capacity building, financial incentives, education and enforcement (fines, rewards, monitoring of practitioner licensing, etc.) are suggested mechanisms for promoting voluntary compliance. There is some evidence of low-scale voluntary implementation and these can be a basis for upscaling voluntary compliance initiatives.

Informal sector

Raising awareness is the main pathway to achieving voluntary compliance in the informal sector. A large part of the population in the case study countries live in informal settlements and rural areas, and the high-rise building standards specified in the codes are simply not feasible. Therefore, it makes sense to begin with the most basic and critical life-saving codes, embodied in the Grey Building Handbook, which is a training manual derived from the research contextualized for Bangladesh and Nepal, where a suite of safe building options is presented to match different incomes and site conditions (Ahmed et al., 2018). The approaches in Nepal, such as specific codes for traditional and small buildings and training of masons, address the safety needs of the large informal sector. While there is scope for upscaling these approaches in Nepal, there is also an opportunity for Bangladesh to benefit from these practices, and contextualize and implement such approaches.

4. CONCLUSION

The overarching goal of this project was to undertake research on approaches and options for promoting voluntary compliance to safe building codes for disaster resilience, focusing on two case study contexts – Bangladesh and Nepal. A secondary, though equally important, goal was to develop a handbook that would enable practitioners, local builders and construction workers in low-income communities to begin the process of constructing disaster-resilient buildings and eventual compliance to building codes.

The project has revealed valuable lessons from the resonance of the findings of the literature review and empirical investigations. The similarity of findings in the two case study countries indicate the problem being related to issues of governance, institutional and technical capacity, and public awareness. Despite the similarities, there were lessons unique to each country, providing an opportunity for sharing of lessons through collaborative research and the considerable benefits that can arise from knowledge sharing and the cross-fertilization of expertise and ideas. Experience from the project has shown that the engagement of a wide range of stakeholders in both countries has helped raise awareness of the building codes issue. Compliance to building codes is a complex issue, yet the signs uncovered of growing awareness and initiatives indicate that disaster resilience through widespread voluntary compliance of safe building codes and regulations is a possibility that might be realized over time in the future.

The research is significant because disaster resilience is of high national concern in both Bangladesh and Nepal because of the frequent and various disasters that impact these countries. At the global level, the significance of the project lies in its alignment to the UN's global agendas including the Sendai Framework for Disaster Risk Reduction and the Sustainable Development Goals, both of which promote safe building practices.

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CORRECTION NOTICE

In the article "Ahmed, I., Gajendran, T., Brewer, G., Maund, K., von Meding, J., Kabir, H., ... Sitoula, N. (2019). Opportunities and challenges of compliance to safe building codes: Bangladesh and Nepal. APN Science Bulletin, 9(1). doi:10.30852/sb.2019.834", a correction was made on 1 June 2021 at the corresponding author's request to include the following entry in the references list of the paper: Ahmed, I., Gajendran, T., Brewer, G., Maund, K., von Meding, J., Kissa, G., ... & Sitaula, N. (2018). Grey building handbook. Callaghan, NSW: University of Newcastle. Corresponding to the correction, citations have been included within the text in sections 1.1, 3.3.3 and 3.3.4, accordingly.

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Assessing the health effects of extreme temperature and development of adaptation strategies to climate change in selected countries in the Asia-Pacific region

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ABSTRACT

While studies show that climate change is exacerbating health effects due to extreme hot weather, scientific evidence in the Asia-Pacific region remains scarce. In this study, we aim to assess the health effects of extreme temperature, identify individual and community factors contributing to population vulnerability, and develop adaptation strategies for temperature-related health risks. Various methods were adopted for different research purposes in the study. Distributed lag non-linear model and conditional Poisson model were used to assess temperature-health associations. Subgroup analysis, hierarchical Bayesian model and logistic regression model were used for identifying vulnerable subgroups. Results showed that extreme temperature is associated with a range of human morbidity or mortality outcomes in the selected Asia-Pacific localities. The interaction of extreme temperature and air pollution also increased health risks. It is projected that heat-related health effects will increase dramatically under climate change scenarios with urban expansion and ageing population in the near future. Vulnerable subgroups in the study were identified as the elderly, people with pre-existing diseases, outdoor workers, residents living in high population density areas, and those with low socio-economic status. In addition, a few cities developed adaptation strategies to manage the health risks as a result of extreme temperatures, such as heat-health action plans and early warning systems. Future efforts should be taken to develop and evaluate the effectiveness of adaptation strategies for alleviating public health impacts of climate change in the Asia-Pacific region.

HIGHLIGHTS

- Extreme temperatures were associated with a wide range of health outcomes in the Asia-Pacific localities.
- The elderly, people with pre-existing diseases, outdoor workers, residents living in high population density areas, and those with low socio-economic status were particularly sensitive to heat exposure.
- Cost-effective adaptation strategies should be developed to address the health impacts of climate change.

1. INTRODUCTION

A range of early impacts of climate change have been observed over recent decades, which include increasing ambient temperatures, changing precipitation patterns and an increase in the frequency of extreme weather events (Stocker, 2014). With growing concerns about global warming and deadly heatwaves, the health effects of temperature are fast becoming a global public health challenge in the 21st century (Hajat, O'Connor, & Kosatsky, 2010; Watts et al., 2018). Health effects due to extreme temperature are the most significant source of weather-related public health problems, and also the most direct and well-understood impact of climate change on human health (Huang, Barnett, Wang, & Tong, 2012; Kinney, 2012). The Intergovernmental Panel on Climate Change (IPCC) has stated that a future increase in temperature will lead to excess mortality and morbidity among vulnerable populations for many regions (IPCC, 2014).

To date, most previous analyses have focused on mortality/morbidity concerning heat events in high-income nations, with few studies investigating low- and middle-income countries (Green et al., 2019; Kjellstrom et al., 2016). Countries in the Asia-Pacific region, which is home to more than half of the world's population, and changes in the Earth's climate are clearly impacting human health and survival. Also, with unique geography and population groups, the Asia-Pacific region is exceptionally diverse, and includes least developed countries, rapidly emerging economies and developed nations. Sensitive population and spatial heterogeneity in terms of heat vulnerability may vary considerably from one environment to another. More importantly, response strategies to address the health effects of temperature have not been sufficiently considered in current public health practices and activities (Benmarhnia, Deguen, Kaufman, & Smargiassi, 2015; Huang et al., 2013).

In this article, we aim to summarize the purpose of the study, the methodology used, and the main research findings. Cities in south China, Viet Nam and Thailand were selected as the study sites for their typically hot and humid climates. Specifically, this study attempted to quantify heat-related health effects, improve knowledge on the burden of disease attributable to extreme temperatures, examine individual and community factors contributing to population vulnerability, and provide decision-makers with adaptation strategies to extreme temperatures.

2. DATA AND METHODOLOGY

2.1 Data sources

Data on health outcomes including mortality and mobility data were gathered in this study. Various forms of data were collected, such as work injury claim and insurance data (Guangzhou, 2011-2012), ambulance dispatch data (Shenzhen, 2015-2016), stroke surveillance data (Shenzhen, 2005-2016), birth registry data (Shenzhen, 2005-2012), life expectancy data (Guangzhou, 2010-2015), medical students survey data (Nationwide, 2017) in China, hospitalization and death data (Ho Chi Minh City and the Mekong Delta Region, 2010-2013) in Viet Nam, and mortality data (Nationwide, 1999-2008) in Thailand. The majority of data were obtained from Health Administrative Departments, Centres for Disease Control, and Hospital Information Systems.

In addition, meteorological and air pollutant data such as daily temperature, relative humidity, particulate matter with an aerodynamic diameter less than 2.5 μm ($PM_{2.5}$), ozone (O_3), and sulphur dioxide (SO_2) were also included. These indicators were obtained from National Climate Centers, Environmental Protection Agencies, and some Real-time Publishing Platforms (e.g., Air Quality Real-time Publishing Platform of China). There are no universal definitions for the terms "extreme temperatures" and "heatwaves". In this study, extreme temperature was defined as daily temperatures exceeding a given threshold value, for instance, 90th/95th of the temperature range. Heatwave was defined based on the magnitude, duration, and frequency of extreme temperatures, such as a few consecutive days of temperatures above a certain threshold.

Ethics approval was granted by the Ethics Committee of Sun Yat-sen University prior to data collection. Descriptive analysis of the meteorological, air pollutant and health outcome variables in different Asia-Pacific cities can be found in the published literature by our team (Bao et al., 2019; Dang et al., 2019; He et al., 2018; Huang et al., 2018; Liao et al., 2019; Liu et al., 2019; Ma et al., 2019; Phung, Chu, Tran, & Huang, 2018; Sheng et al., 2018; Wang et al., 2019).

2.2 Methodology

A variety of statistical methods were used for analysis, ranging from simple linear models to complex non-linear models. In general, ample statistical methods were developed in the field of environmental epidemiology, and the methods used varied for different research purposes.

When assessing the health effects of extreme temperatures, distributed non-linear lag model (DLNM) with an ecological design or conditional Poisson model with a time-stratified case-crossover design are frequently used (Dang et al., 2019; Huang et al., 2018; Sheng et al., 2018). In these models, different mortality and morbidity outcomes (e.g., daily counts of death or ambulance dispatches) were set as dependent variables; environmental exposure indicators (e.g., daily mean temperature or air pollution) were independent variables; and other time-invariant confounders (e.g., socio-demographic characteristics) and time-varying confounders (e.g., long-time trend and seasonality) were also controlled. To identify heat vulnerability such as population characteristics or spatial heterogeneity, subgroup analysis, hierarchical Bayesian model with an ecological design or logistic regression model with a case-only design were adopted in the study (Bao et al., 2019; He et al., 2018; Ma et al., 2019; Phung et al., 2018). All statistical analyses were performed using R software (version 3.4.0).

3. RESULTS AND DISCUSSION

3.1 Heat-related health effects and attributable burdens

A positive temperature-health association was found among different human morbidity outcomes.

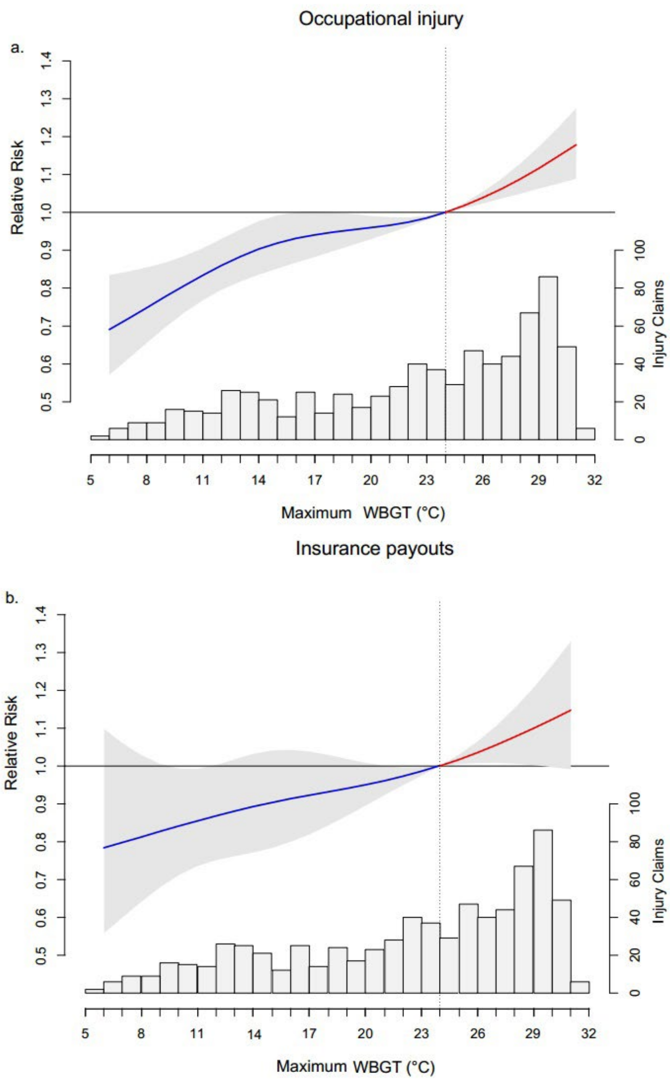

FIGURE 1. The exposure-response relationship between maximum WBGT and occupational injury (a) and insurance payouts (b) in Guangzhou, China.

Risk of work-related injuries increased by 15% (RR=1.15, 95%CI: 1.08-1.22) when wet bulb globe temperature (WBGT) reached 30 °C, with 4.8% of injuries and 4.1% of related insurance payouts attributing to extreme temperatures in Guangzhou, China (Figure 1). Ambulance dispatches during extremely hot days increased by 19% (RR=1.19, 95%CI: 1.11-1.27) in comparison with the optimum temperature of 22 °C in Shenzhen, another most populous city of southern China. In Viet Nam, the Mekong Delta showed 6.1% (95%CI: 5.9-6.2) increase of hospital admissions when average temperatures rose by 5 °C. Besides, the interaction between temperature and air pollutants may further aggravate the situation. For instance, the risk of PM_{10} increased by 90% (95%CI: 19-205) among live births of small for gestational age (SGA) when exposed to extreme temperatures in Shenzhen, China.

In addition, human mortality was also associated with extreme temperatures. Research conducted in Thailand, based on death data from 1999 to 2008, suggested that a higher intensity level of heatwaves resulted in more deaths (RR=1.126, 95% CI: 1.069-1.186) (Figure 2). A similar effect on mortality was also found in Viet Nam. Heatwaves significantly increased the risk of death of cause-specific diseases (e.g., respiratory disease, RR:1.45, 95%CI: 1.25-1.70). Besides, future climate change coinciding with rapid population growth or ageing may also present a big challenge in regard to premature deaths. The annual heat-related years of life lost (*YLLs*) in Guangzhou, China under the RCP8.5 scenarios in the 2030s, 2060s, and 2090s will increase to 2.2, 7.0 and 11.4 thousand, respectively (Liu et al., 2019).

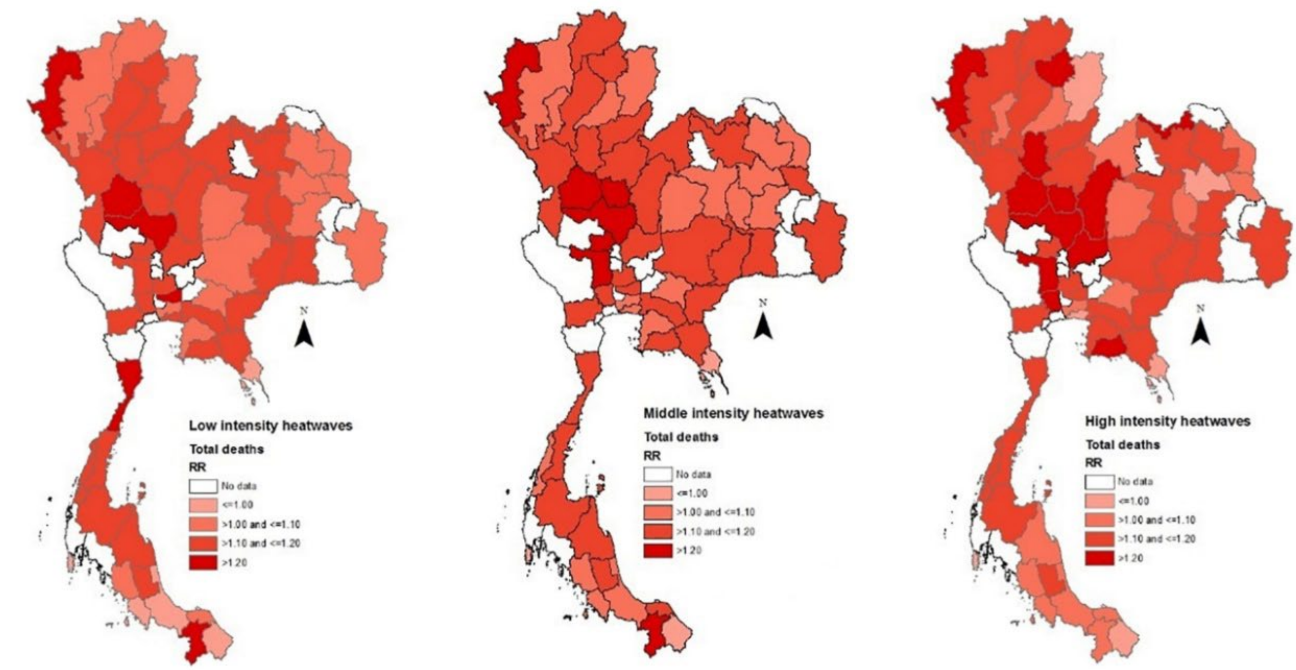

FIGURE 2. Heatwave impacts on total deaths in 60 provinces in Thailand.

These studies reveal that extremely high temperatures increase the risk of different mortality and morbidity outcomes in cities of the Asia-Pacific region. The results are consistent with findings reported in many previous studies around the world. The extreme temperatures are associated with a cumulative 7.5% and 5.1% higher rate of all-cause emergency department visits and deaths from 2005 to 2012 in England (Wellenius et al., 2017), and heat-related mortality increased by 146% from 1960 to 2009 in India (Mazdiyasni et al., 2017). A recent systematic review also reported that 93% of studies found positive associations between heat and morbidity/mortality rates in low- and middle-income countries (Green et al., 2019). Further, since high temperatures accelerate the generation and spread of air pollutants, and also influence the efficacy of toxic substances entering the body, it is biologically plausible that ambient temperature and air pollution can interact to affect health outcomes (Csavina et al., 2014; Gordon, Johnstone, & Aydin, 2014). A recent study in Australia has found strengthened effects of $PM_{2.5}$ exposure in low ambient temperatures on low birth weight (Chen, Guo, Abramson, Williams, & Li, 2018). Also, future climate change coinciding with rapid urban expansion or population ageing may exacerbate health risks in the Asia-Pacific region. This finding was consistent with other projection studies; for instance, the annual additional deaths due to climate change would increase to approximately 250,000 between 2030 and 2050 globally (World Health Organization [WHO], 2014). It has been demonstrated that rapid population growth and demographic change, especially in urban areas, could lead to land use/cover change, air pollution, overcrowding, changes in physical activity patterns, and inadequate service capacity for sanitation. All of them could elevate the human risk of climate change in the future (Li et al., 2016).

3.2 Population vulnerability to extreme temperatures

Temperature-related health effects can be modified by different characteristics of a vulnerable population. In this study, multiple vulnerable subgroups were identified, consisting mainly of the elderly, people with pre-existing diseases, outdoor workers, residents living in high population density areas, and those with low socio-economic status.

Different sensitivity to heat was associated with different individual characteristics. The elderly (RR=1.28, 95%CI: 1.14-1.47) or people with pre-existing respiratory diseases (RR=1.30, 95%CI: 1.19-1.42) were more likely to be hospitalized, and also more likely to die when compared with the optimum temperature in Ho Chi Minh City of Viet Nam (Figure 3). A significant association between ambulance dispatches and extremely high temperatures was identified among the population over 60 years old in Shenzhen, China (RR=1.27, 95%CI: 1.04-1.28). The occupational population in the transport and construction sectors, mainly working outdoors, have an increased injury risk of 50% (RR=1.50, 95%CI: 1.426-1.580) during hot days in Guangzhou, China. Workers with low educational attainment showed a high injury risk with increasing WBGT (RR=1.19, 95% CI:1.08-1.32).

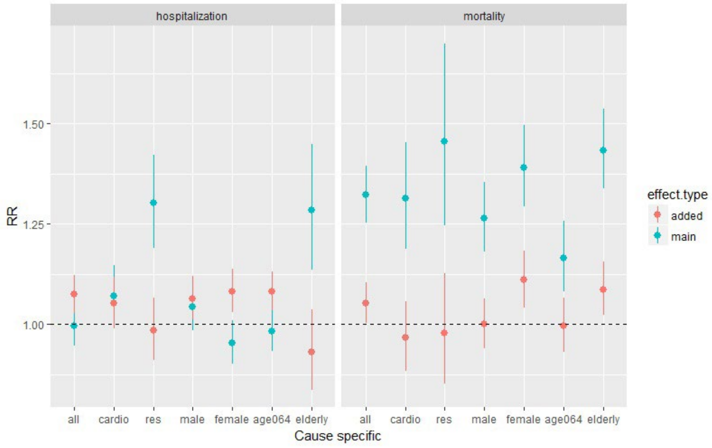

FIGURE 3. Vulnerable subgroups of hospitalization and mortality during hot days in Ho Chi Minh City, Viet Nam. Main effects: compare with the optimum value of temperature. Added effects: compare with non-heatwave days. The left panel is for hospitalization, and the right panel is for mortality. Cardio: cardiovascular disease. Res: respiratory disease.

In addition, spatial heterogeneity in terms of heat vulnerability was also observed. In the Mekong Delta Region of Viet Nam, the district-level risks ranged from 24.4% to 55.2% in admissions per 5 °C increase in average temperature. Temperature-hospitalization risk increased by 1.3% (95%CI: 1.2–1.4) for each increase of 1,000 persons/ km^2 in population density. In contrast, the risk decreased up to 6.8% (95%CI: 6.6-6.9) in those districts with many rural populations. In Thailand, northern and central regions were more vulnerable to heatwaves, and the proportion of the elderly population was the major driver behind the spatial heterogeneity (Figure 2).

Vulnerability can be explained by some possible mechanisms as discussed in the published literature of this study, although the casual effect is not well understood. The older population are vulnerable mainly due to the degeneration of their thermoregulatory systems, the increase of co-morbidities, as well as medication use (Bao et al., 2019; Dang et al., 2019; Huang et al., 2018). Outdoor workers, more likely to be exposed to external thermal environments and produce intra-body heat while engaged in heavy workloads, are also vulnerable to hot weather (Ma et al., 2019; Sheng et al., 2018). The condition of cardiovascular endocrine, urinary and respiratory systems will influence the rate of body heat dissipation. Therefore, people with specific diseases that compromise body cooling mechanisms are more susceptible to heat (Dang et al., 2019). People with low educational attainment or income may have less opportunity to respond to heat warnings, low prevalence of air conditioning, lack of medical care, and health insurance shortage (Ma et al., 2019). With rapid urbanization and population migration, high-density cities and towns are hotter than surrounding rural areas due to a lack of green space and reduction of airflow around highly crowded buildings (Liu et al., 2019; Phung et al., 2018). Residents in high-density areas may face vital health challenges on mortality and morbidity.

3.3 Development of adaptation strategies to climate change

It is suggested that the development of adaptation strategies needs to be better planned and should take into account differences in population sensitivity and future drivers (e.g., climate change, rapid urbanization and population ageing). Considering these challenges, we identified several relevant policies and measures to address the health impacts of heatwaves and climate change in the region.

The differences in sensitivity to heat would play an essential role in developing any response strategy. For instance, considering the significant spatial variation of heat vulnerability in the Mekong Delta Region, our researchers suggested that public health intervention measures should be developed using the city/district scale rather than the province scale (Phung et al., 2018). In addition, evidence also reveals that the rapid urbanization and population ageing would significantly aggravate adverse heat-related effects under all climate change scenarios. The assessment of future health risks could aid in improving the design of public health interventions and policies, preparedness of adaptation strategies, and healthcare planning (Liu et al., 2019). Furthermore, adaptation strategies may fall into autonomous and planned actions. Although autonomous adaptation can occur without coordinated scheming in individual or community levels and are usually reactive by nature, well-planned adaptation will involve deliberate policy actions with conscious intervention based on anticipated risks (Huang et al., 2013; Huang et al., 2011). Thus, planning is more critical for public health communities to cope with the adverse effects of heatwaves.

Several adaptation strategies were proposed in this study. Heat-health action plans (HAPs) could help decrease adverse health impacts of hot weather (Chau, Chan, & Woo, 2009; Tan et al., 2007). For instance, in 2012 the Chinese state government released The Administrative Measures on Heatstroke Prevention (AMHP2012) to address intensive heat events. Some critical countermeasures, including applying new materials and technologies, constructing protective equipment, adjusting shift time, and paying high-temperature subsidies to workers during hot days. Besides, heat-health warning systems (HHWSs) can be developed to cope with impending hazardous hot weather (Hajat et al., 2010). Figure 4 shows the typical process within an HHWS, involving weather forecasting, trigger of the system, risk communication and action recommendation (World Meteorological Organization [WMO] & WHO, 2015). The benchmark for issuing a warning varies from place to place, based on different local health responses to extreme weather. Beyond the threshold point, information is disseminated to various stakeholders so specific interventions can be taken, accordingly. For instance, HHWSs have been set up in several cities such as Shanghai, Nanjing and Harbin in China. A series of operations, such as risk dissemination through various media, health education, mobilization of medical and public services, maintenance of water and cooling facilities, are performed by the health departments, collaborating with other supporting agencies. However, no study has systematically evaluated the effectiveness and economic aspects of HHWSs among these cities.

Although a few Asia-Pacific countries have developed public health adaptation strategies to climate change, the coverage and diversity are far from sufficient. Strategies like urban planning for the cool city, vulnerability

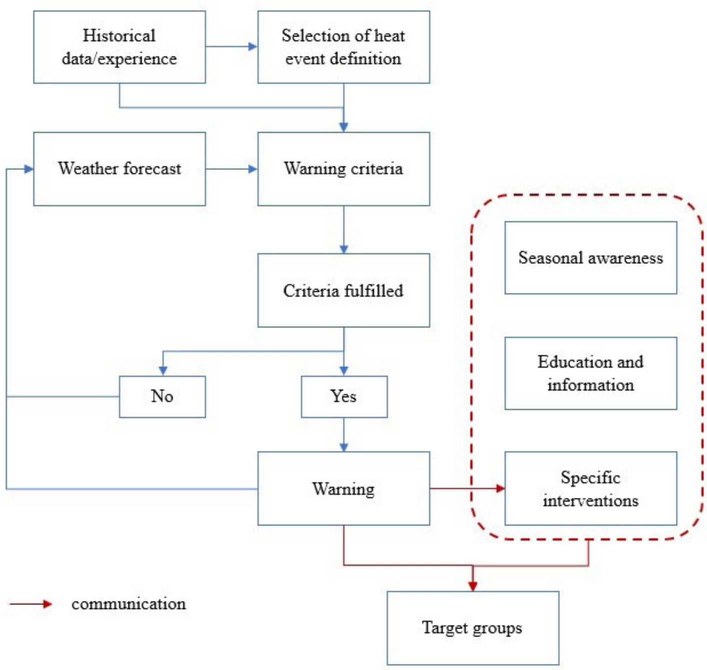

FIGURE 4. Flow diagram displaying the operation of heat-health warning systems (red box includes key elements of action plan after issuing a warning).

mapping, and real-time surveillance systems were only reported in high-income countries (Stone, Hess, & Frumkin, 2010; Wolf & McGregor, 2013). Besides that, the literature on how the strategy is implemented and whether it has a protecting effect on health, is very limited. In addition, a survey conducted in China showed approximately 90% of medical students embraced their role in tackling climate change, but half of them reported themselves and the health sectors were not adequately prepared (Liao et al., 2019). Therefore, multi-city analyses and further exploration of susceptible diseases in the Asia-Pacific region are needed to generate more evidence on heat-related health effects. Adaptation strategies for alleviating public health impacts of climate change should be developed in a timely manner as well as systematically evaluated. In particular, educational efforts should reinforce eco-medical literacy development and capacity building in the era of climate change.

4. CONCLUSIONS

We endeavoured to investigate the health effects of extreme temperature, identify factors contributing to population vulnerability and formulate local adaptation strategies for heat-related health risks. In this study, we provide sound evidence that extreme temperatures are associated with a wide range of human health issues in the Asia-Pacific region and, finally, significant individual- and community-level modifications were explored, and future research directions and policy suggestions were also proposed. The study will have the potential to make a significant contribution to protecting the health of present and future generations in the Asia-Pacific region.

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Comparing effects of untreated and treated wastewater on riverine greenhouse gas emissions

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ABSTRACT

Wastewater may alter riverine fluxes of dissolved organic matter (DOM) and CO_2, yet little is known about how treated and untreated wastewater affects riverine DOM biodegradation and CO_2 emission to a different degree. In order to compare effects of treated vs untreated wastewater on DOM biodegradation and CO_2 emission in downstream rivers, a three-day incubation experiment with river water mixed with wastewater (10%) was conducted under dark laboratory conditions. Initial dissolved organic carbon (DOC) concentrations were eight times higher in untreated sewage from Phnom Penh than in effluents from a wastewater treatment plant. Biodegradable DOC (BDOC) measured as % of initial DOC during the three-day incubation was 31 times higher in sewage than in treated wastewater, indicating abundant labile DOM moieties in sewage. The mixtures showed higher concentrations of BDOC and dissolved CO_2 than the levels expected from the mixing ratio, suggesting mixing-enhanced biodegradation of DOM. Differential excitation-emission matrices (EEMs) exhibited consistent patterns of enhanced consumption of DOM especially in untreated wastewater and its mixtures. Overall results suggest that labile DOM derived from sewage can enhance the biodegradation of riverine DOM and hence CO_2 emission, especially in rapidly urbanizing river systems receiving loads of untreated sewage across developing countries.

KEYWORDS

Biodegradation, CO_2, Dissolved organic carbon, Wastewater

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HIGHLIGHTS

- Untreated sewage greatly contributes to riverine DOM biodegradation and CO_2 emission.
- Labile DOM in sewage enhances DOM biodegradation and CO_2 emission in downstream rivers.
- Untreated sewage has stronger effects on downstream C dynamics than treated wastewater.

1. INTRODUCTION

The input of organic matter (OM) from land to water leads most rivers in the world to be supersaturated with dissolved greenhouse gases (GHGs) (Ward et al., 2017). Recent global syntheses have emphasized the role of inland waters as major sources of CO_2, CH_4, and N_2O to the atmosphere (Bastviken, Tranvik, Downing, Crill, & Enrich-Prast, 2011; Raymond et al., 2013). Climate change and increasing anthropogenic activities have been suggested as key factors affecting riverine biogeochemistry (Evans, Monteith, & Cooper, 2005; Regnier et al., 2013). Urban rivers have been identified as hotspots for riverine GHG emissions, where increased loads of nutrients and OM can enhance riverine metabolic processes such as aerobic and anaerobic biodegradation, nitrification, and denitrification (Yoon, Jin, Begum, Kang, & Park, 2017; Jin et al., 2018). Recent studies have reported that concentrations of dissolved organic carbon (DOC) and dissolved nutrients increase substantially downstream of large metropolitan cities with treated and untreated wastewater discharged to the river (Sickman, Zanoli, & Mann, 2007; Hosen, McDonough, Febria, &

Palmer, 2014). Enhanced bioavailability of nutrients and labile OM derived from wastewater, especially after mixing with the mainstem river, has been associated with increased emissions of GHGs from downstream rivers (Begum et al., 2019).

According to the IPCC report (IPCC, 2017), waste and wastewater account for 2.8% of the total GHG emissions to the atmosphere. Anthropogenic GHG emissions have increased during the last couple of decades with increasing urbanization and industrialization in many parts of Asia. Organic pollution has been rising across Asia resulting in various environmental problems in polluted river reaches, such as eutrophication and hypoxia (Wang et al., 2017; Park et al., 2018). Advanced wastewater treatments used in developed countries can efficiently remove biodegradable OM and inorganic nutrients, resulting in low levels of water pollution in downstream rivers, as observed in the Han River, Korea (Ministry of Environment, 2019). In developing countries, however, untreated wastewater from domestic and industrial sources is directly discharged to downstream rivers resulting in high levels of OM and nutrients in river reaches downstream of large metropolitan areas (Misra, 2010; Bhatt, McDowell, Gardner, & Hartmann, 2014). For example, the Yamuna River traversing the Delhi metropolitan area was declared “dead” with dissolved oxygen level close to zero even in the monsoon season (Misra, 2010). Although it has recently been reported that organic pollution in urbanized rivers receiving treated wastewater effluents can create conditions for high emission rates of dissolved CO_2 and other GHGs (Alshboul, Encinas-Fernandez, Hofmann, & Lorke, 2016; Yoon et al., 2017), the influence of untreated sewage on riverine metabolic processes has rarely been compared with the influence of treated wastewater. Given the high lability of DOM contained in urban sewage (Guo et al., 2014), the mixing of sewage-derived DOM might greatly enhance the biodegradation of riverine DOM, altering rates of GHG emissions. Therefore, the objective of this study was (1) to compare the characteristics of DOM and CO_2 from a treated wastewater effluent from Korea with untreated wastewater from a sewage drain in Phnom Penh, Cambodia; and (2) to investigate how the mixing of wastewater with river water affects the rates of DOM biodegradation and CO_2 emission.

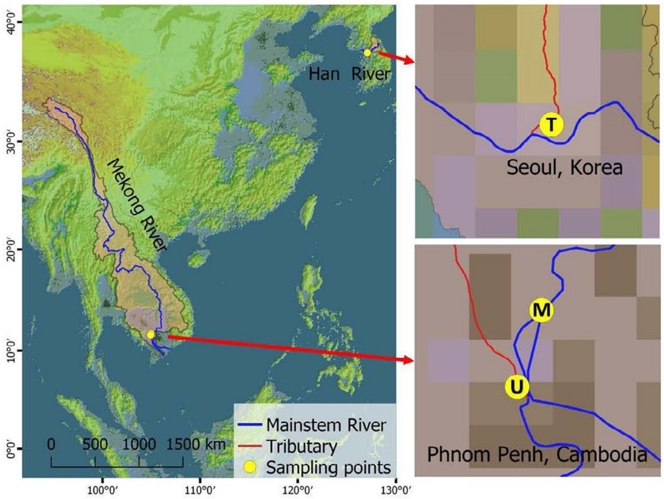

FIGURE 1. Sampling locations in the Mekong and Han River basins. The sampling locations for the mainstem river water, treated wastewater, and untreated wastewater are indicated by “M”, “T”, and “U”, respectively.

2. METHODOLOGY

2.1 Sampling and incubation

In order to compare the effect of treated and untreated wastewater on riverine GHGs, samples were collected from a treated wastewater (termed as “T”) discharge from a wastewater treatment plant (WWTP) in Seoul, Republic of Korea, and untreated wastewater (termed as “U”) from a sewage drain in Phnom Penh, Cambodia in September 2016 and January 2017, respectively (Figure 1). An additional sample was collected from

Treatment	Sample composition (%)			Description	Location	
	River	Wastewater				
		Treated	Untreated		Latitude	Longitude
M	100			Mekong river before entering Phnom Penh, Cambodia	11°43'38.03"N	104°58'23.09"E
T		100		Treated wastewater from Jungnang WWTP effluent in Seoul, Korea	37°33'11.30"N	127°03'52.50"E
U			100	Untreated wastewater from sewage drain in Phnom Penh, Cambodia	11°34'43.61"N	104°55'28.27"E
MT	90	10		Mixture of river and treated wastewater	-	-
MU	90		10	Mixture of river and untreated wastewater	-	-

TABLE 1. Summary of treatments and sampling locations. Five treatments used in the incubation experiment are explained in terms of sample composition and sampling locations.

a mainstem location of the Mekong River, upstream of Phnom Penh city (termed as "M") as the control sample. Samples were transported on ice to the laboratory and frozen overnight until the incubation experiment. River water (M sample) and wastewater (T and U samples) were mixed at a ratio of 9:1 (v/v) to produce two mixture samples termed "MT" and "MU", respectively, before conducting the incubation experiment.

Samples were filtered through a 0.2 µm polycarbonate filter (Whatman, USA) and a three-day incubation was conducted in the laboratory, following the methods modified from Servais, Billen, and Hascoët (1987) and Begum et al. (2019). Three replicates of filtered samples (60 mL) were incubated in 120 mL glass bottles, sealed with butyl septa and aluminium crimps to measure the change in dissolved CO_2 in addition to measuring biodegradable dissolved organic carbon (BDOC). A small volume (1% v/v) of the unfiltered raw M sample was added to each treatment as inoculum to provide the filtered water samples with a common microbial community for biodegradation. The incubation temperature was set to 29 °C to simulate the usual field condition of the Mekong River during sample collection. The concentration of BDOC was calculated as the net change in DOC concentration over the three-day incubation, and %BDOC was calculated as relative proportion in the initial DOC concentration. Dissolved gas samples were collected from each bottle at the beginning and end of the incubation, using manual headspace equilibration method (Begum et al., 2019). CO_2 production from biodegradation was calculated as the net change in dissolved CO_2 during the incubation.

2.2 Sample analysis

In situ measurement of hydroclimatic parameters such as water temperature, barometric pressure, and ambient temperature was recorded during sample collection. Filtered water samples were analyzed for DOC concentration, fluorescence excitation-emission matrices (EEMs), and UV absorbance. As part of quality control of all the analyses, standards with known concentrations and ultrapure water were analyzed for every batch of ten samples. DOC concentration was measured by a total organic carbon analyzer based on high-temperature combustion of OM followed by thermal detection of CO_2 (TOC-VCPH, Shimadzu, Japan). UV absorbance was measured across a wavelength range from 200 to 1100 nm using a UV-Vis spectrophotometer (8453, Agilent, USA). Fluorescence EEMs were collected on a fluorescence spectrophotometer (F7000, Hitachi, Japan) by simultaneous scanning over excitation wavelengths from 200 to 400 nm at 5 nm interval and emission wavelengths from 290 to 540 nm at 1 nm interval. Scan speed was 2400 nm min^{-1}, and the bandwidth was set to 5 nm for both excitation and emission. Corrected fluorescence data were used to calculate humification index (HIX) (Zsolnay, Baigar, Jimenez, Steinweg, & Saccomandi, 1999), fluorescence index (FI) (McKnight et al., 2001) and biological index (BIX) (Huguet et al., 2009).

The equilibrated headspace air sample, as well as a sample from the ambient air used for equilibration, was injected into a gas chromatograph (GC) (7890A, Agilent, USA) equipped with a flame ionization detector (FID) for analysis of CO_2. Details of methods of GC analysis are described in our previous publication (Jin et al., 2018). In brief, high-purity N_2 gas (99.999%) was used as carrier gas at a constant flow rate of 25 mL min^{-1}. The flow rate of the reference gas (N_2) was 5 mL min^{-1}, and temperature settings include the inlet at 250, the oven at 60, the valve box at 100, and FID at 250 °C. The volume of the sample loop was 1 mL. Standard reference gases with various concentration of CO_2 in N_2 balance (RIGAS Corporation, Korea) were used to calibrate the GC signals.

2.3 Statistical analysis

Significant differences in measurements among the treatments were compared by one-way analysis of variance (one-way ANOVA) for data exhibiting normal distribution or non-parametric Kruskal-Wallis one-way analysis of variance on ranks (one-way ANOVA on ranks) in the case of non-normal distribution. ANOVA tests were followed by Student-Newman-Keuls test to identify treatment means that are significantly different from each other. Significant differences between the initial and final measurements were examined by Student's t-test with datasets that exhibited normal distribution. All the statistical analyses were conducted using SigmaPlot (version 12.5, Systat Software, USA) with a significance level at $p < 0.05$.

3. RESULTS AND DISCUSSION

The average DOC concentrations of the T (4.74 mg L^{-1}) and U (40.44 mg L^{-1}) samples were 4 and 35 times higher than the M (1.16 mg L^{-1}) sample, respectively, and the differences were significant (ANOVA on ranks, $P < 0.05$) (Figure 2a,b; Table 2). All three samples were supersaturated with dissolved CO_2 when measured in situ, with highest values found at U site (18131 µatm). These differences in DOC and dissolved CO_2 suggest a large difference in the composition and lability of OM in treated and untreated wastewater. BDOC measured during the three-day incubation was slightly higher in the T samples (on average 0.11 mg L^{-1}; 2.2%) compared to the M samples (0.01 mg L^{-1}; 1.3%); however, BDOC in

Treatments	DOC ($mg\ L^{-1}$)		BDOC ($mg\ L^{-1}$)	BDOC (%)	CO_2 ($mg\ C\ L^{-1}$)		CO_2 production ($mg\ C\ L^{-1}$)	CO_2 -C production (%)
	Initial	Final			Initial	Final		
M	1.16	1.14	0.01	1.3	0.45	0.61 **	0.16	36.38
	-	(0.09)	(0.09)	(7.5)	-	(0.01)	(0.01)	(2.18)
T	4.74	4.63	0.11	2.2	0.73	1.06 **	0.34	46.22
	(0.07)	(0.20)	(0.24)	(5.0)	(0.02)	(0.01)	(0.02)	(4.04)
U	40.44	12.59 **	27.85	68.9	0.85	8.17 **	7.31	858.92
	(0.31)	(0.21)	(0.48)	(0.7)	(0.01)	(0.22)	(0.23)	(36.11)
MT	1.56	1.53	0.02	1.5	0.50	0.74 *	0.24	48.37
	-	(0.07)	(0.07)	(4.2)	-	(0.07)	(0.07)	(13.32)
MU	4.76	2.22 **	2.54	53.4	0.58	1.59 **	1.01	175.32
	-	(0.07)	(0.07)	(1.5)	-	(0.05)	(0.05)	(8.50)

TABLE 2. Summary of DOC, BDOC and dissolved CO_2 concentrations measured for the 5 treatments during the three-day incubation. Significant differences between initial and final measurements are indicated by * for P<0.05 and ** for P<0.001.

the U samples was very high in absolute concentration (27.85 mg L^{-1}) and its relative proportion in the initial DOC concentration (68.9%), 31 times higher than the T sample (ANOVA on ranks, $P < 0.05$) (Figure 2c-f; Table 2). This large amount of labile DOM contained in the untreated wastewater discharged from the city centre of Phnom Penh might be partially responsible for large GHG evasion from the downstream Mekong River. The magnitude of BDOC and CO_2 concentrations measured for the untreated wastewater from Phnom Penh has rarely been observed in river systems receiving treated wastewater such as the Han River, Korea (Yoon et al., 2017; Begum et al., 2019) and rivers in North America (Sickman et al., 2007; Hosen et al., 2014).

To reflect a small portion accounted for wastewater in the total discharge of the riverine OM, the mixture treatments involving 10% wastewater (i.e., MT and MU) were compared with the original samples of river water and wastewater. The MT samples had similar or slightly higher BDOC concentration (0.02 mg L^{-1}) and %BDOC (1.5%) than the expected mixing average of M and T (0.02 mg L^{-1} and 1.39%; Figure 2c,e; Table 2). However, %BDOC in MU (53.4%) sample was significantly higher than their expected mixing average (8.1%), suggesting a mixing-induced enhancement in biodegradation (one-way ANOVA, $P < 0.05$) (Figure 2d,f; Table 2). High biodegradability of the U and T samples was also reflected in the high rates of CO_2 production measured during the three-day incubation. The mean rate of CO_2 production was highest in the U samples (7.31 mg L^{-1}), consistent with the highest BDOC values (Figure 3d; Table 2). Mixing-enhanced biodegradation was also evident in the high rates of CO_2 production in both MT (0.24 mg L^{-1}) and MU samples (1.01 mg L^{-1}); however, the production rate was significantly higher in the MU samples (ANOVA on ranks, $P < 0.05$) (Figure 3c,d; Table 2). These

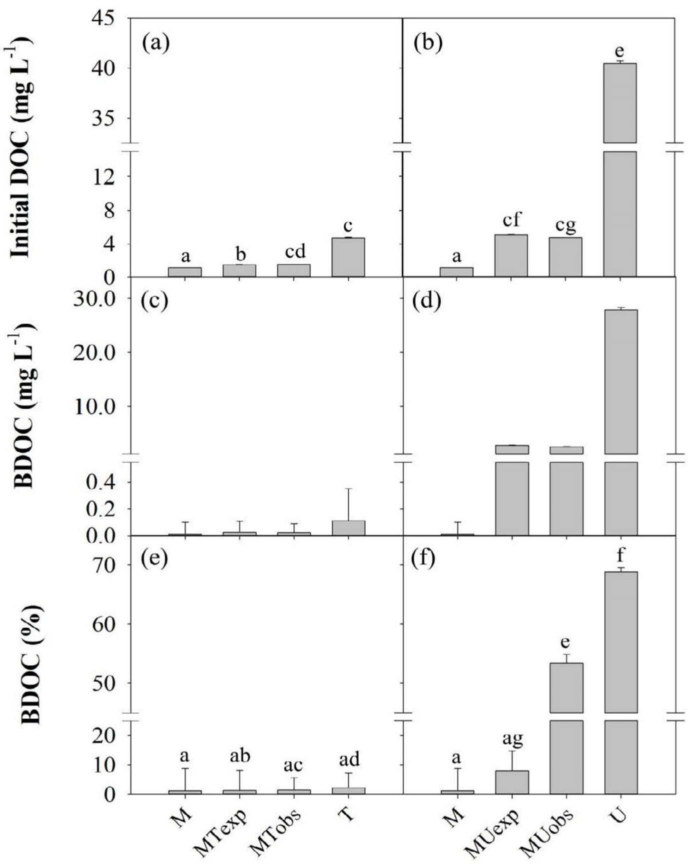

FIGURE 2. Initial DOC concentration (a), BDOC concentration (b), and BDOC (%) (c) of a mainstem river water (M), a treated wastewater (T), an untreated wastewater (U) and their mixtures measured during three-day incubation experiment. Expected (MTexp and MUexp) and observed (MTobs and MUobs) values from mixing the two types of wastewater (MT and MU) with the mainstem water in 1:9 ratio were also included. Significant differences at $P < 0.05$ from one-way ANOVA or ANOVA on rank followed by Student-Newman-Keuls test are indicated by different letters placed above the bars.

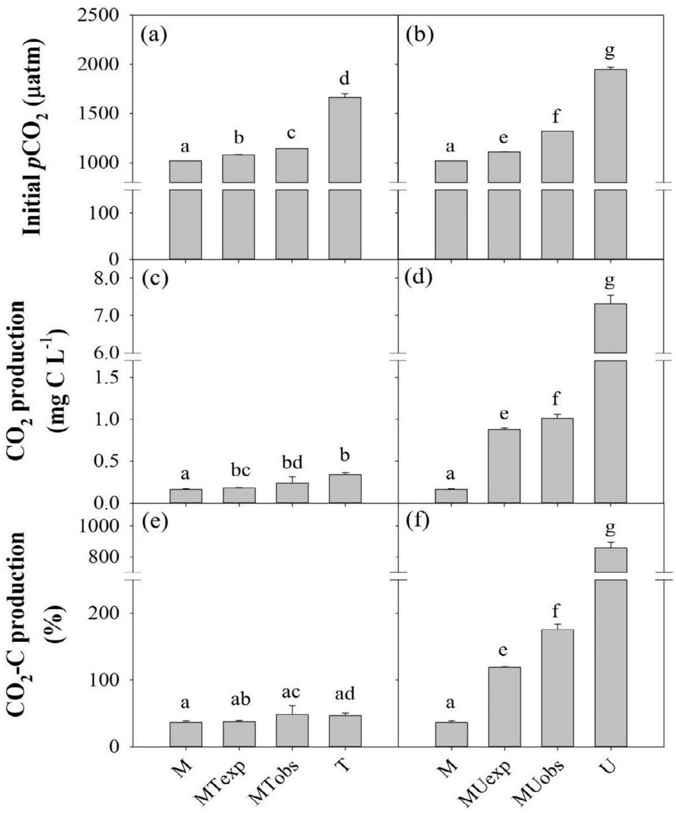

FIGURE 3. Initial pCO_2 (a), production of CO_2 (b), and relative production of CO_2 (c) of a mainstem river (M), a treated wastewater (T), an untreated wastewater (U) and their mixtures measured during three-day incubation experiment. Expected (MTexp and MUexp) and observed (MTobs and MUobs) values from mixing the two types of wastewater (MT and MU) with the mainstem water in 1:9 ratio were also included. Significant differences at $P < 0.05$ from one-way ANOVA or ANOVA on rank followed by Student-Newman-Keuls test are indicated by different letters placed above the bars.

unexpectedly higher values of BDOC and CO_2 suggest that wastewater with labile DOM can play an important role in increasing riverine GHG emissions (Guo et al., 2014).

Labile fractions of DOM that can enhance riverine CO_2 emission were examined by comparing differential EEMs measured for different treatments (Figure 4). Biodegradation of DOM components, particularly in the protein-like region, was pronounced in U samples, consistent with high values of FI and low values of HIX (Figures 4, 5). Even though production of new DOM moieties was also observed in the wastewater samples, the production rate was much higher in the U samples. The significant differences in degradation and production of fluorescent DOM components between the T and U samples (Figure 5) suggest the importance of WWTPs in the metropolitan cities discharging a large amount of labile DOM to the rivers. Wastewater can emit large amounts of GHGs directly from the source to downstream rivers (Alshboul et al., 2016) or indirectly via degradation of labile DOM contained in the discharged wastewater (Yoon et al., 2017; Jin et al., 2018). Furthermore, the discharged wastewater can also exert a synergistic effect on OM processing when it is mixed with the downstream river water (Begum et al., 2019). As shown in Figure 4, the treated wastewater predominantly produces new OM upon mixing with the river water, which lacks in nutrients and other resources for immediate microbial degradation. Instead, humic-like and protein-like DOM components are produced from dead cells and microbial exudates (Huguet et al., 2009; Guo et al., 2014). On the other hand, the labile fraction of protein-like DOM in untreated wastewater can rapidly degrade and produce humic-like DOM from microbial activities upon mixing with the river water, which is also consistent with significant increases in the HIX values, particularly in U and MU samples during the three-day incubation (Figures 4, 5). The EEMs of the MT and MU treatments exhibited merely the net change in DOM components during the three-day incubation; however, differential EEMs with shorter intervals would show the complex patterns of production and degradation of DOM in mixed samples as reported by a previous study (Begum et al., 2019). Considering that organic matter export and GHG emissions from rapidly urbanizing river basins around the world represent one of the major uncertainties in our understanding of global riverine C budgets (Regnier et al., 2013; Park et al., 2018), synergistic effects of wastewater mixing (Figures 2, 3) and ensuing subtle chemical changes in different DOM fractions warrant further tests

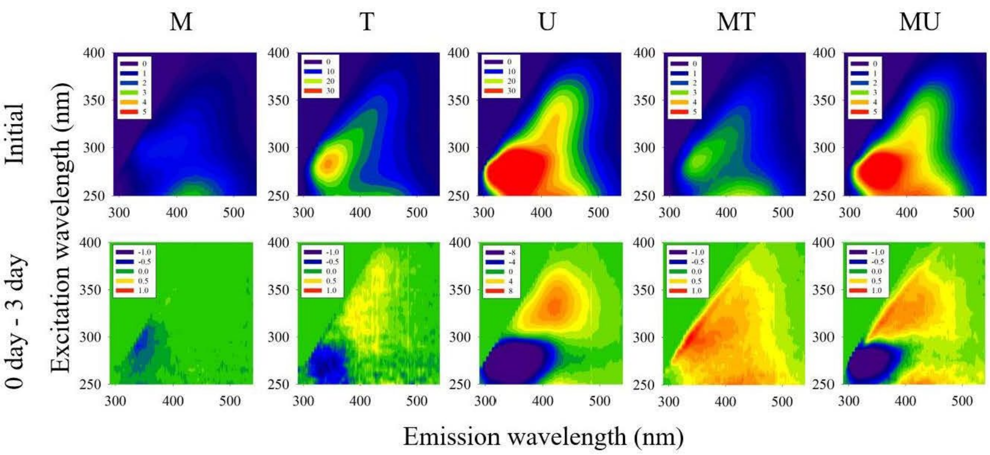

FIGURE 4. Initial (1st panel) and differential EEMs (0 day–3 day) from three-day incubation experiment (2nd panel). Positive (red) and negative (blue) values in the differential EEMs indicate production and consumption of fluorescent DOM components, respectively.

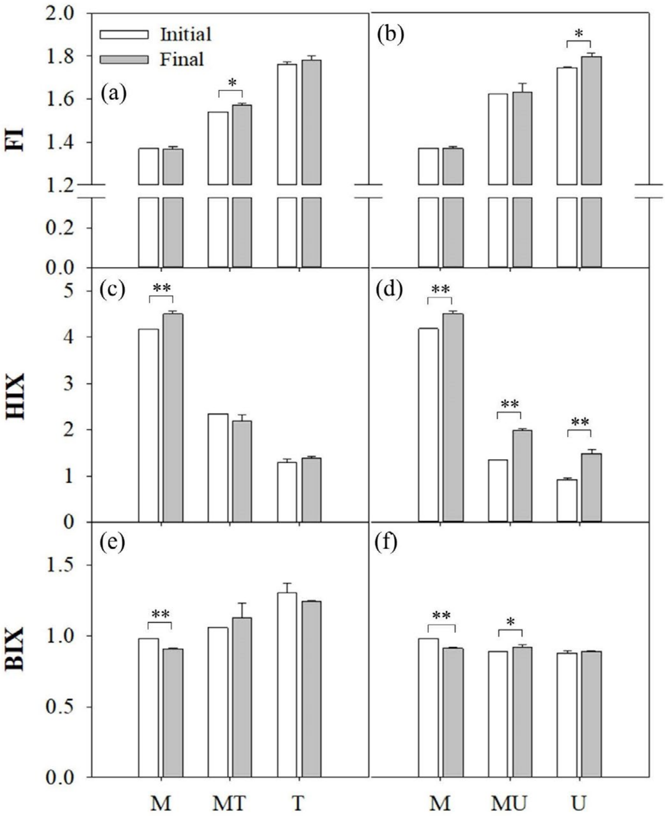

FIGURE 5. Changes in DOM optical properties (FI, HIX, and BIX) during three-day incubation. Significant differences between initial and final measurements are indicated by * for $P < 0.05$ and ** for $P < 0.001$.

across a wide range of organic pollution and river size. In particular, more attention needs to be paid to widely varying characteristics of wastewater discharged from domestic and industrials sources.

4. CONCLUSION

The three-day incubation experiment provided empirical evidence of both treated wastewater and untreated sewage contributing labile DOM and GHGs to downstream reaches in urbanized river systems. Mixing of untreated sewage and river water induced a much higher enhancement of the biodegradation of riverine OM and CO_2 emission, as compared with the moderate effect of treated wastewater. Major findings of this study suggest that the untreated wastewater that is directly discharged into large rivers in many developing countries can drastically increase the rate of GHG emissions from downstream rivers. The negative effect of untreated sewage on DOM biodegradation and GHG emission could be reduced substantially by constructing WWTPs, as demonstrated by the rather moderate effect of treated wastewater on BDOC and CO_2 production. Although this experiment focused on CO_2 only, other GHGs can also be minimized by implementing wastewater treatment facilities. The findings of this case study need to be interpreted with caution, because the response of smaller, more polluted rivers to wastewater addition might be quite different from the observed effects of wastewater addition to the moderately polluted water of the large Mekong River. Another uncertainty is how wastewater mixing would induce some combined effects of other water quality components, such as pH, DO, and nutrients, adding to the singular effect of DOC as explored in this study. Future studies, including other factors such as primary production, necessary nutrients for biodegradation, incubation under light-dark cycles, incubation for a longer period, and incubation with various types of wastewater, can provide more detailed information that is required to mitigate the impact of wastewater on GHG emissions from increasingly urbanizing river systems worldwide.

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Management strategy evaluation: Transdisciplinary and transparent natural resource management

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ABSTRACT

Management Strategy Evaluation (MSE) is a modelling tool used to evaluate sufficiently realistic simulations of potential policy choices in complex systems. As a contribution to the Integrated Marine Biosphere Research (IMBeR) project IMBIZO V, which occurred in October 2017, a workshop was convened with the goal of developing a coherent understanding of best-practice approaches for MSEs. MSEs are becoming standard approaches to characterizing risk across fisheries management organizations globally. MSEs are important tools that aid in delineating objectives, costs, and constraints that define risk and provide a possible mechanism to meet assessment challenges. The MSE workshop considered case studies drawn from different fisheries (including small- and large-scale fisheries), with associated cultural, societal, and management characteristics, to better define best-practice principles of MSE development, implementation, and communication. The needs and benefits of MSE model development for evaluation of management scenarios for small-scale fisheries were identified. Early career scientists and students were introduced to details of MSE development and implementation, and to colleagues who are part of professional networks that have access to the necessary tools for decision-making processes regarding marine resources. Networking and capacity building in MSE expertise in the Asia-Pacific region represent long-term impacts from the workshop.

KEYWORDS

Fisheries management, IMBeR, IMBIZO, Management strategy evaluation, Small-scale fisheries

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HIGHLIGHTS

» Improved understanding of development and implementation of MSEs for small-scale fisheries.

» Networking and capacity building in MSE expertise in the Asia-Pacific region.

» Early career researchers exposed to MSE issues and associated professional networks.

» Learning opportunity provided by access to a Toy MSE model.

1. INTRODUCTION

Marine and human systems are complex, which makes describing their interactions and potential outcomes difficult. Climate change and environmental variability impacts add to the complexity of developing management strategies for marine resource use. Management of fisheries presents challenges because changes in environmental conditions initiate a cascade of responses that appear as social and economic effects. These social and economic responses in turn affect management strategies and policies, which impact the resource.

The Ecosystems Approach to Fisheries (EAF) adopted by the FAO Committee on Fisheries defines Management Strategy Evaluation (MSE) as a modelling-based approach aimed at testing the robustness of possible management arrangements (plans) by examining sets of decision rules, such as those used to adjust total allowable catch or effort controls, to determine which perform best to achieve the management objectives for a fishery (EAF, 2011). Therefore, the MSE approach allows evaluation of sufficiently realistic simulations of potential policy choices in complex systems and associated robustness to uncertainties (Miller et al., 2010; Bastardie, Vintehr, Nielsen, Ulrich, & Paulsen, 2012; Martell, Leaman, & Stewart, 2013; Goethel et al., 2019; Fulton, Punt, Dichmont, Harvey, & Gorton, 2019). Communication with stakeholders and policy makers to obtain information about the range of desired policy outcomes and acceptable potential policy choices provides constraints for scenarios tested with a MSE (Fulton, Smith, Smith, & Johnson, 2014; Goethel et al., 2018; Armitage et al., 2019). Challenges to the MSE approach include poorly specified management objectives, a lack of quantitative datasets for developing operating models for many species (Punt, Smith, & Cui, 2001; International Council for the Exploration of the Sea [ICES], 2019), and robust methods to evaluate risks (Rochet & Rice, 2009; Goethel et al., 2019).

However, even with these challenges, MSEs have been applied to fisheries (e.g. Punt et al., 2001; Punt, Butterworth, de Moor, De Oliveira, & Haddon, 2016) and conservation (e.g. Bunnefeld, Hoshino, & Milner-Gulland, 2011, Dichmont et al., 2013) to compare alternative management strategies (Tommasi et al., 2017), while accounting for uncertainty in environmental, biological, and management inputs (Cooke, 1999; Butterworth & Punt, 1999; Sainsbury, Punt, & Smith, 2000; Punt et al., 2016). Maintaining the environment is part of the management objectives for some species (e.g., Agnew, Beddington, & Hill, 2002; Hurtado-Ferro, Hiramatsu, & Shirakihara, 2010; Pershing et al., 2015; Miller, Hare, & Alade, 2016), but existing MSEs show mixed results about the effectiveness of alternative, potentially climate-robust, management strategies (A'Mar, Punt, & Dorn, 2009; Punt, 2011; Szuwalski & Punt, 2013; Punt et al., 2016; Goethel et al., 2019).

Integrated Marine Biosphere Research (IMBeR), a global environmental change project, has a priority focus on achieving a transdisciplinary understanding of the interactions of ocean-human systems (Hofmann et al., 2015; Hofmann et al., 2016), with emphasis on marine fisheries and their management (e.g. Bundy et al., 2016). To advance progress on MSE applications to marine fisheries, IMBeR convened a workshop as part of its biennial IMBIZO (Zulu word for "a gathering") to assess the current state of MSE implementation for a range of marine fisheries. This workshop focussed on assessing information from natural and social sciences that is essential for MSE development (e.g. the role of institutions), methods and modelling tools for MSE development, methods used to define societal management goals and needs (boundary conditions for the MSE), approaches for MSE evaluation of management options, and development of effective communication strategies to convey MSE predictions (and best-practice principles) to decision-makers.

2. METHODOLOGY

IMBeR IMBIZOs are designed to address current research topics, facilitate transdisciplinary research, and provide assessments of current understanding and future research needs. The IMBIZOs consist of concurrent workshops, each of which considers an important research topic. In addition, plenary presentations provide overviews for each workshop, and cross-cutting activities and poster sessions allow integration across workshops. IMBIZO V, held in October 2017 at the Woods Hole Oceanographic Institution, was developed around the theme of "*Marine biosphere research for a sustainable ocean: Linking ecosystems, future states and resource management*". The workshop on "*Management Strategy Evaluation: Achieving Transparency in Natural Resource Management by Quantitatively Bridging Social and Natural Science Uncertainties*", was designed to develop a coherent understanding of best-practice approaches to MSEs and serve as a learning opportunity for the attendees.

The workshop considered case studies of different fisheries, cultural, and societal characteristics (including small- and large-scale fisheries in the Asia-Pacific

Title	Type	Presenter	Affiliation
Management Strategy Evaluation: Current state and challenges	Plenary keynote	André Punt	University of Washington, Seattle, WA USA
Looking for robust harvest control rules: Learning from MSE applications to specific fisheries	Invited workshop	Ana Parma	Centro Nacional Patagónico, Puerto Madryn, Argentina
What good are MSEs when the oceans, and people that use and manage stuff in them, are so stinking uncertain?	Invited workshop	Jason Link	NOAA Fisheries Directorate, Woods Hole, MA, USA
Toy MSE model presentation	Invited workshop	Gavin Fay	University of Massachusetts Dartmouth, MA, USA

TABLE 1. Summary of title, type, presenter and affiliation for MSE plenary and invited workshop presentations.

FIGURE 1. Infographic illustrating different perceptions of MSE development and implementation presented by André Punt (inset photograph). The three branches show the difficulty in MSE development and implementation for fisheries and the range of perceptions of MSEs, which include a science-based framework for fishery management (upper), confusion and uncertainty about MSEs (middle branch), and lack of understanding about MSEs and their application (lower branch). The infographic was created by Indi Hodgson-Johnson, University of Tasmania.

Country	Student	Early Career Scientist	Researcher
Australia	1		1
Argentina			1
Bangladesh		1	
Brazil	2		
Canada			2
China			1
Costa Rica		1	
Fiji	1		
India			1
Indonesia	1		
Japan		2	
New Caledonia			2
New Zealand			1
Norway		1	2
Philippines			1
Romania		1	
Solomon Islands	1		
Spain		1	
Turkey	1		
United Kingdom			1
USA	1	2	7
Total	8	9	20

TABLE 2. Summary of MSE workshop attendees by country and career stage.

region) to better define best-practice principles of MSE development, implementation, and communication. The workshop was structured around a keynote plenary presentation and invited workshop presentations (Table 1), as well as oral and poster presentations by workshop participants, and discussions. The workshop attendees represented 21 countries and almost 50% were students and early career scientists (Table 2).

3. RESULTS AND DISCUSSION

3.1 MSE overview and application

The keynote plenary presentation (Table 1) provided an overview of management issues for fisheries and examples of MSEs that have been applied to fisheries management. Key challenges for MSEs include achieving balanced and meaningful levels of stakeholder involvement, defining appropriate objectives, and effective communication of results.

The keynote presentation set the direction for discussions during the workshop. It focussed on uncertainties inherent in MSEs, which are typically developed to evaluate management strategies for data-poor systems (Figure 1). The three branches suggested in Figure 1 show the difficulty in MSE development and implementation for fisheries, and the range of perceptions of MSEs by managers. The upper branch is the expected progression for a scientific-based approach that leads to a framework that can be used to understand and quantify management

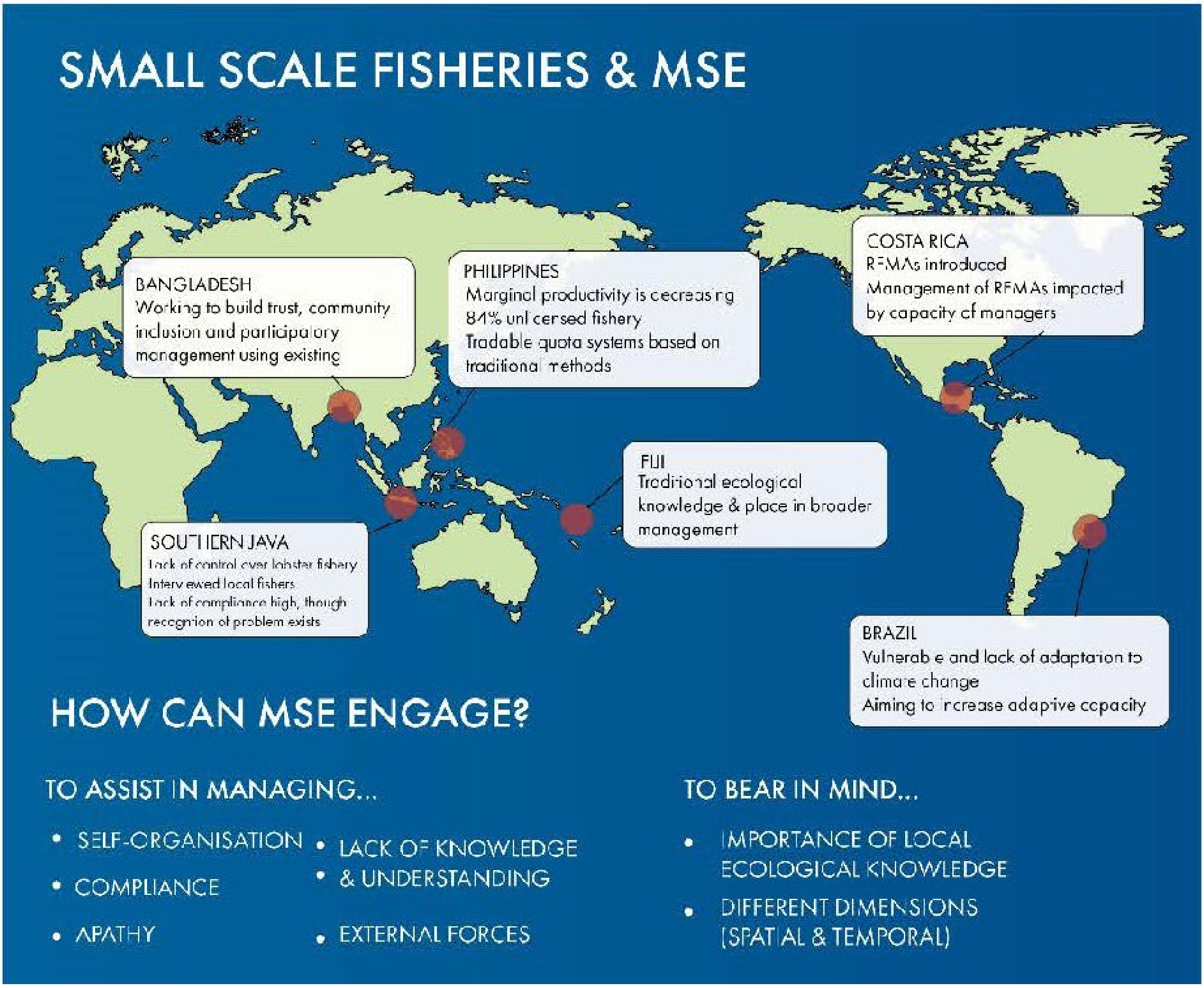

FIGURE 2. Infographic summarizing needs of small-scale fisheries and benefits of MSE model development for evaluation of management scenarios. The distribution of the small-scale fisheries discussed at the MSE workshop and their important characteristics are shown. Also shown are the approaches, issues and limitations of MSE engagement identified in discussions. The infographic was created by Indi Hodgson-Johnson, University of Tasmania.

options for fisheries. The middle branch depicts the perception that managers often have of MSE development and outcomes, which is characterized by confusion and uncertainty as to what an MSE is and how it is implemented to assess management options for fisheries. The lower branch suggests that the strengths of MSEs for evaluating management options are not understood or appreciated.

An important point highlighted for MSEs used in the management of fisheries is that learning from previous mistakes is critical (Figure 1, upper branch). This knowledge is needed so that "history does not repeat itself" in the evaluation of management options. The explicit need for detailed datasets is clear, as is that the level of skill required to develop MSEs using time series data is integral to the upper branch (Figure 1) to result in a useful MSE framework. These requirements for expertise and skills to process the data are not equally distributed across countries. For example, low income countries frequently have less access to the necessary specialized skill and detailed datasets are often not available.

The invited talks for the MSE workshop (Table 1) expanded and reinforced the ideas presented in Figure 1. The first presentation focussed on using an MSE to evaluate harvest control rules with specific application to the design and implementation of approaches to rebuild the stock of southern blue fine tuna (Table 1). This presentation clearly articulated social and natural science data needs and provided guidance on defining the societal management goals that underpin MSE implementation. Similarly, the second invited presentation dealt with issues of uncertainty and application of MSEs. The importance of community consultation and involvement was clearly illustrated. Without community involvement in developing the MSE and understanding the intent and contents, implementation can be compromised. The third presentation illustrated the natural and social science information needed for an MSE, the MSE as a tool, and again the need for communication of results was emphasized. A "Toy MSE application" developed for the tuna fishery (Table 1) was demonstrated and workshop participants were given access to this model (https://puntapps.shinyapps.io/tunamse). The contributed talks for the MSE workshop dealt with specific aspects and applications of MSEs. In addition, workshop participants considered the application of MSEs to Small-scale Fisheries (SSF), which included examples of several case studies.

3.2 Advancing MSEs

The workshop presentations considered aspects of SSFs and the application of MSEs to develop management strategies for these socio-ecological systems.

General themes that emerged from these discussions focussed on barriers to MSE development and implementation. As an important aspect of MSEs, the availability of robust data and time series and reasonably accurate estimates of catches, regular monitoring and data collection is central. In addition, a level of community compliance with the rules is required to be able to predict MSE outcomes with any level of accuracy. The engagement of communities in MSE use requires communities to self-organize and agree to develop compliance procedures for implementation of management strategies (Figure 2).

Barriers to MSE engagement stem partly from a lack of knowledge and understanding, general apathy towards management policies and external factors, such as socio-economic and climate controls. The range of spatial and temporal scales that need to be considered in MSEs was recognized, as well as the importance that data be collected at appropriate scales. Also, inclusion of local ecological knowledge (LEK) was recognized as being critical to successful MSE implementation (Figure 2). The incorporation of LEK was not considered to be straightforward, as no standard procedures were available to incorporate this type of knowledge nor were there generally accepted approaches to verify the "scientific usefulness and accuracy" of local knowledge.

The requirements of the SSFs discussed at the workshop and the benefits of implementing an MSE for management vary with the individual fishery, each of which has unique complexities and differences (Figure 3). The MSE has clear benefits in assisting with decision making and in providing a framework for formalization and integration of information about a system. The MSE also provides a structure for looking at effects that extend beyond just fisheries and for communicating science and policy. Trade-offs in MSE development and use come from data availability, the need for robust decisions, and the tensions that often arise between communities that develop MSEs and those that implement MSEs (Figure 3).

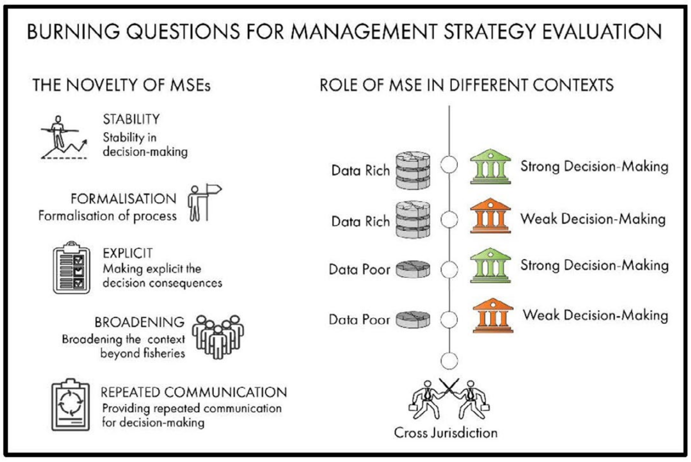

FIGURE 3. Infographic illustrating the capabilities and advantages of an MSE (left panel) and the trade-offs between data availability and the ability of an MSE to support decision-making (right panel). The infographic was created by Indi Hodgson-Johnson, University of Tasmania).

Best practice procedures for MSEs are outlined in Punt et al. (2016) and include the selection of objectives and performance metrics, selection of uncertainties, identification of candidate management strategies, simulation of the application of the management strategy, presentation of results and selection of a management strategy. The challenges around SSFs with respect to MSE best practices are partly the result of the management situation, including lack of knowledge and data, different culturally specific behavioural responses to rules and regulations, and the ability to include local knowledge in these types of approaches.

To achieve best practice, assessment of the applicability of MSEs to SSFs requires identifying common traits between the two that are amendable to MSE analysis and developing an MSE process that can be applied to data poor and culturally unique situations. Addressing these issues will provide guidance on when an MSE is needed (or not) and identify the core components of the MSE process, including the operation model for SSFs.

4. CONCLUSION

In general, MSEs are important tools that aim to help delineate objectives, costs, and constraints that define risk and provide a possible mechanism to meet assessment challenges. MSEs are becoming accepted for identifying different management approaches and characterizing risk across fisheries management locally, regionally, and globally. The workshop convened at

IMBIZO V is a first step in a longer-term effort to expand the use of MSEs in fisheries management. Research priorities that can be identified on the basis of the workshop results include: i) development of culturally sensitive, effective, and comprehensive community consultation to ensure MSE implementation; ii) defining appropriate objectives and building further knowledge around MSE development and implementation in data poor situations; iii) development of approaches that effectively communicate MSE results and build interactions at the science-policy interface; and iv) development of approaches to continue building capacity of interdisciplinary scientists to ensure a socio-ecological systems approach to MSE.

Participation by students and early career scientists supported by the Asia-Pacific Network for Global Change Research (APN) in the MSE workshop provided exposure to issues surrounding development and implementation of MSEs and the associated professional networks. Access to professional networks, facilitated by the workshop, provided the necessary tools for these individuals to fully participate in decision-making processes regarding marine resources and assessing the usefulness of MSEs in their national context. These workshop participants have a start at understanding the tools that will allow them to fully participate in decision-making process regarding marine resources. Networking and capacity building in MSE expertise in the Asia-Pacific region represent long-term impacts from the workshop. A lesson learned from the workshop is that the development of opportunities for early career scientists especially in countries where SSFs play an important role is critical for MSE development and implementation. Opportunities for identifying relevant data collection and targeted interpretation in SSFs is also key for future undertaking of MSEs. The priorities for future research specific to SSFs and more broadly applicable MSE-related topics provide a tangible approach for capacity building because these will involve early career scientists and dissemination of the workshop results to the larger scientific community.

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Peripherality as key to understanding climate-associated risk and resilience for Pacific island communities

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ABSTRACT

To address the lack of effective sustained interventions for climate-change adaptation in Pacific island communities, a study to capture individual community risk and resilience profiles using peripherality was undertaken. Based on questionnaires completed in 73 communities, three peripherality indices were tested and refined and demonstrated to adequately capture various things such as community exposure to climate change and autonomous community coping capacity. The implications of this study are many, not least in helping define national policy towards greater self-sufficiency but also in helping design more effective and sustainable external interventions for future climate change adaptation.

HIGHLIGHTS

» Peripherality captures community diversity.

» Peripherality allows community risk and resilience profiling.

» Peripherality measurements can optimize future interventions.

1. INTRODUCTION

For several decades it has been clear that most externally-designed and funded interventions for climate-change adaptation in Pacific island communities have failed to be effective or sustained (Nunn & Kumar, 2018; Piggott-McKellar, McNamara, Nunn, & Watson, 2019), a situation that is worrying considering recent accelerations in climate change and revised projections for the future (Nurse et al., 2014; World Meteorological Organization, 2019). This situation requires that past methods of addressing climate risk in such communities are revisited, especially through acknowledging the diversity of community exposure. In addition, it is clear that most past interventions have ignored culturally-grounded community resilience in favour of global solutions, a situation that is increasingly acknowledged as unsustainable (Granderson, 2017; Makondo & Thomas, 2018; Nalau et al., 2018; Nunn, Runman, Falanruw, & Kumar, 2017).

This study sought to inform improved interventions for climate change adaptation in developing-world communities by addressing the latter two points: first by demonstrating the diversity of community exposure rather than assuming that "one-size-fits-all" and, second, by showing the existence and diversity of culturally-grounded community coping in communities. In these ways, a better understanding of risk and resilience among these communities has been obtained.

2. METHODOLOGY

For 73 communities involving 630 people (47% male, 53% female) in the island countries of the

Federated States of Micronesia (FSM) and Fiji, diversity was researched using peripherality, the notion that communities are arranged in such island groups along a continuum from (developmental and economic) cores to peripheries (Nunn & Kumar, 2018). Data for measuring peripherality were obtained from in-depth community interviews (based on 97 questions) and were then analysed to derive three "peripherality indices" that could then be used to predict particular aspects of risk and resilience for such communities (details and questionnaire in Nunn & Kumar, 2019b).

Initial data were obtained from 15 Fijian communities in Bua Province, data that allowed development of preliminary peripherality indices that were then re-applied to those communities and others in northern Fiji to ascertain their efficacy in measuring risk and resilience. Peripheral communities are those where the time/cost/effort needed to travel to the closest urban centre (core) often reduces use of its facilities by community residents and, conversely, leads such communities to be more autonomous. The final three peripherality indices developed were then tested elsewhere in Fiji and in FSM and their effectiveness confirmed. These indices refer to Geography (Index 1), Population and Employment (Index 2), and Tradition and Global Awareness (Index 3) and could be calculated through answers to 15 context-specific questions.

All data collection was carried out with appropriate ethics approvals and in the vernacular languages of the target populations, mostly by the four authors. Results of this study have been conveyed back to key community stakeholders and disseminated internationally through publications and conference presentations.

3. RESULTS AND DISCUSSION

This study has produced results that are relevant to future climate change adaptation at various levels, including community and subnational, national and regional, and international and global. The nature of these results at each level are illustrated through the following three subsections, followed by a discussion that highlights the relevance of this study beyond the countries studied.

3.1 Results at community and subnational level

The three peripherality indices were applied to capture the risk/resilience profile of particular groups of communities in different parts of FSM and Fiji. In 14 communities in Bua (Fiji), peripherality was used to "predict" community "preferences" for western/traditional medicine (Figure 1), a preference for western medicine, which is expensive and difficult to access and consequently regarded as less sustainable than a preference for traditional medicine (Nunn & Kumar, 2019a; Nunn & Kumar 2019b). The word "preference" is used here to indicate dominant community usage of medicine type, not necessarily their desire/trust of this. As detailed in Korovulavula, Nunn, Kumar and Fong (in review), the inappropriate use of traditional remedies for new ailments (like NCDs) is an example of the failure of development in contexts such as those studied.

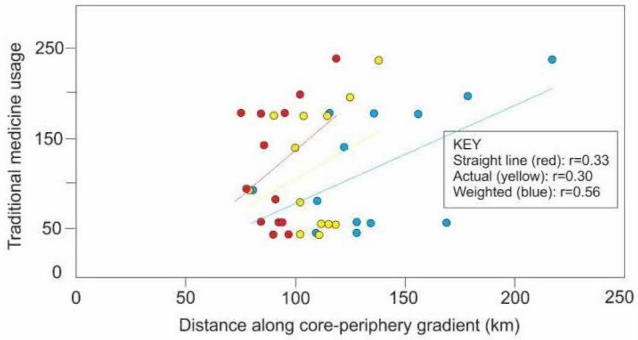

FIGURE 1. Use of peripherality to predict traditional medicine usage among communities of Bua (Fiji Islands).

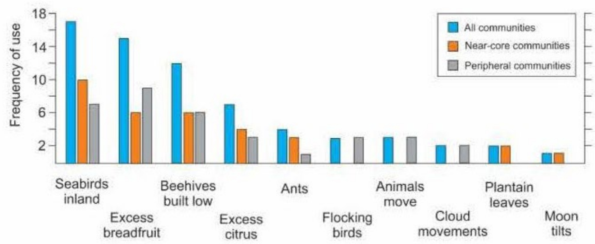

FIGURE 2. Use of traditional disaster precursors predicted by peripherality among communities along the cross-island road, Viti Levu Island (Fiji).

Similar research applied peripherality indices to 11 communities along the cross-island road on Viti Levu Island (Fiji) to capture autonomous community coping capacity (Korovulavula et al., in review). This shows up well as the understanding of traditional disaster precursors, a form of culturally-grounded knowledge that is considered suitable as a basis for future intervention combined with global knowledge (Figure 2).

In both these examples, the measurement of community peripherality within a group of rural Pacific island communities has shown their diversity and, most importantly, separated those communities that are most at risk from climate change (because they are least autonomous and more dependent) from those communities that are most resilient (because they are autonomous or have the potential—through the existence of traditional coping—to be so). These examples therefore illustrate how peripherality can be used to quickly and easily assess community diversity and therefore inform the optimal design and delivery of interventions for climate change adaptation.

3.2 Results at national and regional level

The acceleration of climate change, especially – in a small-island context – the accelerating sea-level rise in the Pacific (Nerem et al., 2018), is likely to lead to a situation within the next few decades where large numbers of rural communities, especially along coasts, will need to be assisted to sustain themselves in the face of unprecedently rapid climate change. Interventions will likely be underfunded and will therefore depend for their success on differing degrees of autonomous community coping. Results show that more resilient communities are likely to be those with existing traditional/indigenous knowledge, be it about traditional healthcare or disaster preparation, while more risk-exposed (less resilient) communities are likely to be those that have "lost" most of their traditional/indigenous knowledge and are almost wholly dependent on outside assistance for their sustainability. Peripherality measurements of the kind described in this study will allow the rapid capture of community diversity, allowing national and regional planners to quickly understand which communities are more in need of external help in order to sustain themselves and which communities are better able to cope autonomously with climate change challenges.

The use of peripherality to capture community needs is also something that national (government) and regional planners could use now to prepare communities for the future. Trends of increasing dependency on external/western solutions to a range of developmental challenges (which are costly and often unreliable) are unsustainable, both because of the growing inability of island countries to afford them but also because their supply is likely to decline in the future. A recent study (Nunn & Kumar, 2019a), arising from the current project, argues that trends of increasing dependency by island countries (and developing nations more broadly) on other countries for climate change adaptation are unsustainable because, within a few decades, the costs of domestic adaptation to climate change for these countries will become so great that they will be unable to afford to be as generous as they are today towards their poorer island neighbours. The likelihood of this underlines the urgency for island nations (and other developing countries) to become more self-reliant, especially at meeting the challenges of climate change adaptation, or risk societal breakdown as livelihood loss multiplies over the next few decades.

3.2 Results at international and global level

Similar comments refer to the international/global level but here the results of this study are considered more to be instructive rather than directional. Many of the failed interventions for climate change adaptation in Pacific island countries (and elsewhere) have been designed and costed elsewhere, meaning that they are not always well aligned to the actual situation to which they are applied. For example, hard structures (like seawalls) for shoreline protection may often be constructed within the context of a particular project but, when they require maintenance (or need rebuilding), it is assumed that beneficiary communities will do so. Often these communities lack the necessary resources, so the interventions fail and may even prove maladaptive.

Given the growing urgency of making sure that future climate change interventions in rural communities in the Pacific Islands (and elsewhere) are both effective and sustainable, it is considered important that international/global stakeholders are better educated about target-community needs (risk profile) and autonomous coping ability (contributing to resilience). Use of peripherality indices to rapidly measure risk-resilience in these contexts would allow better-informed and more sustainable interventions in the future.

4. CONCLUSION

Peripherality measurements of rural Pacific island communities allow their risk and resilience profiles to be readily and accurately determined. This provides a ready tool for measuring community diversity in developing-country contexts. This is considered essential in order to optimally tailor future interventions for climate change adaptation so that these are effective and sustainable.

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