Sustain. Water Resour. Manag. (2018) 4:63–78
https://doi.org/10.1007/s40899-017-0123-6

ORIGINAL ARTICLE

Megacity Dhaka: 'water security syndrome' and implications for the scholarship of sustainability

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Received: 21 December 2015 / Accepted: 18 April 2017 / Published online: 28 April 2017

Abstract The potentials of the scholarship of sustainability present new possibilities for integrated analysis to address syndromes in human-environment systems. A syndrome here means a big-picture complex problem or issue with sustainability implications, such as urban sprawl, land contamination, mass tourism, waste dumping, etc. Through a case history—that of a 'water security syndrome'—this paper explores key conceptual aspects for the potential scholarship of sustainability. First, it outlines the scope of this syndrome within the context of one megacity, Dhaka (Bangladesh). Through a holistic literature analysis utilizing system's approach six themes are then elucidated, including patterns of change, sectoral impacts, climate change implications, and opportunities to capitalize. A model is constructed representing a 'water security syndrome' in the perspective of developing world, and implications are drawn for the potential scholarship of sustainability.

Keywords Water problem · Water management · Scholarship of sustainability · Megacity · Dhaka · Bangladesh

Electronic supplementary material The online version of this article (doi:10.1007/s40899-017-0123-6) contains supplementary material, which is available to authorized users.

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Introduction

The negative impacts of anthropogenic utilization of the Earth's resources have become so numerous and entangled that they often overwhelm policy-making and thus limit planning for sustainable futures (Ayres 2000). In an attempt to describe this problem the German Advisory Council on Global Change (WGBU 1996) identified categories or archetypical patterns in the complex problems of human-environment relationships we now face. Each of these categories of problems, termed sustainability 'syndromes', is a 'core problem of global change' being "the product of characteristic constellations of socioeconomic, geographical and political trends … and can be identified in many regions of the world" (ibid. 1). In response, various transdisciplinary contributions from both natural and human sciences are advocated to trace the complexity and indicating areas for solutions (Raven 2002; Kates et al. 2001). The potential scholarship of sustainability is expected to provide concepts and methods for undertaking integrated analysis in transdisciplinary research (Kates et al. 2001; Clark et al. 2004; Clark 2007). This case history demonstrates a way in which the syndrome of water security in megacities of developing world may be investigated, with implications for the potential scholarship of sustainability.

From the 1700s to 1950, rural to urban migration and industrialization were associated with significant demographic shifts in Europe and North America. During the latter half of the twentieth century, urbanization in the developing world accelerated (Jones and Kandel 1992). By 1996, 17 of the largest 20 cities were in developing countries, up from seven in 1950 (Domeisen and Palm 1996). In 2010 the world's population living in urban areas crossed the 50% threshold, and it is predicted to reach 70%

by 2050 (UN-HABITAT 2012). The developing countries are expected to cross the 50% urban threshold by 2017 (United Nations 2004).

As one of the 'new' megacities (Karn and Harada 2001), Dhaka became the ninth largest megacity in the world in 2007 with 13.5 million inhabitants, and it is expected to become the fourth largest by 2025 with 22 million inhabitants (United Nations 2008). Facing systemic challenges with water supply and management, Dhaka is presented as an example of a 'water security syndrome', where 'syndrome' is intended as a neutral concept describing a big-picture cluster of problems and/or issues in sustainability (WGBU 1996).

In this study, we systematically analyzed the available literature on water management and water bodies in Dhaka, and identified different layers of organizations described as 'themes'. Using a 'bottom–up approach', these layers are interconnected in patterns through employing system's approach, referencing secondary data from the literature. The equivalent 'water security syndrome' of selected other developing world megacities are also summarized, and the general issues relating to the development of a sustainability scholarship are identified.

As we argue in this paper, a clear challenge for the potential scholarship of sustainability is in epistemological, theoretical and methodological incompatibilities, incoherence and cleavages that arise from the fragmentary nature of discipline-based knowledge within and between the natural and human sciences. Synthesizing knowledge for a pluralistic approach such as the potential scholarship of sustainability requires fundamental innovations in epistemological, theoretical and methodological avenues. This case history, thus, puts forth the example of 'water security syndrome' of Dhaka to reveal the complexity that the scholarship of sustainability must address in pursuit of integrative sustainability innovation.

Water problems in megacities and the need for integrative water security research

The lack of material and human resources in developing country megacities, such as Dhaka, is a distinguishing factor in water-related problems. For example, lack of water distribution systems is considered a major concern for water managers in the developing world (UN-HABITAT 2003), especially in informal settlements. Moreover, due to lack of data on urban provision of water and sanitation in the developing world, the reality is likely to be far worse than most international statistics suggest (UN-HABITAT 2003). Therefore, municipal authorities in such megacities face serious challenges that will worsen, given the projected increases in urban populations discharging ever increasing quantities of waste into freshwater bodies, threatening water quality and aquatic ecosystems (Cohen 2006). Table 1 showcases the types of problems that other developing world megacities face with respect to sustainable water management.

Table 1 reveals the interlocking root causes and impacts of water insecurity in developing world megacities, which include:

- rapid urban expansion,
- chemical and microbial water pollution,
- poor, or lack of, sewerage facilities,
- shortage of safe drinking water,
- flooding, which can combine with sewerage to the detriment of public health, and impact on economic activities,
- limited water infrastructure,
- excessive groundwater extraction causing risks of land subsidence and salt water intrusion,
- industrial and domestic pollution into water bodies,
- eutrophication, and
- poor urban governance.

All these issues are also characteristic to the 'water security syndrome' of Dhaka, articulated throughout "Holistic analysis of the Dhaka water security syndrome". Besides, in recent time the linkage between water security and the science agenda has come to question. Wheater and Gober (2015) summarize the situation with the following:

> "The freshwater environment is facing unprecedented global pressures. Unsustainable use of surface and groundwater is ubiquitous. Gross pollution is seen in developing economies, nutrient pollution is a global threat to aquatic ecosystems, and flood damage is increasing. Droughts have severe local consequences, but effects on food can be global. These current pressures are set in the context of rapid environmental change and socio-economic development, population growth, and weak and fragmented governance. We ask what should be the role of the water science community in addressing water security challenges. Deeper understanding of aquatic and terrestrial environments and their interactions with the climate system is needed, along with trans-disciplinary analysis of vulnerabilities to environmental and societal change. The human dimension must be fully integrated into water science research and viewed as an endogenous component of water system dynamics. Land and water management are inextricably linked, and thus more cross-sector coordination of research and policy is imperative." (p. 5406)

Similar question has been asked by Zeitoun et al. (2016) in contrasting between reductionist and integrative research

Table 1 Unsustainability of water and water bodies in some megacities

Coastal megacities in Asia (Yeung 2001)	Stressed by environmental risks due to rapid expansion, and leading to widespread bacterial pollution of near-shore waters as sewage treatment is an exception
Megacity Mumbai in India (Pacione 2006)	One-third of households not having access to safe drinking water, major infra-structural deficiency; as well as water pollution becoming a serious environmental problem
	Contamination and inadequate sewerage leads to spread of diseases
	Prone to flooding; a July 2005 flood paralyzed the city for days and resulted in hundreds of deaths
Megacity Calcutta in India (Basu and Main 2001)	Despite a natural abundance of water, the contamination, and limits of the authority's water sources and supply leave millions prone to health risks from drawing water directly from natural sources
Hong-Kong, in connection to China (Cullinane and Cullinane 2003)	Water pollution and sewage disposal are serious problems as nearly 80% of this megacity's water comes from mainland China, needing to be sterilized in order to meet WHO standards, while most sewage is only screened in a preliminary way before being discharged into Victoria Harbor
Jakarta Bandung Region (Firman 2009)	Excessive groundwater extraction is a severe environmental problem as a result of socio-economic development over the past three decades
	Neither economically nor environmentally sustainable, groundwater extraction causes land subsidence and salt water intrusion, especially in coastal areas
Metropolitan Cairo (Araby 2002)	Various kinds of untreated industrial and domestic pollutants from the city pour into the Nile River, which has become dangerously polluted, with the level of dissolved oxygen at almost zero
	Around 1.5 million m^3 of wastewater is released every day
	Urban governance and policies for water management are not comprehensive
Megacity Istanbul (Baykal et al. 2000)	The six major water sources of drinking water undergoing 'eutrophication' as: sources close to denser settlements with greatest urban land use within their watershed have already exceeded the eutrophic limit, while those further away from industry and dense settlement are in mesotrophic phase

approaches to complex water security challenge. The authors elucidate the advantages of an integrative approach over the reductionist approach in terms of the capabilities of addressing a range of uncertainties otherwise unaddressed, as well as recognizing diversity in society and environment, incorporating water resources that are less-easily controlled, and the consideration of adaptive approaches to move beyond the conventional supply-side prescriptions.

Given these recent concerns resulting in 'water security' to emerge as a rapidly developing new research area (Huai and Chai 2016), holistic research on elucidating the water security syndrome in the context of megacities holds much promise for advancing deeper understanding and treatment of the issues associated with promoting water security in urban areas. In this light, Schenk et al. (2009) criticize the prevailing Integrated Water Resources Management (IWRM) methodology as IWRM does not provide a clear definition of what should be integrated as well as the various water-related issues addressed separately although well encompassed in the literature. Therefore, the authors argue on the necessity of a holistic, system-based description of water management that emphasizes on the interrelations of the issues. Thus, Schenk et al. (2009) have constructed a system model for water management that includes a graphical representation and textual descriptions of the various water issues and their components and interactions, followed by the demonstration of its utility with two case studies (Birmingham, England, and Belo Horizonte, Brazil). In a similar way, Chen and Wei (2014) applied the concept of system dynamics to water security research and revealed the utility of it in terms of elucidating the progress and deficiencies in the current research based on flood security, water resource security, and water environment security as the three basic elements of a water security system. System's approach is also undertaken in elucidating the links between water and health in cities (Rietveld et al. 2016) using case studies from a range of urban socioeconomic and regional contexts. In addressing the holistic need of elucidating a megacity water security syndrome in the perspective of developing world, similar methodology is adopted in the present study. The utility of system's approach for water management, as articulated by Rietveld et al. (2016) follows as:

> "Decision-makers at all levels face new challenges related to both the scale of service provision and the increasing complexity of cities and the networks that connect them. These challenges may take on unique aspects in cities with different cultures, political and institutional frameworks, and at different levels of development, but they frequently have in common an

origin in the interaction of human and environmental systems and the feedback relationships that govern their dynamic evolution. Accordingly, systems approaches are becoming recognized as critical to understanding and addressing such complex problems, including those related to human health and wellbeing. Management of water resources in and for cities is one area where such approaches hold real promise.” (p. 151)

Holistic analysis of the Dhaka water security syndrome

Bangladesh is a lower-riparian country lying between the Ganges, Brahmaputra, and Meghna (GBM) rivers, and comprises approximately 7% of the GBM basin. Externally generated runoff in upper catchments of the basin provide up to 80% of the water in Bangladesh, while the rest comes from local rainfall (Chowdhury 2007).

Founded as a provincial capital in the sub-continent in 1608 and emerging as the capital of Bangladesh through independence in 1971, Dhaka has been witnessing an increase in population at an annual rate of over 5% (Khondaker 2006). It is bordered by four rivers, the Buriganga (South), Turag (West), Balu (East), and Tongi (North), into which the city’s drainage pours. Canals (khals) criss-cross the city, collecting runoff, wastewater and drainage as do the several permanent lakes. However, these surface water bodies are used much less as sources of water than the city’s groundwater storage. The main source of groundwater in the city is Dupi Tila sands aquifer, underlying Madhupur Clay with an average 10 m thickness, whereas the thickness of the aquifer varies from 100 to 200 m. This aquifer is exposed along the riverbeds of the peripheral rivers which facilitates recharge in the aquifer, and the groundwater becomes available at a depth of 15–20 m at these peripheries while not any lesser than 25–30 m at the central part of the city (Banglapedia 2006).

Dhaka is characterized with subtropical, humid climate with an annual mean rainfall of 1920 mm, approximately 87.5% of which falls during May to October, with June–August being the period of the heaviest rainfall (Fig. 1) (BBC 2010). This seasonal rain distribution provides context for many of the city’s water problems, as excessive water pours during some part of the year, causing flood and other associated problems, while drastic decrease in rainfall leads to drying up and other associated problems in the other parts of the year.

Outlined in Fig. 2 and elucidated in detail in the following sections, the holistic analysis of ‘water security syndrome’ exhibits a highly complex and complicated mosaic of interlocking connections. Some of these connections are summarized in Tables 3 and 4. Substantiated by detail secondary data (Table SM1, supplementary material), these insights are generated through the merit of systematic literature analysis designed in a ‘bottom–up’ manner. Through laying down these insights with interconnecting patterns using system’s approach (see “Water problems in megacities and the need for integrative water security research”), the ‘water security syndrome’ with respect to Dhaka is synthesized, organized, and presented

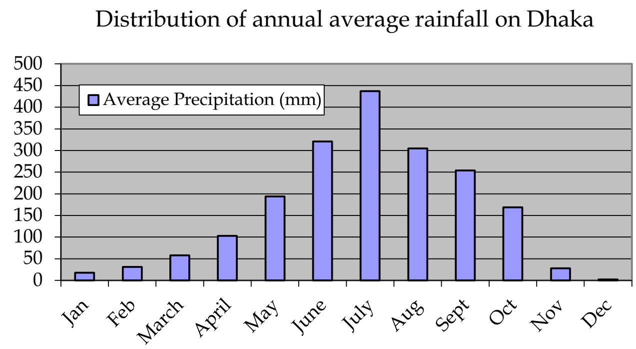
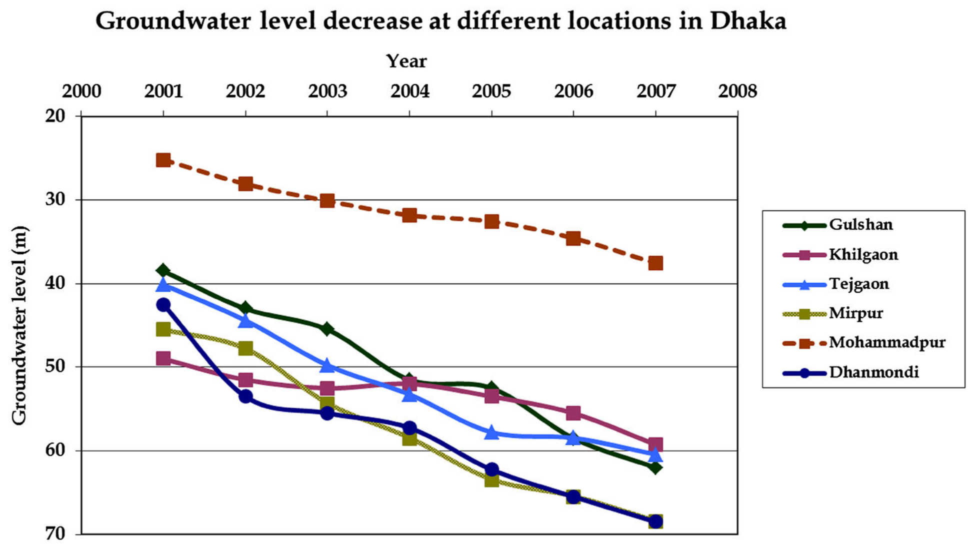


Fig. 1 Distribution of annual average rainfall on Dhaka (BBC 2010)

A. Sources of water supply and use in the city	
B. Patterns of change	
B1.	*Groundwater storage and pollution*
B2.	*Shrinkage and pollution of surface water bodies*
C. Causes of the changes	
C1.	*Population growth, urban translocation and carrying capacity*
C2.	*Excessive groundwater extraction*
C3.	*Impervious surface from urban developments, resulting in impeded groundwater recharge*
C4.	*Pollution sources*
C5.	*Expansion of city area*
C6.	*Encroachment and filling-up*
C7.	*Siltation from debris from urban development activities*
C8.	*Change in land-use*
D. Sectoral impacts	
D1.	*Water treatment and supply*
D2.	*Groundwater availability*
D3.	*Waterlogging, flood and living conditions of inhabitants*
D4.	*Public health*
D5.	*Sanitation*
D6.	*Fishery and biodiversity*
D7.	*Ecology and environmental health*
D8.	*Risks of geo-hazards (e.g. land subsidence, earthquake)*
D9.	*Increase in arsenic in groundwater*
D10.	*Aesthetic aspects and recreation*
E. Climate change dimensions	
E1.	*Temperature fluctuation and fish life cycles*
E2.	*Effects of temperature and seasonal pattern, linked with dry season water flow and water quality for treatment and supply*
E3.	*Precipitation pattern linked with — flood and waterlogging, rainy season water flow and groundwater recharge*
F. Opportunities	
F1.	*Rainy season phenomena*
F2.	*Suitability of seasonal open water bodies for fishery*
F3.	*Shifting of Hazaribagh tanning area underway*

Fig. 2 Overall structure of the holistic analysis

Fig. 3 Groundwater levels at various locations in Dhaka between 2001 and 2007



in Fig. 6. The syndrome details the causes and impacts in a number of entangled feedback loops illustrating how such problems should overwhelm policy-making, thus otherwise limiting sustainable future planning (Ayres 2000). In situations as complex as the syndrome presented in the Fig. 6, decision-making is not a straightforward process. The conventional fragmentary approach can be greatly limiting in such situations, given that a single change in the cause–impact mosaic might trigger other impacts, with the possibility of worsening the overall balance.

The analysis reveals six major themes constituting the water security syndrome (a–f in Fig. 2; all substantiated by secondary data). The list of these themes also structures the holistic analysis presented throughout the remainder of this section.

A. Sources of Dhaka's water supply and use

With surface water becoming increasingly polluted and costly to purify, public water utilities and other water users have turned to groundwater as a potential source of cheaper and safer supply. Deep-tube wells are heavily used by public institutions as well as private owners (The Daily Star 2009), providing over 86% of Dhaka's water supply in the year 2007 (DWASA 2007). Groundwater extraction has a number of severe environmental and social consequences, and urban growth in the city is leading to a situation where the ensuing water demand could not anymore be met by groundwater extraction alone (IFCDR 1996). Therefore, it is pivotal to maximize the use of surface waters.

B. Patterns of change

The most pronounced changes include: deteriorating aquifer characteristics, drastic lowering of groundwater levels, microbial contamination of groundwater (UNEP 2003), and hydrocarbon contaminants from chemical hazards and industrial pollution (DWASA 2006). Severe organic, inorganic and microbial contaminations have occurred to all river waters (Rahman 2004). The tannery complex in Hazaribagh is polluting groundwater, canals and rivers through discharge of solid wastes and effluents. The previously confined aquifer is increasingly becoming unconfined with a drastic drop in piezometric surface over the last three decades (Haque 2004). The groundwater table of the upper aquifer has been declining by 2–3 m/year (DWASA 2006), with drastic lowering of groundwater levels at some locations (see Fig. 3). Anthropogenic encroachment and infra-structural and industrial activities have also led to shrinking of drainage channels.

The Fig. 3 traces rapid lowering of groundwater table at different locations in the city. Associated with this are significant shrinkage of inland water bodies and open waters. During the period 1968–2001, there was a 54.54, 10.18 and 6.44% shrinkage in inland water bodies, open waters and fluvial bodies, respectively (Sultana 2005). A linkage is suspected between the groundwater lowering and the rapid rate at which wetlands have been drying up over the last four decades. The open water bodies and wetlands in eastern and western Dhaka have become substantially reduced and sporadic (Sultana 2005), coupled with filling-up and elevation of low-lying areas.

These extensive shrinkages of water sources have been accompanied by widespread organic, inorganic and microbial pollution of all waters. The primary causes are linked to increased urbanization, which has resulted in—severe organic pollution of Buriganga River (Karn and Harada 2001), extremely severe water pollution in the city in dry season (WARPO 1999), and also high levels of pollution in the city's storm water from residential areas (Khan and Chowdhury 1997). The widespread lack of sewerage treatment systems and the deterioration of existing facilities have substantially polluted the surface water bodies. Over 20% of Dhaka's residents do not have any acceptable sanitary disposal system while leaking, damaged, and broken trunk sewerage lines are polluting the groundwater (The Daily Star 2003), resulting in more than two-thirds of Dhaka's sewage being discharged into rivers (The Daily Star 2008a). Figure 4 presents the alarming picture of Dhaka's surface water pollution and its hotspots.

C. Causes of the negative impacts

There are eight main contributors to the deterioration of Dhaka's water supplies.

C1. Population growth and urbanization

Population growth mainly due to urban migration from other parts of the country to Dhaka has been the main reason for the negative impacts on urban water supplies and quality. Between 1975 and 2000, Dhaka experienced a 7% annual population growth compared to 2.1% for the whole country within the same period (United Nations 2000). Figure 5 shows urbanization in Dhaka compared to the rest of the country. While it is associated with centralization policies of governments (BBS 2001; Jahan and Rouf 2007), the continued growth of Dhaka did not only have deleterious effects on groundwater availability and sanitation but also on aesthetic aspects of the city and its ecological and human health status.

C2. Excessive groundwater extraction

Groundwater extraction has sharply increased over a 40 year period (1963–2001) (see Table 2). Dhaka's water requirements have increased more than tenfold during the period, with a similar increase in the number of operating deep-tube wells, while the shortfall in supply still increased from 20 to 380 million liters (DWASA 2001). Excessive groundwater extraction can have severe impacts on groundwater availability and water treatment and supply; while IFCDR (1996) predicted that by 2020 Dhaka's water demand will extend beyond groundwater availability, raising risks of land subsidence, earthquakes, and arsenic poisoning (see "Holistic analysis of the Dhaka water security syndrome"—'D. Sectoral impacts').

C3. Impervious surface from urban developments, resulting in impeded groundwater recharge

The impervious surfaces resulted from urban developments have impeded groundwater recharge with resultant increase in surface runoff. The residential areas result in higher runoff than commercial areas (Chowdhury et al. 1998).

C4. Pollution sources

Figure 4 exhibits pollution 'hotspots' in Dhaka's river and canal system in dry seasons as well as concentrated industrial zones and scattered industries and factories. Tanneries, textiles, pulp and paper mills, fertilizer, industrial chemical production and refineries are the most problematic for water in the city. Extensive pollution has occurred in all rivers around Dhaka. The Hazaribagh tannery area contributes the most in the pollution, greatly impacting the Buringanga River water quality (Zahid et al. 2004; Hossain et al. 2007). A long stretch of the Turag River is being encroached on and filled-up for business purposes (The Daily Star 2008a), while illegal encroachment on the Buriganga River is reducing the city's natural drainage capacity (Tawhid 2004). The Balu River is badly contaminated by urban and industrial wastes from Tongi and effluents emanating from the Tejgaon industrial area transported through the Begunbari Khal.

The concern of local residents, increasingly depending on polluting industries for their livelihood, tends to overwhelm concerns about the environmental effects of the industries. Although industrial pollution has been the major pollution source, unauthorized domestic sewer connections and poor municipal waste disposal pollute the rivers, inland and open water bodies as well as storm water. Waste dumping on roadsides, near water bodies, and into 'open surface drains' also contribute to pollution, sometimes through blocking the drains. The pollution of catchments is becoming more complex by transfers of polluted waters through connecting trunks (Rahman and Chowdhury 1999). A very small fraction of municipal solid waste is guided through DWASA's (Dhaka Water Supply and Sewerage Authority) sewerage network for treatment (UNIDO 2000).

C5. Expansion of city area

Expansion of the city area has: (a) filled-up low-lying areas and depressions (Shams 1999), (b) increased groundwater demand, waterlogging and flooding, in turn disrupting and challenging living conditions of the local inhabitants, as well as with (c) fishery and biodiversity of the waters impacted.

C6. Encroachment and filling-up

Encroachment and filling-up of water bodies has cost loss of nearly half the number of drainage canals that Dhaka had in the 1960s (The Daily Inqilab 2004), while the major hydrologic feature of the city was the volume of criss-crossing and well distributed drainage canals. The continued violation of 'Wetland Conservation Act, 2000' has resulted in dramatic increase in waterlogging (Tawhid

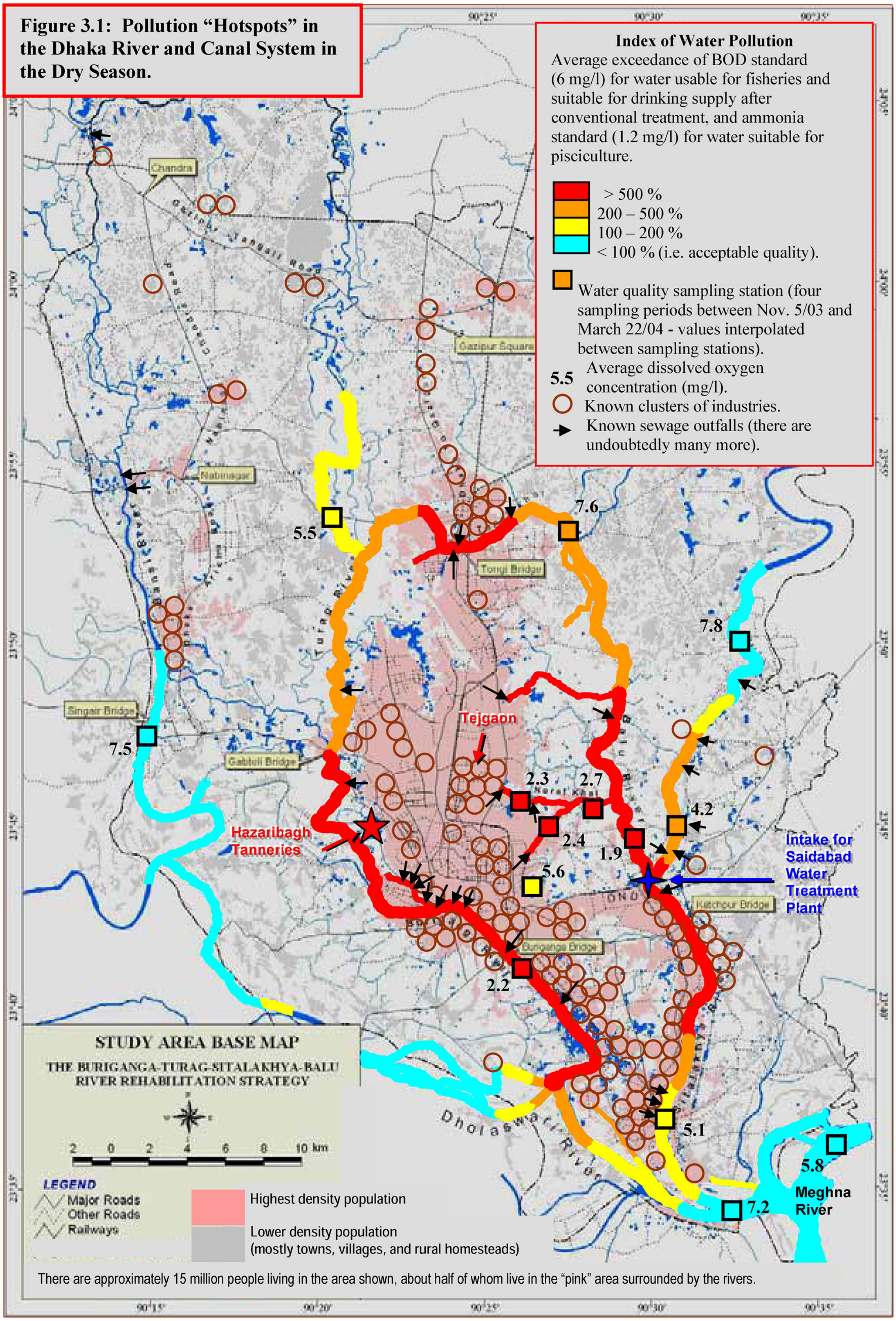


Fig. 4 Pollution "Hotspots" in Dhaka's river and canal system in dry season (World Bank 2006)

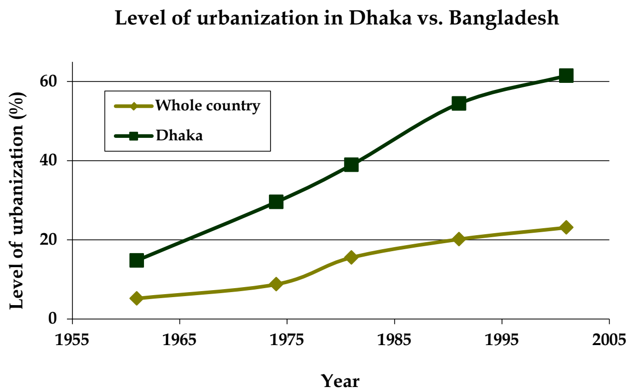


Fig. 5 Level of urbanization in Dhaka vs. the whole country

Table 2 Groundwater extraction over a 40-year period Source: DWASA (2001)

Year	Population, in million	Water requirement, in million liters	Deficit in supply, in million liters	Deep tube-well number in operation
1963	0.85	150	20	30
1980	3.03	550	250	87
2001	10	1600	380	336

2004), while water stagnancy also causes building foundation failures (Chowdhury et al. 2001). Encroachment has taken place on rivers, resulting in reduced carrying capacity and causing additional secondary problems (listed in Table 3).

C7. Siltation from debris from urban development activities

Dhaka's water bodies and reservoirs have been impacted by construction materials, leaves, household waste, street sweepings, and so on, being carried out by rain water and causing siltation. In addition, flood control embankments and sluice gates across the rivers and canals, coupled with debris flowing from urban development activities results in raised riverbeds and reduced drainage and runoff capacity (Tawhid 2004).

C8. Change in land-use

In 1980s Dhaka had numerous wetlands, Khals (i.e., drainage canals), and channels (JICA 1991), however, urbanization has caused massive deterioration in its hydrographic features, wetlands, and natural storm drainage, due to the resultant land-use changes. Raised constructions, built to avoid waterlogging and flooding have, ironically, contributed to more waterlogging and flooding in the city. Land-use changes have had adverse effects on wetlands and natural storm drainage (Chowdhury et al. 2001), while suspended particles originating from agricultural activities and deforestation have led to pollution and siltation of water bodies. Filling-up of wetlands have also caused impaired natural drainage.

All these eight processes identified so far have had secondary impacts; adversely affecting the sectors (impact sectors) listed in Table 3.

D. Sectoral impacts

The water security issue of the megacity Dhaka with particulars of sources and patterns of changes as well as factors causing such changes are adversely affecting a number of sectors in a number of ways. Through utilizing a bottom–up approach with the data from relevant literature, these adverse effects can be grouped based on ten sectors; therefore, the adverse effects being described with these ten sectoral impacts.

D1. Water treatment and supply

Increased pollution of surface water bodies is making surface water treatment costlier. The increasing demand for water, contributing to enhance pollution of water bodies and excessive groundwater dependency, and greatly outpacing its natural recharge capacity, limits its availability for future. Managing groundwater can only provide a partial solution. The main solution, however, must center on management of surface water bodies, and improved and efficient water treatment and methods of supply.

D2. Groundwater availability

Dhaka had only 21.57% open space remaining by the turn of the year 2006, projected to reduce alarmingly with continual land occupation and encroachment (Haque 2006). Such reduction in open space can greatly limit groundwater recharge, leading to increased lowering of groundwater level.

D3. Waterlogging, flood and living conditions of inhabitants

Conventional inadequate drainage system, uncontrolled siltation from urban sources (often being ignored), ill-developed inlets and outlets, over-disposal of solid wastes, and lack of proper maintenance are the prime reasons of drainage system blockage and waterlogging. Seasonal tidal effect also causes waterlogging, as flooding in Dhaka occurs in two forms: (1) high water levels in the peripheral rivers rendering any natural drainage impossible, and (2) high intensity rainfall runoff, causing flood even in situations where natural drainage could have been possible. However, in recent times the increasingly impaired natural drainage in Dhaka due to uncontrolled and over urbanization has been the main reason of waterlogging leading to flood. The filling-up activities due to urbanization

Table 3 Causes of negative impacts and the sectors of impact

Causes—(C)	Impact sectors—(D)
C1 (Population growth, urban translocation and carrying capacity)	D2 (Groundwater availability)
	D5 (Sanitation)
	D7 (Ecology and environmental health)
	D8 (Risks of geo-hazards [e.g. land subsidence, earthquake)], and
	D10 (Aesthetic aspects and recreation)
C2 (Excessive groundwater extraction)	D1 (Water treatment and supply)
	D2 (Groundwater availability)
	D8 (Risks of geo-hazards [e.g. land subsidence, earthquake)], and
	D9 (Increase in arsenic in groundwater)
C3 (Impervious surface from urban developments, resulting in impeded groundwater recharge)	D2 (Groundwater availability)
	D3 (Waterlogging, flood and living conditions of inhabitants), and
	D8 (Risks of geo-hazards [e.g. land subsidence, earthquake)]
C4 (Pollution sources)	D1 (Water treatment and supply)
	D4 (Public health)
	D6 (Fishery and biodiversity)
	D7 (Ecology and environmental health), and
	D10 (Aesthetic aspects and recreation)
C5 (Expansion of city area)	D7 (Ecology and environmental health), and
	D10 (Aesthetic aspects and recreation)
C6 (Encroachment and filling-up)	D1 (Water treatment and supply)
	D3 (Waterlogging, flood and living conditions of inhabitants)
	D6 (Fishery and biodiversity)
	D7 (Ecology and environmental health), and
	D10 (Aesthetic aspects and recreation)
C7 (Siltation from debris from urban development activities)	D1 (Water treatment and supply)
	D3 (Waterlogging, flood and living conditions of inhabitants), and
	D6 (Fishery and biodiversity)
C8 (Change in land-use)	D1 (Water treatment and supply)
	D3 (Waterlogging, flood and living conditions of inhabitants)
	D6 (Fishery and biodiversity), and
	D10 (Aesthetic aspects and recreation)

irrespective to the landform results in obstructed wetlands and depressions which previously were acting as drainage basins, thereby resulting in water congestion (Chowdhury et al. 1998).

Flood in Dhaka can create large infrastructural problems for the city and a huge economical loss in production (Mark and Chusit 2002). Disruption of traffic movement and normal life, damage to structures, destruction of vegetation and aquatic habitats, and loss in income potential are some of the effects on city life.

D4. Public health

Pollution of storm water with solid wastes, domestic waters, clinical wastes, silts, and a range of anthropogenic contamination sources contribute in causing water-borne diseases. Stagnant water acts as breeding sites for disease-vectors.

D5. Sanitation

The water-borne sewerage system in Dhaka provides sanitation facilities to a mere 30% of the inhabitants, while 20% among the rest use separate sewerage system, 11% using septic tank, 18% with pit sanitation, and the rest of the people not having any acceptable sanitary disposal system (The Daily Star 2003). A study by the World Bank revealed that a modern waterborne waste disposal system replacing the existing one, broken or leaked at many points, would cost US$ 300 per city dweller (The Daily Star 2003). Annual flooding has become a challenge for adequately designing sealed latrine systems, while poor management of wellhead areas contributes to fecal contamination (apart from direct aquifer pollution).

D6. Fishery and biodiversity

Pollution levels have been reported to be too high in the Buriganga River and most parts of the Turag River to support survival of living organisms, except for some invertebrates and small organisms, even during the rainy season high water flow period (The Daily Star 2008b).

D7. Ecology and environmental health

The clayish layer on which Dhaka city stands varies from less than 1 m to more than 45 m in thickness, and may become dried up due to the excessive groundwater withdrawal (Haque 2003). The Dhanmondi Lake is polluted in part due to its hydraulic connections with the Satmosjid Road catchment, such that an estimated one-third of storm runoff from the catchment goes into the lake (Hossain et al. 2001).

D8. Risks of geo-hazards (e.g., land subsidence, earthquake)

As Dhaka is situated on clay soil, the declining groundwater trend (revealed in Fig. 3) can greatly increase associated risks during earthquakes. A government study reveals that some 78,323 buildings in Dhaka would be completely destroyed by a deep 6-magnitude earthquake, whereas a 7.5-magnitude earthquake originating from Madhupur Fault could destroy some 72,316 buildings and damage a further 53,166 buildings with a resultant economic loss of about US$ 1112 million in structural damage alone (The Daily Star 2010). The shrinking of clay underneath Dhaka due to rapid lowering of the groundwater table could exacerbate the likelihood and strength of an earthquake along the Madhupur clay Fault.

D9. Increase in arsenic in groundwater

'Iron- and arsenate-reducing' bacteria have been found to be associated with elevated groundwater arsenic levels (Weldon 2007). Iron reducing bacteria can be stimulated by the addition of organic carbon to release arsenic into the water phase (Islam et al. 2004). Thus, groundwater contamination by hydrocarbons can trigger arsenic contamination in Dhaka's water. Although Dhaka has previously been considered mostly safe in this regard (GoB 2000), the decreasing groundwater level could promote alteration of oxidation–reduction conditions, triggering the reducing microorganisms to act to release more arsenic.

D10. Aesthetic aspects and recreation

The seasonal stored monsoon waters in Ashulia in Savar charge the Turag River system and thus, provide recreational resources for the residents of Dhaka (Khan et al. 2007).

The Fig. 2 lists the ten impact sectors elucidated so far, while their linkages are described in "Holistic analysis of the Dhaka water security syndrome" ('C. Causes of negative impacts'), classified under eight major causes. The current section ("Holistic analysis of the Dhaka water security syndrome"—'D. Sectoral impacts') elucidates the cause–effect relations. Table 4 presents a map of relations between the impact sectors and the causes impacting them. These are grouped together in Table 4 instead of repeating in the above discussions on the ten impact sectors. The "Holistic analysis of the Dhaka water security syndrome" and "Implications for the potential scholarship of sustainability" also elucidate various types of cross-sectoral linkages among the impact sectors. These cross-sectoral linkages impart further complexity in the water security syndrome as they create feedback loops among the triggering causes and the resultant problems. This cross-connectedness of the impact sectors are indicated by connecting these impact sectors with broken lines in Fig. 6, referring to the reinforcing potentials among the impact sectors.

E. Climate change dimensions

The Fig. 2 lists three climate change dimensions with definitive linkages to the impact sectors, which impart further complexity into the interactive matrix of the holistic analysis. Here three examples of these processes are briefly described.

E1. Temperature fluctuation and fish life cycle

Fish larvae are very sensitive to temperature. Depending on the adaptive capacity of different species, fish larvae can be affected by temperature fluctuations in a changing climate. Khan et al. (2007) have shown that the seasonal open water bodies in Dhaka had a temperature range suitable for optimal growth of fish larvae.

E2. Effects of temperature and seasonal pattern, linked with dry season water flow and water quality for treatment and supply

Dhaka has witnessed an increase of 1.8 °C in average temperatures over the past 100 years, with the greatest increases in the busiest parts of the city (The Daily Prothom Alo 2008). This may be a result of various contributing factors such as decreases in the groundwater level, the heat island effect and climate change. Delays in onset of seasons are becoming pronounced, offering another indication of changing climate. Such changes in temperature and seasons can affect both dry season water flow and its quality, reducing suitability of its use and cost-effectiveness of techniques for water treatment and supply. Given the excessive groundwater extraction in the city, surface water bodies are likely to be increasingly sought and exploited, although the existing surface waters are already polluted and are expected to be affected further by changes in temperature and seasonal patterns, especially in dry periods. The dry season water flow can be adversely implicated with the impact sectors of water treatment and supply, fishery and biodiversity, as well as aesthetic, amenity and recreation; while the dry season water quality is mainly implicated with water treatment and supply.

E3. Precipitation pattern linked with—flood and waterlogging, rainy season water flow and groundwater recharge

During May to October (the monsoon period) the surrounding rivers' water levels remain higher than the inland drainage levels in the city (Mark and Chusit 2002). The degree of severity of monsoonal rain can be a major contributing factor to the severity of flooding and waterlogging. Climate change is generally expected to make wet zones wetter and dry zones drier. Any such change in precipitation patterns due to a changing climate could adversely affect flooding and waterlogging; while on the other side of the same coin such being advantageous for increased water flow and groundwater recharge. Thus, flood and waterlogging due to any potential future change in precipitation pattern can be linked to five impact sectors

Table 4 Map of relations between the impact sectors and the causes impacting them

Impact sectors—(D)	Causes—(C)
D1 (Water treatment and supply)	C2 (Excessive groundwater extraction)
	C4 (Pollution sources)
	C6 (Encroachment and filling-up)
	C7 (Siltation from debris from urban development activities), and
	C8 (Change in land-use)
D2 (Groundwater availability)	C1 (Population growth, urban translocation and carrying capacity)
	C2 (Excessive groundwater extraction)
	C3 (Impervious surface from urban developments, resulting in impeded groundwater recharge), and
	C5 (Expansion of city area)
D3 (Waterlogging, flood and living conditions of inhabitants)	C3 (Impervious surface from urban developments, resulting in impeded groundwater recharge),
	C5 (Expansion of city area)
	C6 (Encroachment and filling-up)
	C7 (Siltation from debris from urban development activities), and
	C8 (Change in land-use)
D4 (Public health)	C4 (Pollution sources)
D5 (Sanitation)	C1 (Population growth, urban translocation and carrying capacity)
D6 (Fishery and biodiversity)	C4 (Pollution sources)
	C5 (Expansion of city area)
	C7 (Siltation from debris from urban development activities), and
	C8 (Change in land-use)
D7 (Ecology and environmental health)	C1 (Population growth, urban translocation and carrying capacity)
	C4 (Pollution sources)
	C5 (Expansion of city area), and
	C6 (Encroachment and filling-up)
D8 (Risks of geo-hazards [e.g. land subsidence, earthquake)]	C1 (Population growth, urban translocation and carrying capacity)
	C2 (Excessive groundwater extraction), and
	C3 (Impervious surface from urban developments, resulting in impeded groundwater recharge)
D9 (Increase in arsenic in groundwater)	C2 (Excessive groundwater extraction)
D10 (Aesthetic aspects and recreation)	C1 (Population growth, urban translocation and carrying capacity)
	C4 (Pollution sources)
	C5 (Expansion of city area)
	C6 (Encroachment and filling-up), and
	C8 (Change in land-use)

(see Fig. 6), while the rainy season water flow linked to three, and the groundwater recharge to four impact sectors.

F. Opportunities

As identified from the literature, there are three known opportunities to address Dhaka's water problem. The first involves harnessing the rainy season conditions to the advantages of water management. As more than 80% of the annual rainfall occurs during June to October (Chowdhury 2007), this could be utilized as an extremely significant opportunity for recharging groundwater table. Instead of merely considering monsoon rains as disadvantageous, the development of giant underground structures such as in Tokyo might seem appropriate (CNN 2012), which could also partially offset the rainy season stress. The second opportunity involves establishing fisheries in seasonal open water bodies, following Khan et al. (2007) for Ashulia. This might assist in enhancing biodiversity, ecological and environmental health, as well as providing an economic return to the local community, and thus, could also be connected to economic imperatives to maintain surface water quality. A third opportunity belongs to the plan already underway for shifting the Hazaribagh tanning area. Operating for over 50 years, the Hazaribagh tanning area

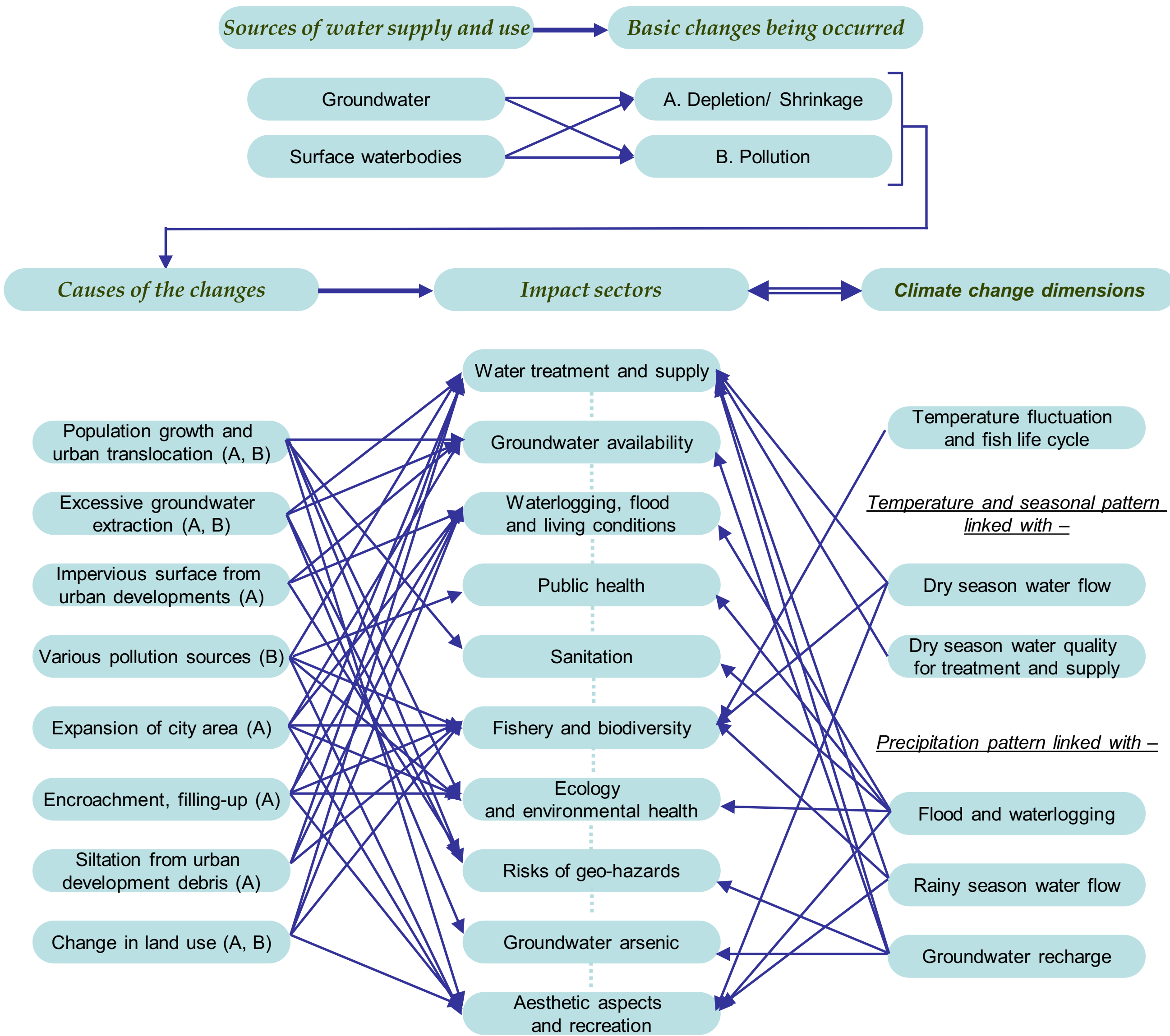


Fig. 6 'Water security syndrome' of the megacity, Dhaka

has been identified as the principal water pollution source in Dhaka. Of course, this is contingent upon a successful clean-up project.

Implications for the potential scholarship of sustainability

Sustainability innovation requires interconnectivity of components. With regard to the water security syndrome developed in this case history, the focus on interconnectivity reveals issues and provides ways forward for their resolution, as articulated in "Holistic analysis of the Dhaka water security syndrome". However, five general issues regarding the syndrome are also identified and described in this section, raising implications for the potential scholarship of sustainability.

Duh et al. (2008) pointed out that some regions are better represented than others in the growing literature linking urbanization and environmental quality. In proceeding with the potential scholarship of sustainability, the practice has to identify gaps and under-representations in the existing knowledge base, including regions—such as Dhaka. This is particularly required for addressing as well as integrating unique, complex and fragmentary pools of knowledge across various bodies of literature.

In turn, this illuminates the importance of globalization, which increasingly affects the resilience, vulnerability, and adaptability of coupled human-environment systems as reflected in the mega-trends such as the rise of megacities

(Young et al. 2006). Economic globalization has become a major concern to planners and governments with regard to global-city-making (Han 2005). As cities increasingly become central to sustainability concerns, they must reconcile between the global-city tensions and the city's needs (Egger 2006). In accounting for scale, the scholarship of sustainability needs to address such multi-scalar phenomena.

A third issue is that of urban development as a competitive, unregulated and unplanned enterprise in the global economic system (Yulong and Hamnett 2002). Taking the Asia–Pacific region as a case study, Marcotullio (2001) uses the idea of a 'functional city system' acting as the engine of urban growth, and in so doing differentiating the urban, environmental and social issues among the rapidly developing cities. In the rush for development it is estimated that over 70% of contemporary growth happens outside the planning process (McLearn et al. 2005), thus, creating significant challenges in addressing various sustainability problems.

Fourth, sustainability knowledge in the urban field rests upon underdeveloped understanding of the complexity of urban systems. Bettencourt et al. (2007) have called for predictive and quantitative theories of urban organization and sustainable development, given the majority of the world's population now living in cities. Offering urban simulations as a useful approach to understanding the consequences of current planning policies or their incompleteness, Barredo and Demicheli (2003) have stressed the need for such simulations to involve tools embracing the complexity of an urban system. The general point here is that urban theory—although interdisciplinary in nature—is underdeveloped.

Finally, the scholarship of sustainability is ultimately about the social needs, rather than resolving technical and/or environmental problems per se. Thus, it is partly through examining and addressing the social disadvantage and resources that sustainable systems could be established. For example, in a model for Tokyo in Japan, Uitto (1998) stresses the importance of including social vulnerabilities in vulnerability assessments of mega-cities, along with the usual human statistics and economic dimensions, so that 'special needs' groups such as the homeless—who are at risk in megacities—are included in such assessments.

These issues raise a range of implications for the scholarship of sustainability and also point to fields that are fertile territory for addressing such issues. Some already proposed frontier components of sustainability scholarship include: 'tipping' elements in Earth system analysis (Hornborg and Crumley 2007; Schellnhuber 2009), land cover and land use change science (Turner et al. 2007), and sustainable health (Bloom 2007; Gruen et al. 2008). Along with water management challenges, the 'urban system'—for example—presents a range of crucial sustainability issues that require serious focus. Considered as 'hot spots' of unsustainability, and driving environmental change at scales of great elasticity (Grimm et al. 2008; Moran 2010), urban areas invite the need for the development of a comprehensive approach to act as a platform for innovations and system of organization for new knowledge with regard to urban issues.

Valentine and Heiken (2000) propose the scientific community embraces 'urban system science' as an important and credible field of research. Through emphasizing on the increasing effects of cities on Earth, they proposed more collaboration among physical and biological scientists, social scientists, economists and engineers, as well as recognition for the need of government laboratories harnessing their interdisciplinary power for the goal of improving urban conditions. Aware of the reality that such a task would not be easy given the inertia built up over the twentieth century, Valentine and Heiken (2000) proposed 'urban system science' as a new mode of knowledge organization, and advocated interdisciplinary research for integrated management from a number of perspectives that are currently segregated. They hoped that future scientists would be interested in coming out of 'working in a box' to engage in urban studies from a multidisciplinary perspective, and thus, offering—what we recognize as—an approach for the scholarship of sustainability with regard to urban areas. Addressing the city's economy, environment and society through an innovative collaboration of natural and human sciences and technologies does conform to the necessity of the potential scholarship of sustainability, although cleavages and gaps in knowledge—and as integrated theories and research methods evolve—could greatly limit innovation. In the development of the scholarship of sustainability, as eclectic add-ons rarely conform to holistic goals, the scholarship needs to develop pluralistic manifestations in epistemological, theoretical and methodological avenues.

Conclusion

Exploring solutions to complex sustainability problems requires the development of a scholarship of sustainability. In complex integrated megacity studies, the particulars of geography and climate are critical. However, we argue that defining and analyzing the Dhaka water security syndrome yields insights for both the local management and the broader development of the scholarship of sustainability.

Portraying a simplified picture of a syndrome in the form of a set of problems and a set of solutions—as has been in conventional practice—presents inevitable constraints. Articulating a 'water security syndrome' takes more than a set of problems and potential solutions. It includes all interactions and feedback loops as important as individual causes and potential solutions. The holistic analysis—summarized in schematic of the syndrome in Fig. 6—reveals this. Synthesizing this syndrome guides the scope of developing as well as applying the potential scholarship of sustainability in exploring options for the sustainable management of water and water bodies. However, in bridging the gap between 'the conventional practice of dealing with a set of causes and a set of potential solutions', and 'taking consideration of the interactions and feedback loops being as important as individual causes and potential solutions', the scholarship of sustainability faces challenges in developing coherent epistemological, theoretical and methodological identities. Future research should actively advance the agenda of developing the scholarship of sustainability in these regards, along with taking in consideration the urban, or 'urban system science' as a critical spatial dimension.

Acknowledgements The research contained in this paper was conducted as part of a PhD work supported by the IPRS-and-APA PhD scholarships from Australia Government for which the corresponding author is grateful. The corresponding author also gratefully acknowledges a 'Higher Degree by Research Publication Grant' awarded to him from the RMIT University, Melbourne, Australia, for facilitating the preparation of this article out of the PhD work.

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