Prospects of pond ecosystems as resource base towards community based adaptation (CBA) to climate change in coastal region of Bangladesh

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ABSTRACT

Climate-induced hazards are adversely affecting the pond ecosystems in Bangladesh. Most of the poor communities collect water from isolated ponds for drinking and other domestic needs. This paper explores how the small pond ecosystems and associated livelihoods of the coastal communities are vulnerable and argues that the pond ecosystem can be a potential resource base for community based adaptation in the coastal regions of Bangladesh. A set of quantitative and qualitative tools were applied to 309 households across five villages. The study showed that 96% of the respondents are dependent on pond water for drinking. More than 50% households expressed that temperature, rainfall variations and salinity intrusion, directly and indirectly, affect the pond water. Physical parameter values of temperature, pH and salinity from the ponds showed changes across different seasons. Drinking water scarcity during pre-monsoon (March–May), winter (Dec–Feb), disaster and immediate post-disaster period among the communities is high. Salinity intrusion and surface runoff caused by excessive rainfall in short periods also cause deterioration in the quality of pond water. However, successful examples of pond water usage emerged through the discussions, especially during a post-disaster crisis, which strengthens the idea that ponds could be a resource base for community-based adaptation in the coast of Bangladesh.

Key words | adaptation, climate change, coast, ponds, resource base

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INTRODUCTION

Climate change induced hazards are the characteristics of climate change, such as droughts, floods, increasing temperatures, sea level rise (SLR) and frequency of heat waves (Oppenheimer *et al.* 2014). According to Stern (2007) and Otzelberger (2014), climate change will increase the frequency of heatwaves and strong winds, along with an increase in both the frequency and intensity of droughts and rainfall. Such climate change induced hazards, as well as others including SLR, cyclones, storm surges, salinity intrusion and water logging, adversely affect both water resources and human health, especially in the coastal regions (Rabbani *et al.* 2013a, 2013b). Indeed, salinity intrusion in freshwater will threaten access to safe water to use for drinking and other household purposes (Huq & Rabbani 2015).

Increase in temperature resulting in a rise in sea level would exacerbate the impacts of cyclones and storm surges on the quality of water in Bangladesh, as such events have the potential to spread pollution from contaminated sources. For example, Cyclone Sidr in 2007 spread saline water to more than 6,000 ponds in Bangladesh (Rabbani *et al.* 2010). The coastal region of Bangladesh is particularly vulnerable, due to cyclones. On the other hand, salinity became one of the biggest problems for the coastal zones of Bangladesh. This may be happening due to the low flow of fresh water from the Ganges and ingress

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of salt water from the Bay of Bengal. So the effect of SLR and salinity may disrupt surface water systems, for example pond water, agriculture practices (e.g. reduction of rice), mangroves including the Sunderbans and coastal ecosystem including ponds, and create additional health problems in the local communities. The poor and marginal groups would be critically affected by the possible SLR and salinity intrusion in the coastal zone of Bangladesh.

In Bangladesh, ponds are being used for many purposes including domestic needs, sanitation and cleaning, small scale irrigation for rice fields, vegetable farming, social forestry/home gardening, fish cultivation, etc. According to a World Fish Centre (WFC) report, the ponds produced 0.8 million tons of fish in 2006 (Dey *et al.* 2008). Pond water is useful for producing freshwater fish and winter crops; it also keeps the community engaged in activities related to producing these fish and winter crops. For instance, women can be engaged in fish nurturing and production activities and can even earn money by selling the fish. This demonstrates that ponds can be an excellent source of nutrition and it can also give the community opportunities to earn money. There are numerous abandoned ponds in many coastal villages in Bangladesh, which could be turned into potential resource base during crisis. An Integrated Water Resources Management (IWRM) approach could help the local communities to maximize benefits and improve resilience. Khadim *et al.* (2013) recommend an IWRM approach to overcome conflicts and challenges of water problems and demands in developing countries. The paper shows the threats of these ponds in the face of climate change followed by uses and scopes of their recovery for enhancing community based adaptation.

This research mainly focused on climate-induced hazards on pond-based livelihoods of the local communities. It also considered the long-term changes of temperature and rainfall and their seasonal variation. Salinity, pond water temperature and pH were also measured to understand the changes in physical parameters.

The analysis of the trends of climate parameters, seasonal changes of physical parameters of the pond water and perception of the local communities on the livelihoods practices over the period are complicated by various uncertainties. These uncertainties are associated with reliability of the meteorological data, technological variations for physical test, lack of data and scientific consensus how the climate change will push the SLR in the coast and frequency and intensity of the cyclonic events and perception itself. One of the major limitations of the research was that it covers only one out of 19 districts in the coastal zone, such that the results may not apply to all districts of the coast or the coast of other countries. Long-term salinity data in the ponds are not available. The research had to depend on the perception of the local communities on the salinity and general quality of water issues of the pond.

To overcome all the challenges, the study took a comprehensive approach of conducting household surveys, in-depth interviews and group discussions with study communities helping to capture the local knowledge, practices and climate induced challenges related to pond based livelihoods. Time series data and changes in pond characteristics also helped in linking the findings.

This paper comprises four sections. The first section presents a brief overview of climate change induced hazards and potential impacts on water resources, followed by a section describing the approach and methodology used to conduct the research. The penultimate section emphasises research findings, including the perception of the households on climate change induced hazards in the study areas, current livelihood options related to the pond ecosystem, existing climate change impacts and vulnerability on the ponds and provide a strong ground on how pond ecosystem can be active for community based adaptation. Finally, concluding remarks are based on the arguments and findings.

MATERIALS AND METHODS

The research followed a comprehensive methodology, employing quantitative and qualitative tools to determine the climate change impacts on pond ecosystems and associated livelihoods of the study communities.

Literature review

A rigorous literature review was carried out to meet the objective of the research. It was done to serve three main purposes: (1) it provided a basis and a basic structure of the argument of existing works related to climate change, coastal zones and implications on wetlands/ponds ecosystem; (2) it also provided the knowledge gaps related to this research and identified opportunities for further works on the issue; (3) the trend of these climate parameters and people's knowledge on impacts and vulnerabilities were studied. Overall, the literature of major climatic hazards affecting the coastal zone of Bangladesh, climatic hazards affecting ponds and associated livelihoods of the communities and relevant policy documents were mainly reviewed. The literature that deals with climate change impact on isolated ponds and associated livelihoods are very rare. Most of the current literature emphasizes the general impacts of climate change on a national level on different sectors including water resources. There is very little literature addressing the implications of climate parameters on pond water quality at a global level. Some literature discusses fisheries and management aspects of the ponds but climate change related to pond ecosystem issues are not well addressed. These studies do not have adequate coverage on the pathways and mechanism of how deterioration of water quality of ponds caused by climate change and climate variability implicate with livelihoods, social dimension, environmental and economic settings of the poor local communities. The pond ecosystem also provides cultural services and religious services to the communities in many ways. However, this great resource of the rural poor communities is being adversely affected by climate change and climate variability.

Primary data collection

Measuring physical parameters

The study analysed the climate parameters, for example temperature and rainfall pattern, i.e. the key physical parameters of the ponds. Existing literature demonstrates that these parameters have an impact on wetlands (Brönmark & Hansson 2002; Karafistan & Arik-Colakoglu 2005; Erwin 2009). de Roda Husman & Schets (2010) mention that climate change and water-related infectious diseases are also intertwined. The pH and salinity of water of all the ponds were measured *in situ* to examine the variation of the water quality in different seasons. The water temperature, pH and salinity were measured by a thermometer, pH meter and portable refractometer respectively. Four readings were taken from the surface water for each of the ponds in three different seasons (pre-monsoon, monsoon and winter) of the study year (2012). Physical parameters including the area and depth of the ponds were measured using conventional scale measurements (Table 1).

People's perception through survey, focus group discussions and interviews

The study included a number of tools for understanding the pond characteristics with climatic parameters and household understanding of the scenario. To understand people's perception of climate change impacts on ponds and associated livelihoods and adaptation options, the survey was carried out with a semi-structured questionnaire. The households were randomly selected from the list of pond users/beneficiary households. In total, 309 beneficiary households were surveyed to meet the objective of the research (please see Table 2 for details of surveyed population). Focus group discussions (FGDs) were conducted among the direct beneficiaries of the households and other relevant stakeholders. Participants included the Union Chairman, respondents from the Department of Fisheries, District Project Implementation Officer (PIO), Union Parishad members, teachers, NGO representatives, among many. A total of nine FGDs were conducted and the FGD conducted included 12–14 participants. In-depth interviews

Table 1 | Information on the selected study ponds in Satkhira

				Depth (meter)	
Pond no.	Union	Village	Size (ha)	Highest (Jul–Sept)	Lowest (Mar–May)
1	Munshigonj	Jelekhali	0.32	2.7	1.4
2	Munshigonj	kultoli	0.16	2.4	1.4
3	Munshigonj	kultoli	0.32	2.1	0.9
4	Burigoalini	Pankhali	0.28	2.1	1.2
5	Munshiganj	Jelekhali	0.32	2.1	1.2
6	Burigoalini	Kalbari	0.16	1.8	0.9
7	Burigoalini	Datnakhali	0.28	2.1	1.2
8	Burigoalini	Datinakhali	0.40	2.3	1.2

Table 2 | Details of the surveyed pond beneficiary population

Pond no.	Union	Village	Population of the village[a]		Pond beneficiary households (approx. min. no)	Surveyed households (no.)	% of beneficiary households surveyed
			Total	Households			
1	Munshigonj	Jelekhali	2,346	516	100	39	39.00
2	Munshigonj	Kultoli	1,372	319	150	49	32.67
3	Munshigonj	Kultoli	1,372	319	60	18	30.00
4	Burigoalini	Pankhali	1,380	326	200	80	40.00
5	Munshiganj	Jelekhali	2,346	516	100	35	35.00
6	Burigoalini	Kalbari	1,775	406	60	21	35.00
7	Burigoalini	Datnakhali	2,220	513	120	36	30.00
8	Burigoalini	Datinakhali	2,220	513	110	31	28.18

[a]*Source:* BBS (2014).

were carried out among the most knowledgeable people of the community who were selected from the FGDs to be candidates able to best express and explain the current condition in the study area. As such, seven well-known people of the community were interviewed. The in-depth interviews were conducted to gain a thorough insight to the problem. The advantages of using these techniques are that this is a comprehensive method of assessing the situation of pond livelihood in the study area. The research does not solely depend on the surveys but cross-checks with expert opinions conducted during the interviews with the knowledgeable people of the community in order to assess the situation. The study also incorporates the findings of the FGDs to assess how findings from the other methods make correlations with the results. Some feasible alternative tools for this study could be conduction of some workshops with the beneficiaries of the ponds. However, the focus of this study was mainly given on the FGDs. and it gave many more advantages too. During the discussion, the opinions and information from the women were collected and emphasized on since they are the main water bearers, managers and users of the household water brought from the pond. Their opinions and remarks were cross-matched with those provided by the other members of the households, especially those collected from the knowledgeable members of the study area.

FGDs and Key Informant Interviews were also conducted to supplement and complement the survey findings. The group discussion and interviews provided a deeper understanding on specific adaptation issues. The study also provided social, environmental and economic pathways of vulnerabilities of the communities related to pond-based livelihoods. The current knowledge, understanding and practices were also captured to explore future needs and potential opportunity under changing condition.

Secondary data collection

Time-series temperature and rainfall data analysis

The information on time series data (local) on the main climatic elements, for example temperature and rainfall, were collected from Bangladesh Meteorological Department (BMD) to determine the state and trend of annual, seasonal and monthly averages. Additionally, the state and trend of the main secondary elements of climate change at the study location were carried out.

Data analysis

The analysis was carried out in three stages. In stage 1, as mentioned above, time series data on temperature and rainfall of Satkhira Meteorological station were collected from BMD for analysis. The long-term local data were analysed which was carried out to determine the state and trend of temperature and rainfall. Stage 2 provided the opportunity to look at some key abiotic factors including pond water temperature, pH and salinity of the ponds during different seasons of the study year (2012). It helped to find a seasonal relationship between climatic elements and the physical quality of pond water. A thermometer, pH meter and potable refractometer were used to collect water temperature, pH and salinity of the pond water respectively. Stage 3 presents the critical part of the research. It covers the analysis of ponds based livelihoods, services of ponds, current problems, and potential risks of climate change and climate variability on the ponds. It also imparts how the coastal communities are currently adjusting to the adverse effects and the ways and measures that they plan to adapt in case of increased intensity of the extreme events related to climate change.

RESULTS

Introduction of the study ponds in Satkhira, coastal district

The study area is located in Shyamnagar Upazilla (sub-district) in Satkhira district, some 50 km south of the main city (Figure 1). Shyamnagar was chosen as the study area because it was mostly affected during the cyclones in 2007 and 2009. Shyamnagar is a coastal sub-district, which is highly vulnerable to frequently occurring climate induced disasters. The rationale to select this study area was to study the most climate vulnerable and climate affected community in the district.

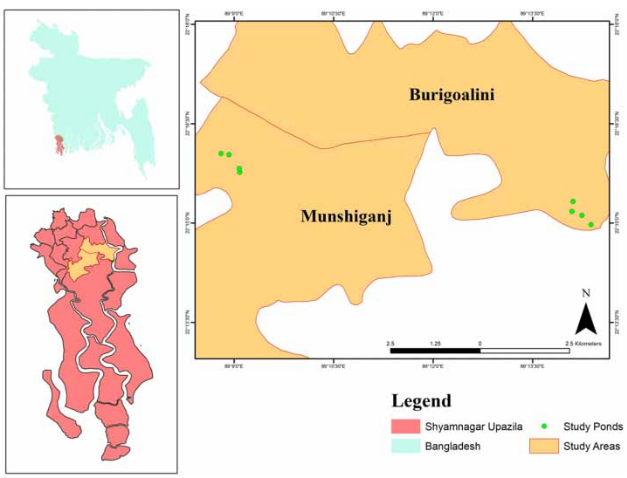

Figure 1 | Study locations in Shyamnagar, Satkhira.

Bangladesh has nearly 2.5 million ponds of different sizes. The total area of these ponds is approximately 0.3 million ha (Dey *et al.* 2008). The number of ponds has increased over the years due to the rise in fisheries cultivation (Kranzlin 2000; Dey *et al.* 2008) but many poor communities are still using these ponds as a source of drinking water, sometimes connecting ponds with Pond Sand Filter (PSF) technology. Table 1 shows the study ponds, locations, size and depth of the ponds.

Analysis on pond's physical parameters, climate parameters and climate induced hazards

A set of specific physical parameters of the pond and climate parameters was chosen for analysis. In addition to size and depth of the ponds, physical parameters including pond water temperature, pH and salinity of the ponds were chosen to determine the water quality in different seasons. Annual and seasonal temperature and rainfall was explored for any linkage with physical parameters of the ponds.

Physical parameters of the study ponds

Pond water temperature. The seasonal mean surface water temperature of the study ponds was measured in 2011. The highest temperature of each of the ponds was reached in the pre-monsoon season (March–May). The lowest temperature of all ponds was found during winter. The pre-monsoon average temperature ranged between 32.35 (Pond 2) and 35.5 °C (Pond 6). The average temperature of the ponds was between 31 (Pond 1) and 34.35 °C (Pond 8) during monsoon. The winter temperature reached 20.3 (Pond 6) to 22.2 °C (Pond 4). Pond 6 showed the highest temperature in pre-monsoon and lowest temperature in winter.

pH. Figure 2 shows the annual average pH of the study ponds in Satkhira in 2011. The pH value of the study ponds is quite variable in different seasons of the year. It ranges between 7.45 and 9.05. Most of the study ponds (except Pond 6) experienced the highest pH in winter and the lowest in pre-monsoon. Some ponds (Ponds 1 and 5) faced the lowest pH in monsoon. The highest (8.7) annual average pH was reached by Pond 2 while the lowest (7.8) was marked by Pond 7. On average, Pond 1 shows the second

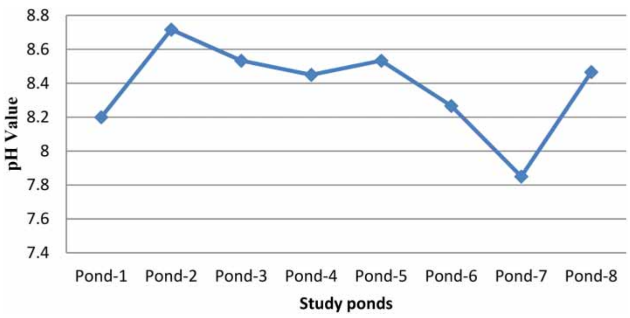

Figure 2 | Annual average pH of the study ponds in Satkhira in 2011.

lowest pH value with the highest depth among the ponds, while Pond 6 shows slightly higher than the second lowest pH value with the lowest depth among the ponds.

Salinity. Salinity in the water bodies of the coastal region of Bangladesh is a very common phenomenon now. Cyclone and storm surge overflows of river and canals due to tidal surge or SLR and low flow in the rivers cause intrusion of saline water in both surface and ground water resources. Freshwater ecosystems, including ponds, are extremely threatened by salinity intrusion resulting from climate-induced hazards. Nielson *et al.* (2003) suggest that salinity intrusion will adversely affect the physical ecosystem processes. Cyclones Sidr and Aila inundated over 6,000 ponds with saline water along Bangladesh's coast (Rabbani *et al.* 2010, 2013b). In all measurements, pond water had salinity from 1 PPT (Pond 8 in monsoon) to 5.1 PPT (Pond 6 in pre-monsoon and winter). The highest mean salinity (5.01 PPT) was found in Pond 6, and the lowest mean salinity was in Pond 8. The salinity level was higher during the winter in each of the studied ponds (Figure 3). Lower salinity was experienced during monsoon. There is a positive relationship between salinity level and the size of the ponds. Pond 8 showed the lowest mean salinity with the largest in size while Pond 6 showed the highest mean salinity with the lowest depth and size. Table 3 shows the relationship among the salinity level, average depth and size of the study ponds in Satkhira in 2011.

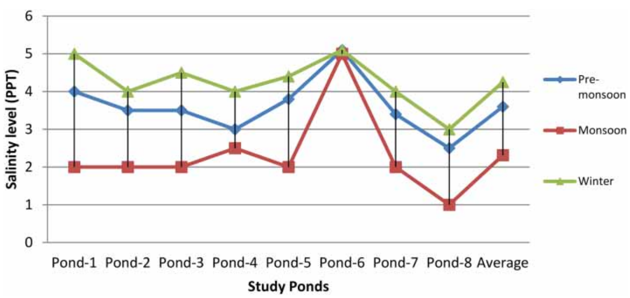

Figure 3 | Salinity level in different seasons in the study ponds (2011).

Temperature and rainfall pattern of the study locations

Temperature. Data collected from Satkhira station from the BMD reveal that over the last 35 years (1981–2015), maximum and minimum average temperatures in pre-monsoon were on a decreasing and increasing trend respectively. However, in the last 20 years (1996–2015), the trend of both maximum and minimum average temperature in pre-monsoon was increasing.

Rainfall. The pattern of total rainfall for the period of 1981–2015 was quite irregular. The study indicates that the trend of annual rainfall is slightly decreasing over the period (Figure 4). The monsoon of 1986 received the highest rainfall (1,105 mm) compared to other years in the period of 1981–2015. Over the years, the number of days without rainfall is increasing or the rainy days are decreasing (Figure 5). It was also observed that the trend of days with over 100 and

Table 3 | Relationship among mean salinity, average depth and size of the study ponds

Pond no.	Mean salinity (PPT)	Average depth (meter)	Size (ha)
1	3.67	2.05	0.32
2	3.17	1.9	0.16
3	3.33	1.5	0.32
4	3.17	1.65	0.28
5	3.40	1.65	0.32
6	5.07	1.35	0.16
7	3.13	1.65	0.28
8	2.17	1.75	0.40

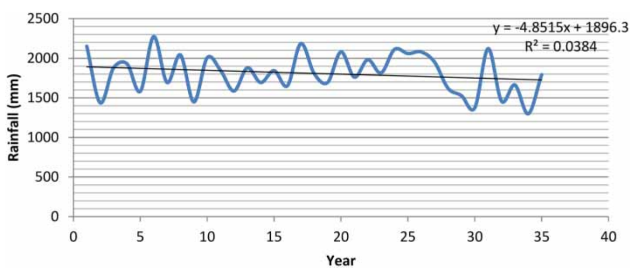

Figure 4 | Trend of annual (total) rainfall in Satkhira during 1981–2015.

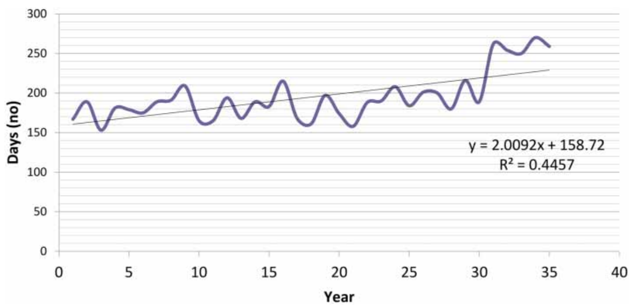

Figure 5 | Trend of 'no of days without rainfall' during 1981–2015 in Satkhira.

150 mm of rainfall is decreasing (Figure 6). On the seasonal rainfall pattern, pre-monsoon, monsoon and winter rainfall followed a decreasing pattern from 1981 to 2015 while post-monsoon shows a slightly increasing trend for the same period (Figure 7).

Cyclonic events, salinity and SLR in the study district

One of the predictions of the IPCC AR4 is the intensification of the extreme weather events such as cyclones and associated storm surges. There is evidence of decreasing frequency of monsoon depression and formation of the cyclone but an increase of intensity in the Bay of Bengal since 1970 (Cruz *et al.* 2007). Studies indicate that 38 cyclonic events affected the southwest coastal region (Greater Khulna) including the study district, Satkhira, during 1877–2010 (Islam & Peterson 2008). Four severe cyclonic storms and one super cyclonic storm have affected this region since 1973.

Figure 8 shows the number of cyclonic events in different months of the year between 1877 and 2009 on the southwest coast. Cyclone Sidr and Cyclone Aila devastatingly affected the study region in 2007 and 2009, as mentioned above, and this indicates that cyclones usually hit the south-west coast between May and December. Monsoon and post-monsoon are the main seasons for cyclonic events in the greater Khulna region, including Satkhira. In the cyclone history, the highest occurring month was found to be June (eight times) followed by October (seven times) during the mentioned period.

SLR and salinity intrusion are already affecting the coastal communities in Bangladesh. It is projected that the possible SLR may severely influence the coast of the country. A recent report showed that Bangladesh would face the largest impacts due to SLR (World Bank 2007). It was modelled that if the SLRs by 25 cm then, 40% of the Sundarbans will be submerged, and in the case of the sea level rising by over 60 cm, the whole Sundarban will disappear (Hare 2003).

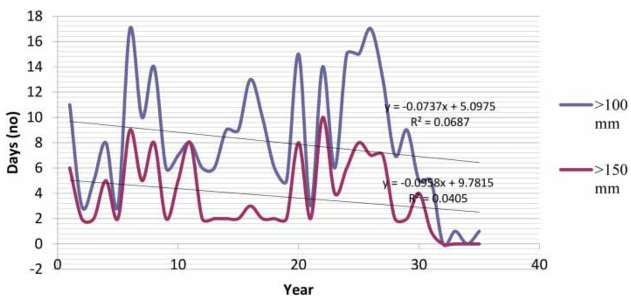

Figure 6 | Trend of days with above 100 and 150 mm rainfall in Satkhira during 1981–2015.

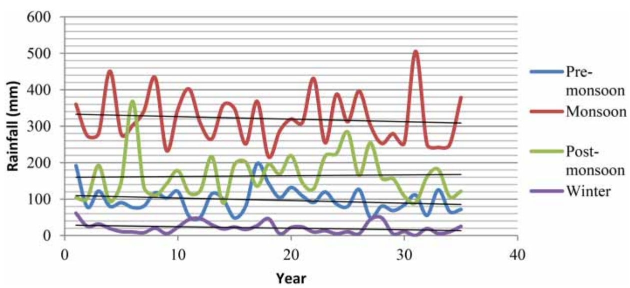

Figure 7 | Trend of average seasonal rainfall (total) between 1981 and 2015 in Satkhira.

Socio-economic context of the study communities

Gender and age demographics

Less than 40% of total respondents interviewed were male as many of them were at work during the daytime. Female

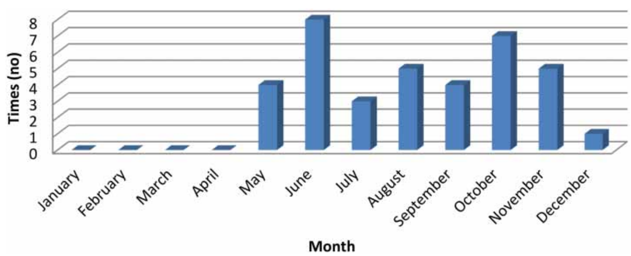

Figure 8 | Southwest coast (Khulna region) affected by cyclonic events in different months during 1877–2010.

members of the households have a role on household level work, and male members are usually out of the house for work. *About 98% of household heads are male so very few households are women headed.* Nearly an equal number of male and female constitutes the demographic structure of the study area. The male population is slightly higher (52%) than the female population (Figure 9). Age demographics of the study population reveal that a significant portion of the population is within the working age group with 43% of the population between the ages of 30–44 (Figure 10). Less than 10% of the population is over 60 years of age. The average household size was 4.5, which is slightly more than the national household size of the country (4.4). Most of the respondents had at least junior school education while one-fifth of them do not have any academic qualification. Male respondents were found to have higher qualifications than females.

Economic conditions

Regarding its socio-ecological settings, coastal zone differs from the rest of the country. Poverty and illiteracy in the coastal areas are high. Among the study population, 31% of the respondents fall under the category of 'extremely poor'. They face problems with livelihoods (insecure occupation), often take two meals a day, have poor housing and no land for cultivation. Half of the respondents perceive their economic condition as poor; they have limited earning members in the family, face frequent changes of livelihoods and food deficits in some seasons. Only 19% of the household level respondents think that they are not poor. They can afford three meals a day, earn from different sources, for example agriculture products, own additional land, foreign remittance, business, shrimp farming, etc. This categorization was completely based on their own perception and the way they think about their economic status. The annual income of non-poor is almost three times higher than the annual income of extreme poor in the study locations. Income differences between extremely poor and poor are not so high. This income distribution is not an absolute measure. It is based on their self-declared economic status and perception of the study communities.

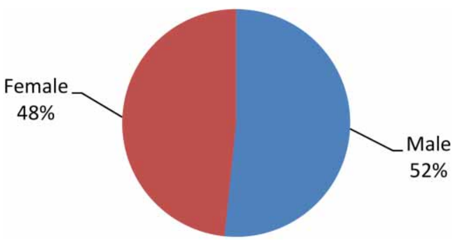

Figure 9 | Gender distribution of study population.

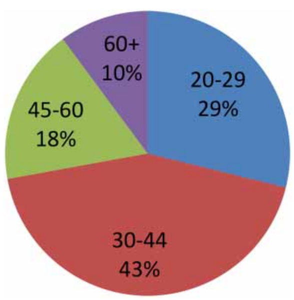

Figure 10 | Age distributions of the respondents by percentage.

Social and political aspects/conflicts in the study district, Satkhira

Satkhira, being one of the most climate vulnerable districts, indicates a substantial increase in literacy rate from about 46 in 2001 to 52 in 2011. However, female literacy is significantly lower (39) than the national average (51). Satkhira's poverty at 46% is much higher than the national average of 31.4% (Khondker & Mahzab 2015). In fact, Satkhira ranked eighth in the list of 15 high poverty districts of the country. Due to frequent climate induced disasters, for example Cyclone Sidr in 2007 and Cyclone Aila in 2009, local livelihoods of the communities are affected. Most of the poor people struggle with live and livelihoods. Usually, the socio-political situation deteriorates during disaster and post-disaster periods. Mallick *et al.* (2017) state 'coastal areas are densely populated with an increasing trend toward conflicts due to a scarcity and unequal use of resources'. Freshwater supply and sanitation practices remain one of the major challenges in the study areas.

Pond-based livelihoods

In Bangladesh, the pond is being used for many purposes including domestic needs, sanitation and cleaning, small scale irrigation for rice fields, vegetable farming, social forestry/home gardening, fish cultivation and so on (Rabbani et al. 2013a, 2013b). Nearly 65% of the total ponds in Bangladesh are being used for fish cultivation. According to WFC report, the ponds produced 0.8 million tonnes of fish in 2006 (Dey et al. 2008) which indicates how the ponds are providing a livelihood opportunity in the country. It is worth noting that single households or a small group of households in most of the coastal districts own a pond. In many cases, the households cultivate fish on a small scale and protect the ponds for core domestic uses.

The pond plays a particularly important role among disadvantaged groups as a main or supplementary source of employment, livelihood and income. The poor households recently brought significant changes in vegetable and fruit farming (e.g. watermelon) in many places in the country. On the south-west coast, most have a small vegetable farm around their housing. In many cases, without pond water, it is very difficult, especially for the winter crops. Most of the hotels and restaurants located at the local *bazaar* (village market) also collect water from the nearest ponds. They use this water for cooking and washing at the restaurant. Sometimes, especially in the peak season (July–August), some restaurants keep the pond water for drinking. The study shows that 96% of households collect water from these ponds for drinking purposes (Rabbani et al. 2013b). The pond water is also being used for bathing, cleaning, cooking, washing, small-scale irrigation, fish cultivation and so on. Therefore, protection and ensuring the quality of water of these ponds could help poor people to avoid water crises year round.

Climate change impacts and vulnerabilities on ponds and associated livelihoods

Respondents expressed that climate change impacts have negative multi-faceted effects on pond water sources. Erratic rainfall patterns (70% of households), high temperatures in pre-monsoon seasons (60% of respondents), frequent cyclones and storm surges (58% of respondents), and higher tides and salinity intrusion (37% of those surveyed) are the major climate change associated hazards impacting on the ponds in the locality (Rabbani et al. 2013b). Salinity intrusion caused by cyclones and storm surges have already resulted in devastating effects on Satkhira's coastal ecosystem, including small ponds. Perception on some significant impacts and vulnerabilities are outlined below:

1. *Water quality and usage*: When the volume reduces, the water quality deteriorates due to the presence of contaminants. The volume of pond water depends heavily on seasonal variability. Most of the respondent (76%) stated that they have the lowest quality of water during the pre-monsoon (March–May) season. Their argument is that long spans of rainless days may be one of the possible reasons for the depleting water level. One year after Cyclone Aila, which struck in 2009, the usability of pond water was largely reduced as the quality of water dropped significantly beneath acceptable salinity levels. Only 5% of the total respondent households mentioned using pond water for drinking purposes during this period. However, one year later, respondent dependency on pond water for drinking sharply increased to 67% and currently it is about 96%. Salinity intrusion in pond water also notably reduced the dependency of respondents on its use for cooking purposes. Only 21% of respondent households depended on pond water for the kitchen, with this dependency increasing to 77% one year after Cyclone Aila struck.
2. *Diseases*: The respondents were found to be suffering from a number of climate sensitive diseases like diarrhoea, dysentery and skin diseases. The female respondents were found to mostly suffer from diarrhoea, fever and headache and skin disease. On the other hand, their male counterparts seem to frequently suffer from dysentery. Fever and headache were found to be the most common, followed by dysentery and diarrhoea. The children of the respondent households were found recurrently suffering from diseases like fever and headache, diarrhoea, cholera, dysentery, skin disease and others, such as jaundice, etc. Deterioration of water quality is the leading cause of diarrhoea and dysentery as reported by more than 60% and 40% of respondents respectively. Some respondents, close to 20%, held skin disease as a consequence of degraded water quality.

   On the other hand, around 15% of respondents even felt that the deteriorating quality of water also causes them to suffer fever and headaches. The frequency of occurrence of different diseases also depends largely on seasonal variability. According to the respondents (91%), the incidence of illness derived from poor water quality is highest during pre-monsoon season when the pond water quality is at the lowest. However, a smaller percentage (6%) also suffer from different water-borne diseases frequently during monsoon. The occurrence of illness was found to be the lowest in winter among the respondents.

3. *Nutrition*: The study reports that about 77% of the studied households suffer from a deficiency of food around the year ranging from a few weeks to a few months. It mainly depends on the production of crops, for example rice and vegetables. Food deficit remains high during August–September, mentioned by 59% of the households (HHs) while it is the lowest in April (15.5%). Many of the respondents mentioned lower production of the rice due to salinity in the soil, late rainfall, seasonal drought and damage to crops and vegetables because of excessive rainfall. Seasonal food deficiency is becoming a crucial issue for the study areas as informed during the FGDs and interviews. As many families depend on these ponds to water their homestead garden, ponds play a significant role in maintaining food security.

Increased cyclonic events and storm surges (Singh *et al.* 2001; Rahman *et al.* 2011), shrimp farming, tidal surges, increased level of water in water streams (rivers and canals) and low flow in the river causes intrusion of salinity in freshwater water resources and soil in the coast of the country. Cyclonic events have pushed the salinity into the groundwater resources (Shamsuddin *et al.* 2006; Rahman *et al.* 2007, 2011; Rabbani *et al.* 2010). Analysis of the primary and secondary data shows that there are links between changes in climate and pond characteristics and associated livelihoods (Table 4).

DISCUSSION

The changing climate of the world is having implications on its natural resources. The pond ecosystem in Bangladesh is a suitable example to demonstrate this. The people of the coast of Bangladesh are exposed to different climate induced hazards (Rabbani *et al.* 2013a, 2013b). Predicted SLR is expected to augment current risks already impacting upon coastal livelihoods in various ways. Das & Radhakrishna (1991) argued that an average mean SLR of 15–38 cm by 2050 may affect coastal zones, including pond ecosystems. Warrick *et al.* (1996) pointed out that the SLR in the Bay of Bengal is influenced by a set of local factors including tectonic settings, sedimentation and deltaic subsidence. All these factors will eventually create serious impediments for the smooth functioning of the ponds ecosystems in the future.

Vulnerability of pond ecosystem due to climate change

The study district, Satkhira, is very vulnerable because of low land elevation, weak defences against large tidal/storm surges/flood and low-level resilience (South Asia Meteorological Research Centre (SMRC) 1998 in Karim & Mimura 2008). It is evident that there are variations in temperature, erratic rainfall behaviour (late onset, excessive rain over a short period, lack of rain in a particular time of the season), cyclonic events, storm surge induced salinity intrusion and potential SLR. These changes in the climate system jeopardise the interaction between pond ecosystems and the local communities. Increased SLR will bring the water line further inwards. Consequently, the effect of storm surge will penetrate deeper into the landmass. These are going to largely affect pond-based agricultural production, health, loss of livelihood and increase in poverty of this region. The people who depend on these ponds for drinking water and other domestic needs are going to be largely affected as raised in all FGDs and interviews. Salinity became one of the largest problems for the coastal zones of Bangladesh, which may be due to the low flow of fresh water from the Ganges and ingress of salt water from the Bay of Bengal. So the effect of SLR and salinity may disrupt agriculture (e.g. reduction of rice), mangroves including the Sunderbans and coastal ecosystem including ponds and create additional health problems in the local communities.

Depletion of local species and the importance of restoration

Local species disappearing from the water bodies is a consequence of increasing salinity levels in the ponds, especially

Table 4 | Linkages between climate parameters, pond characteristics and associated livelihoods

Climate change major elements	Changes of climate parameters	Changes in pond characteristics	How does it affect livelihoods (social, environmental, physical and financial)
Rainfall	• Variations in rainfall influence the hydrology of the study ponds	• Affects quantity and quality of water of the ponds; • Rainfall variations influence in drying up ponds	• Reduce production of fisheries • Increased incidences of water-borne diseases and associated cost
	• No. of days without rainfall is on increasing trend • Decadal average no of days 'without rainfall' increased from 180 (1981–1990) to 228 days (2005–2015) • Decadal average monsoon rainfall dropped from 330 (1981–1990) to 318 mm (2000–2010) while decadal average post-monsoon rainfall increased from 157 (1981–1990) to 184 mm (2000–2010) • High-intensity (638 mm rainfall in August 2011 in Satkhira) rainfall tends to increase runoff pattern	• Changes in rainfall in different seasons controls the depth and concentration of salt of the ponds • Increase salinity in the pond water in pre-monsoon/winter; • Rainfall caused surface runoff deteriorates quality of water of the ponds	• Salinity affects agro-biodiversity • Transmission of diarrheal diseases and loss of working days • Reduced income • Bound to change livelihoods • Influence temporary migration
Temperature	• Variations in temperature in different seasons controls the depth and concentration of salt of the ponds • Decadal average monsoon maximum temperature increased from 32.56 (1981–1990) to 32.85 °C (2006–2015) while it is on a decreasing trend in other seasons	• Indigenous species may change their distribution pattern in response to temperature increase with an expansion of warm water species (Shuter & Post 1990; Brönmark & Hansson 2002) • Heat loading may have strong effects on the biota, altering the species composition of phytoplankton, zooplankton, benthic invertebrates and fish (Magnusson *et al.* 1997)	• Incidences of diarrheal diseases are high especially in pre-monsoon when temperature is also greater than any other seasons • Loss of working days • Local species of fish are no more available • Reduced income • Exotic species are being cultivated
Cyclone and Storm surge	• Increased frequency and intensity on south west coast • Storm surge (salinity water intrusion) • Cyclone mostly occurs between May and October of the year	• Risk of inundating ponds • Salinity in pond water (six out of eight study ponds were inundated during Cyclone Aila in 2009) • Damage to pond structure • The risk of contamination of pond water	• Lack of water for domestic purposes including drinking, sanitation and hygiene practices • Loss and damage of fisheries and dependent livestock • Increased water-borne diseases and additional cost for health treatment • Additional burden with decontamination cost and cost for reconstruction/repair of the ponds • Social conflict with water options • Reduced overall household income
Drought	• Changes in hydro-periods causing low flow of fresh water in river ecosystems • Shifting of rainfall	• Declining water level in the ponds • Water quality goes down	• No freshwater for small irrigation • Water supply for domestic uses is critically challenged • Incidences of water-borne diseases

(*continued*)

Table 4 | continued

Climate change major elements	Changes of climate parameters	Changes in pond characteristics	How does it affect livelihoods (social, environmental, physical and financial)
Tidal surge, salinity and potential SLR	• Increased frequency of tidal surges • Coast of Bangladesh is predicted to experience SLR	• Risk of inundating ponds • Salinity in pond water • Damage to pond structure • Contamination of pond water	• Loss of ponds if not protected • Loss of fisheries production because of salinity intrusion • Lack of domestic water supply • Lack freshwater supply for home gardening/social forestry • Forced migration

during pre-monsoon and winter seasons. The coupled or combined effect of temperature and salinity on the homoeostasis of the pond environment in particular may be even more harmful. This is because the synergistic impact of both temperature rise and an increase in salinity further debilitates the survival conditions of the fish species. Erwin (2009) explains the compounded impact of temperature and salinity, which causes a reduction in a species cover in the targeted wetlands of his research. This occurred both for fish as well as phytoplankton. This proves that both water-based plants and animal species are highly susceptible to increasing changes in temperature and salinity. The impact on human livelihoods for such detrimental changes will reflect on health implications. Diarrheal diseases in the pre-monsoon seasons have been seen to be higher than other months due to the temperature rise, as perceived by the local communities. This results in loss of working days and overall reduction of family income (Table 4). In addition to shrimp, many local people also cultivate freshwater fish in the ponds, which they mostly cultivate for their domestic consumption. However, many of them have additional income by selling the fish produced in their ponds. The study finds that many of the common fish species are no longer available in their ponds. Over the years, many fish species have died due to rising salinity, while fewer varieties have been introduced which can tolerate a certain degree of salinity. A similar situation is seen with changes in pH values of the water. When the pH becomes too deviant from the neutral (pH of 7.0), it impacts on several measures: both aquatic plants and animals along with human health. The too acidic environment is dangerous for good breeding of the fish, which could eventually kill the young eggs or even prevent the eggs to mature. As such the total stock of fish will eventually experience a steep fall, which could inflict impacts on human health, as consumption of fish will reduce.

Pond as a potential resource base

The study villages have some shared and private ponds used as tanks for water storage capacity, now becoming defunct. Due to inattention to make use of these potential resource bases, many ponds are left in abandoned conditions in the study region. These ponds have been a subject to salinity intrusion or are sometimes at risk of excess exposure to surplus rainfall (runoff) or dry spells at critical stages. There is also the incapacity of villagers to put investments into it because the process of recuperating the ponds from an obsolete condition to use is expensive. There is a huge shortage of resources after any natural disaster. Along with post-disaster trauma from losing homes and even family members, victims struggle to find even a glass of clean water to drink. It is due to lack of knowledge or guidance from local government that people are depriving themselves from a potential source of clean water, i.e. the ponds that they own or share. This picture can experience a complete transformation towards a sustainable livelihood pattern by implementing a resource-based adaptation technique. Through this, the ponds could essentially become productive and life-saving assets for the villagers at times of crises, especially in post-disaster periods if community level adaptations come into play, the ponds could be invested in to produce a good stock of quality water resources and fish, and such investments could potentially enhance and fulfill the nutritional values of the people after the calamity, i.e. in terms of providing fresh or clean water and protein sources for maintaining proper health of the climate victims, eventually preventing diseases experienced right after the disasters. It can also prevent people from seasonal food crises.

The 6th Sustainable Development Goals (SDGs) addresses the importance of access to safe water and sanitation. It states that 'due to bad economics or poor infrastructure, every year millions of people, most of them children, die from diseases associated with inadequate water supply, sanitation and hygiene', this is particularly true when a disaster hits a community. The water scarcity situation negatively affects food security, resulting in difficult livelihood choices to be made. The findings of this research align with such a situation and advocate the possibility to turn obsolete ponds into use. Thereby, the rural community especially in the coastal zone, can benefit from safer and relatively cleaner water while also securing food security, hence contributing to attain the second and third goal set by the SDGs, which is dedicated to a world with 'no hunger' and 'good health'.

Forecasting would help in protection of pond ecosystems

The study area households would highly benefit if they have a reliable forecasting of climate induced hazards, including cyclone and storm surges, excess rainfall in short periods, or flood, which largely affect the pond ecosystem and associated livelihood activities. At present, there are several studies for improving the rainfall predictions including the model, modular artificial neural network (MANN) for accurate and timely rainfall forecasting which is important for the prevention of natural disasters including flooding and also for reservoir operations (Wu *et al.* 2010). Other researchers have been investigating to further this estimation through the use of the auto-regressive integrated moving average (ARIMA) model coupled with the ensemble empirical mode decomposition (EEMD) which is presented for forecasting annual runoff time series (Wang *et al.* 2015).

Owing to the powerful ability of global optimization, the population-based optimization algorithms have also recently been applied to hydrological forecasting (Chen *et al.* 2015). On the other hand, advancements such as using hybrid models coupled with singular spectrum analysis are now being researched to conduct daily rainfall prediction (Chau & Wu 2010). If the results and utilization of these techniques could be implemented in the remote villages of Bangladesh, the villagers dwelling in the rural sectors could greatly benefit in terms of better forecasting of natural disasters and preparing for enhanced community-based adaptation.

Ponds for community base adaptation to combat climate change impacts

One of the options for taking adaptation measures to safeguard at least one of the ponds is to raise the elevation of the boundary of the ponds. This practice was observed in one of the eight ponds in the villages visited. Prior to Cyclone Aila, communities gathered to protect at least one of the ponds to provide clean water, which later served as a life-saving decision. Therefore, when the cyclone hit and all the ponds were inundated, the community used this pond water for feeding children and the elderly and carried out the most essential activities, which saved them times of immense hardship and fatigue. This explains ponds can be used as a potential resource base at times of crisis.

Current national policies

The current policy and institutional arrangements, especially in pond management, is not very clear. A number of ministries perform water related activities, for example, the Ministry of Agriculture works on Deep Tube Well (DTW) irrigation for increasing food production; the Ministry of Water Resources is responsible for flood control and drainage system through Bangladesh Water Development Board (BWDB). They collaborate with the Ministry of Agriculture in irrigation projects (Kranzlin 2000). The Department of Public Health Engineering (DPHE) under the Ministry of Local Government, Rural Development and Co-operatives implements rural water supply and sanitation projects and programmes. The Department of Fisheries under the Ministry of Fisheries and Livestock implements pond related projects mainly to improve fisheries production. However, according to the Tank

Improvement Act (1939) (generally known as the Pond Development Act), the local government institutes (Upazilla Nirbahi Office/Sub-district Executive Office) are responsible for taking measures to improve the functions of the tanks (ponds) at the local level (tank means a reservoir or place which has been used as a reservoir for the storage of water whether formed by excavation or by the construction of one or more embankments or place where water naturally accumulates, and includes any part of a tank and the banks thereof except such portions of the banks as are homestead, garden or orchard lands).

This Tank Improvement Act (TIA) (amended in 1986) emphasised the necessary institutional procedures for improved management of tanks or ponds. In practice, the local government institute hardly ever intervenes on the locally owned pond, even if it is derelict. However, some organisations, such as BWDB, locally manage some of their owned ponds. BWDB ponds are mainly being used for a drinking water supply in many areas including Satkhira, the study location. However, in general, it appears that there are strategic gaps in the pond management approach of the government of Bangladesh. In reality, there is no practical strategy of the government to improve the administration of the ponds in rural areas, including the coastal zone. This strategic gap of the government would catalyse (under changing climate scenarios) the vulnerability of the local communities dependent on the ponds for water supply, livelihoods, income and employment. In addition, pathways and mechanisms of current and future changes in local climate, their impacts and vulnerabilities to pond ecosystems and local communities need to be well understood for effective adaptation in the future.

CONCLUSIONS

The study shows that dependency on pond water is multipurpose. Pond water is being used for drinking, cooking, vegetable gardening, irrigation, fish cultivation and other market-related activities. The pond-based livelihoods and associated changes due to climatic hazards are the areas where the knowledge needs to be updated for effective adaptation for rural, disadvantaged poor communities on the coast. It is necessary to look at the existing state of household's natural/environmental resources (e.g. ponds) as capital for future adaptation planning. Work is required if households are to successfully undertake longer-term sustainable adaptation practices to current climate variability and potential future climate change impacts on a pond ecosystem. Locally driven immediate and longer-term adaptation strategies (based on local knowledge, resources or capitals) generated through the active participation of local people is likely to support households in undertaking sustainable livelihood practices. A clear understanding of climate change vulnerability, current institutional arrangement and potential local community driven adaptation options for pond ecosystems could help the policy makers. As most of the households either individually or in partnership own a pond, which mainly provides social, environmental and economic services, a strategy for effective management of it may be a better adaptation option for the poor. Using ponds as a resource can contribute to sustainable livelihoods, especially in the coastal areas of Bangladesh. Limitations of the research included uncertainties in meteorological data and dependence on people's perception, but the use of comprehensive tool including conducting household surveys, interviews and FGDs added a valuable impact on the overall results, which minimized error.

The limitations for not being able to study all 19 districts in the coastal zone leaves scope for future research as an extrapolation of this study. The findings of this research can be used as an example to be implemented in the extended studies that can be carried out in neighbouring districts to neighbouring countries in south Asia which can contribute to community-based adaptation techniques.

Through this, the ponds could essentially become productive and life-saving assets for the villagers at times of crises, especially in post-disaster periods if community level adaptations come into play, the ponds could be invested in to produce quality sources water resources and a good stock of fish. Moreover, such investments could potentially enhance and fulfil the nutritional values of the people after the calamity, i.e. in terms of providing fresh or clean water and protein sources for maintaining proper health of the climate victims, eventually preventing unwanted diseases experienced right after the disasters. It can also prevent people from dying from hunger. In fact, ponds could be considered as existing capital or an adequate resource base for community-based adaptation in the vulnerable coastal zone.

REFERENCES

BBS 2014 *Population and Housing Census – 2011*. Community Report-Satkhira. Bangladesh Bureau of Statistics, Government of Bangladesh.

Brönmark, C. & Hansson, L. A. 2002 Environmental issues in lakes and ponds: current state and perspectives. *Environ. Conserv.* **29** (3), 290–307.

Chau, K. W. & Wu, C. L. 2010 A hybrid model coupled with singular spectrum analysis for daily rainfall prediction. *Journal of Hydroinformatics* **12** (4), 458–473.

Chen, X. Y., Chau, K. W. & Busari, A. O. 2015 A comparative study of population-based optimization algorithms for downstream river flow forecasting by a hybrid neural network model. *Eng. Appl. Artif. Intell.* **46** (A), 258–268.

Cruz, R. V., Harasawa, H., Lal, M., Wu, S., Anokhin, Y., Punsalmaa, B., Honda, Y., Jafari, M., Li, C. & Huu Ninh, N. 2007 Asia: Climate change 2007: impacts, adaptation and vulnerability. In: *Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* (M. L. Parry, O. F. Canziani, J. P. Palutikof, P. J. van der Linden & C. E. Hanson, eds). Cambridge University Press, Cambridge, UK.

Das, P. K. & Radhakrishna, M. 1991 Trends and pole tide in Indian tide gauge records. *Proc. Indian Acad. Sci (Earth Planet. Sci.)* **100**, 177–194.

de Roda Husman, A. M. & Schets, F. M. 2010 *Climate Change and Recreational Water-Related Infectious Diseases*. National Institute for Public Health and the Environment, RIVM rapport 330400002, The Netherlands.

Dey, M. M., Bose, M. L. & Alam, M. F. 2008 *Recommendation Domains for Pond Aquaculture. Country Case Study: Development and Status of Freshwater Aquaculture in Bangladesh.* World Fish Center Studies and Reviews No. 1872. The World Fish Center, Penang, Malaysia.

Erwin, K. L. 2009 Wetlands and global climate change: the role of wetland restoration in a changing world. *Wetl. Ecol. Manage* **17** (1), 71.

Hare, W. 2003 Assessment of Knowledge on Impacts of Climate Change – Contribution to the Specification of Article 2 of the UNFCCC: Impacts on Ecosystems, Food Production, Water and Socio-economic Systems. Berlin, Germany.

Huq, S. & Rabbani, M. G. 2015 Climate adaptation technologies in agriculture and water supply and sanitation practice in the coastal region of Bangladesh. In: *Climate Change and the Coast: Building Resilient Communities* (B. Glavovic, M. Kelly, R. Kay & A. Travers, eds). CRC Press, Taylor & Francis Group, Boca Raton, FL, pp. 185–202.

Islam, T. & Peterson, R. E. 2008 Climatology of land falling tropical cyclones in Bangladesh 1877–2003. *Nat. Hazards* **48**, 115–135.

Karafistan, A. & Arik-Colakoglu, F. 2005 Physical, chemical and microbiological water quality of the Manyas Lake, Turkey. *Mitig. Adapt. Strat. Glob. Change* **10** (1), 127–143.

Karim, M. F. & Mimura, N. 2008 Impacts of climate change and sea level rise on cyclonic storm surge floods in Bangladesh. *Glob. Environ. Change* **18**, 490–500.

Khadim, F. K., Kar, K. K., Halder, P. K., Rahman, M. A. & Morshed, A. K. M. M. 2013 Integrated water resources management (IWRM) impacts in south west coastal zone of Bangladesh and fact-finding on Tidal River Management (TRM). *J. Water Resour. Protect.* **5**, 953–961.

Khondker, B. H. & Mahzab, M. M. 2015 *Lagging Districts Development.* Background Study Paper for Preparation of the Seventh Five-Year Plan. Ministry of Planning, Government of Bangladesh, Dhaka, Bangladesh.

Kranzlin, I. 2000 Pond management in rural Bangladesh: problems and possibilities in the context of the water supply crisis. *Nat. Resour. Forum* **24**, 221–223.

Magnusson, J. J., Webster, K. E., Assel, R. A., Bowser, C. J., Dillon, P. J., Eaton, J. G., Evans, H. E., Fee, E. J., Hall, R. I., Mortsch, L. R., Schindler, D. W. & Quinn, F. H. 1997 Potential effects of climate changes on aquatic systems: Laurentian Great lakes and Precambrian Shield region. *Hydrological Processes* **11**, 825–871.

Mallick, B., Ahmed, B. & Vogt, J. 2017 Living with the risks of cyclone disasters in the south-western coastal region of Bangladesh. *Environments* **4** (13), 1–17.

Nielson, D. L., Brock, M. A., Rees, G. N. & Baldwin, D. S. 2003 Effects of increasing salinity on freshwater ecosystems. *Australian Journal of Botany* **51**, 655–665.

Oppenheimer, M., Campos, M., Warren, R., Birkmann, J., Luber, G., O'Neill, B. & Takahashi, K. 2014 Emergent risks and key vulnerabilities. In: *Climate Change 2014: Impacts, Adaptation and Vulnerability – Contributions of the Working Group II to the Fifth Assessment Report* (C. B. Field, V. R. Barros, D. J. Dokken, K. J. Mach, M. D. Mastrandrea, T. E. Bilar, M. Chatterjee, K. L. Ebi, Y. O. Estrada, R. C. Genova, B. Birma, E. S. Kissel, A. N. Levy, S. MacCracken, P. R. Mastrandrea & L. L. White, eds). Cambridge University Press, Cambridge, UK, pp. 1039–1099.

Otzelberger, A. 2014 *Tackling the Double Injustice of Climate Change and Gender Inequality.* CARE International, Geneva, Switzerland.

Rabbani, G., Rahman, A. A. & Islam, N. 2010 Climate change and sea level rise: issues and challenges for coastal communities in the Indian Ocean region. In: *Coastal Zones and Climate Change* (D. Michel & A. Pandya, eds). The Henry L. Stimson Center, Washington, DC, pp. 17–29.

Rabbani, G., Huq, S. & Rahman, S. H. 2013a Impacts of climate change on water resources and human health: empirical evidences from a coastal district (Satkhira) in Bangladesh. In: *Impact of Climate Change on Water and Health* (V. I. Grover, ed.). CRC Press, Taylor & Francis Group, Boca Raton, FL, pp. 272–285.

Rabbani, G., Rahman, S. H. & Faulkner, L. 2013b Impacts of climatic hazards on the small wetland ecosystems (ponds): evidence from some selected areas of coastal Bangladesh. *Sustainability* **5** (4), 1510–1521.

Rahman, A. A., Alam, M., Alam, S. S., Uzzman, M. R., Rashid, M. & Rabbani, M. G. 2007 Risks, vulnerability and adaptation in Bangladesh. A background paper prepared for human development report 2007, Dhaka, Bangladesh.

Rahman, M. H., Lund, T. & Bryceson, I. 2011 Salinity impacts on agro-biodiversity in three coastal, rural villages of Bangladesh. *Ocean & Coastal Management* **54**, 455–468.

Shamsuddin, S., Xiaoyong, C. & Hazarika, M. K. 2006 Evaluation of groundwater quality for irrigation in Bangladesh using geographic information system. *J. Hydrol. Hydromech*. **54**, 3–14.

Shuter, B. J. & Post, J. R. 1990 Climate, population viability and the zoogeography of temperate fishes. *Trans. Amer. Fish. Soc*. **119**, 314–336.

Singh, O. P., Ali Kahn, T. M. & Rahman, S. 2001 Has the frequency of intense tropical cyclones increased in the North Indian Ocean? *Current Science* **80**, 575–580.

SMRC 1998 The impact of tropical cyclones on the coastal regions of SAARC countries and influence in the region. SAARC Meteorological Research Center, Dhaka SMRC-No. 1. In: Karim, M. F. & Mimura, N. 2008 Impacts of climate change and sea level rise on cyclonic storm surge floods in Bangladesh. *Glob. Environ. Change* 18, 490–500.

Stern, N. 2007 *The Economics of Climate Change: The Stern Review*. Cambridge University Press, Cambridge, UK.

Tank Improvement Act (TIA) 1939 (amended in 1986). Ministry of Law and Justice, Government of the People's Republic of Bangladesh.

Wang, W. C., Chau, K. W., Xu, D. M. & Chen, X. Y. 2015 Improving forecasting accuracy of annual runoff time series using ARIMA based on EEMD decomposition. *Water Resour. Manage.* **29** (8), 2655–2675.

Warrick, R. A., Bhuiya, A. H., Mitchell, W. M., Murty, T. S. & Rasheed, K. B. S. 1996 Sea level changes in the Bay of Bengal. In: *The Implications of Climate and Sea Level Change for Bangladesh* (R. A. Ahmad, eds). Kluwer Academic Publishers, Dordrecht.

World Bank 2007 The Impact of Sea Level Rise on Developing Countries: A Comparative Analysis. World Bank Policy Research Working Paper 4136, Washington DC, USA.

Wu, C. L., Chau, K. W. & Fan, C. 2010 Prediction of rainfall time series using modular artificial neural networks coupled with data-preprocessing techniques. *J. Hydrol.* **389** (1–2), 146–167.

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