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Healthy waterways and ecologically sustainable cities in Beijing-Tianjin-Hebei urban agglomeration (Northern China): Challenges and future directions

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ABSTRACT

The cities across the northern dry region of China are exposed to multiple sustainability challenges. Beijing-Hebei-Tianjin (BTH) urban agglomeration, for example, experiences severe water shortages due to rapidly expanding urban populations, industrial use and irrigation-intensive agriculture. Climate change has further threatened water resources security. Overuse of water resources to meet the demand of various water sectors has far-reaching health and environmental implications including ecosystem sustainability. Surface water and groundwater pollution present public health risks. Despite the extraordinary policies and efforts being made and implemented by the Government of China, the BTH region currently lacks coordination among stakeholders leading to poor water governance. Consultation among scientists, engineers and stakeholders on regional water security issues is crucial and must be frequent and inclusive. An international symposium was held in Shijiazhuang in early November 2019 to identify some of the key water security challenges and scope of an idealized future eco-city in the region by developing a sustainability framework. This work drew on experiences from across China and beyond. Scientists agree that integration of science, technology, and governance within an appropriate policy framework was particularly significant for combating the issue of water insecurity, including in the region's newly developed city, Xiong'an New Area. An emerging concept, 'Healthy Waterways and Ecologically Sustainable Cities' which integrates social, ecological and hydrological systems and acts as an important pathway for sustainability in the twenty-first century was proposed in the symposium to tackle the problems in the region. This high level biophysical and cultural concept empowers development goals and promotes human health and wellbeing. The framework on healthy waterways and ecologically sustainable cities can overcome sustainability challenges by resolving water resource management issues in BTH in a holistic way. To implement the concept, we strongly recommend the utilization of evidence-based scientific research and institutional co-operation including

national and international collaborations to achieve the Healthy Waterways and Ecologically Sustainable Cities goal in the BTH in future.

Key words: Healthy waterways; ecologically sustainable city; water security; Beijing-Tianjin-Hebei (BTH) urban agglomeration; social-ecological-and-hydrological system; northern China; water governance

1. INTRODUCTION

Securing freshwater resources has become one of the greatest challenges of humanity in the 21st century as today four billion people experience water scarcity in at least one month of the year, and about 400 million people face extreme water shortages on a daily basis (Mekonnen and Hoekstra, 2016, Kattel, 2019). People residing in the world's larger cities have been profoundly affected by water insecurity due to rapid population growth and increased water demand for daily use. Water sources including lakes, reservoirs, rivers and groundwater aquifers which supply our cities are exposed to both anthropogenic pollution and climate-induced droughts and floods. These conditions have further imposed pressure on environmental flows, threatened ecosystems and biodiversity, food security, economic growth and well-being of urban people (Vollmer et al., 2018). Cities located in drier regions of densely populated countries such as China are becoming increasingly vulnerable to diminishing freshwater resources, as a result, the management of which is becoming less sustainable.

China's water security is threatened by overuse and pollution of water resources. Fluctuating water resources in drier northern China, due to the large inter-annual variation in climatic conditions (e.g. annual rainfall) has played a significant role in constraining the region's efforts in socio-economic development (Liu and Yang, 2012). By 2030, the total water deficit in northern China is expected to reach 30 billion m^3 (Kattel et al., 2019). Water abstraction is predominately for irrigation with other uses including hydroelectricity, industrial and domestic supply. Agriculture in the dry alluvial plains of northern China is heavily dependent on irrigation of 175×10^6 ha of cultivated areas. A population of more than 214 million people including the large urban metropolises of Beijing-Tianjin-Hebei (BTH) also leads to significant water demand (Wei, 2005). In seeking to develop and maintain these world-class urban centers, the BTH also has an obligation to support 8.18% of the country's population with only 0.75% of the nation's available water resources (HRWC, 2014). Concentrated manufacturing industries distributed across the BTH urban fringe have also led to severe water pollution problems, wetland degradation, groundwater overexploitation and land degradation (Han et al., 2020), aggravating this water scarcity. Additionally, while enabling this dry region to produce 10% of China's total grain production, agricultural fertilizer use has led to widespread eutrophication of waterways (Li et al., 2012a).

The BTH urban agglomeration experiences an erratic climate, including severe droughts, and sporadic flood events (Kattel et al., 2019). Over the past six decades, the average regional temperature has risen by 0.23 ºC. Urban heat island effect accounts for a further average of 0.438 ºC temperature rise in the cities in the past 10 years (Wang et al., 2017b, Cao et al., 2019). Although a downward trend in the frequency and amount of extreme precipitation in Beijing was recorded over 1960-2012, annual rainfall at the center of Beijing is still higher than in outlying areas (Ren et al., 2020). The high rainfall in BTH has led to an increased release of inorganic and organic rich compounds into waterways. Heavy metal/loids such as chromium, cadmium and arsenic, and persistent organic pollutants (POPs) such as polychlorinated biphenyls (PCB) are of particular concern to water quality and ecosystem health due to the large scale of pollution and the wide ranging potential for impacts on public health (Zhang et al., 2013). Diffuse pollution often presents a more difficult issue to address than point sources in complex waterway systems (Huang et al., 2019, Ji et al., 2019). Unprecedented urban agglomeration in BTH (Figure 1) has had a dramatic effect on the health of waterways and ecological sustainability, hampering the mitigation efforts on the government authorities in water conservation and management.

Water efficient irrigation technology for social, economic and natural benefits in BTH is becoming increasingly critical due to rapid regional environmental changes. For instance, long term centennial stream flow records show that the recent past contains the most severe and persistent decadal droughts together with low flows and extreme variability (Qian et al., 2014), with consequences including water shortage, water quality deterioration, drinking water safety due to limited flushing of nutrients and problems with water drainage system and flood control due to poorly recharged groundwater aquifer (Sun et al., 2014). In order to enhance urban ecology and combat pollution, innovations in wastewater treatment and water recycling programs have been the focus in BTH. Fundamental changes in wastewater treatment plant designs, policy and technologies have been made to revolutionize the recycling or destruction of urban pollutants (Qu et al., 2019).

a. Beijing-Tianjin-Hebei b. Baoding City

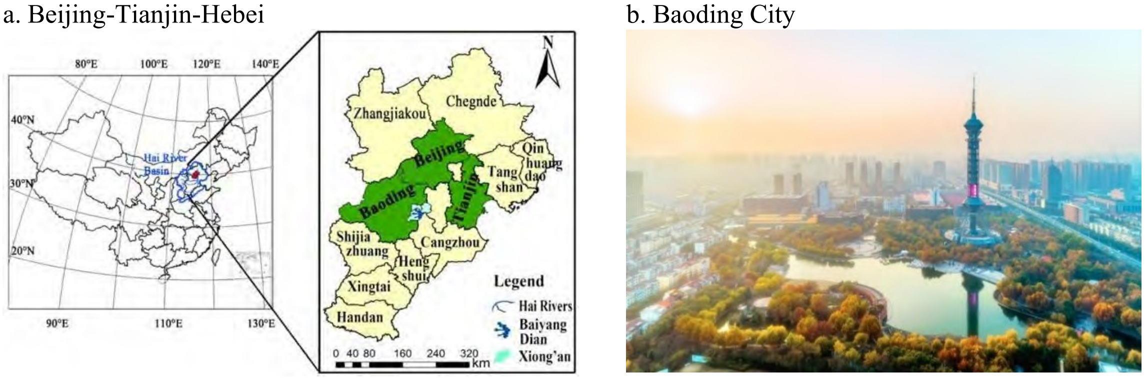

FIGURE 1. (a) Beijing-Tianjin-Hebei (BTH) urban agglomeration with densely populated areas at the center, Baiyangdian Lake (BYDL) and Xiong'an New Area, located close to the City of Baoding, and (b) City of Shijiazhuang (Hebei) in northern China (source: ctrip.com).

Healthy waterways and ecologically sustainable cities are linked to the idea of social-ecological and social-hydrological integrated systems (Wilkinson, 2011, Pickett et al., 2013, Kattel et al., 2013, Dewulf et al., 2019). Social-ecological-and-hydrological system resilience operationalizes sustainability, while sustainability drives social goals, combines social equity, economic viability and enhances ecological and hydrological integrity (Pickett and Zhou, 2017, Yu et al., 2017, Sivapalan et al., 2014). Hence, the social-ecological and social-hydrological framework models have become a successful metaphor for ecologically sustainable cites. These framework models strongly integrate ecosystem functions with social and hydrological dynamics. Evidence suggests that the social-ecological system is transformed from one state to the other by sudden or unforeseeable disturbances or shocks posed by demographic and environmental perturbations (Alberti, 2004). As a result, social-ecological and social-hydrological system resilience has been used in urban planning including disturbance control measures (Wilkinson, 2011). The social-ecological-and-hydrological system has a capacity to resist various impacts without changing the basic structure, function and identity of the system. Such a system addresses the reciprocal feedbacks between people and water resources for which human behavior and social norms play an integral part (Yu et al., 2017, Srinivasan et al., 2017). For example, the resilient city with intact hydrological connectivity and ecosystem functioning is better able to withstand ongoing environmental shocks with high societal sensitivity (Leigh and Lee, 2019). Social-ecological-and-hydrological system resilience framework identifies lags among social patterns and memories, changes in waterways and ecosystem dynamics when interrupted by disturbances and associated feedbacks of the social and biophysical systems and ultimately help address the sustainability issues of healthy waterways in cities (Liu, 2007).

By using a schematic (Figure 2), we propose an idealized healthy waterways and ecologically sustainable city (eco-city) in BTH, in which human society is fully integrated with the natural environment and green infrastructure (Fenner, 2017, Jiang et al., 2017, Breuste et al., 2015, Golden and Hoghooghi, 2018). Ecosystem functioning in such urbanizing landscapes is maintained by river and wetland connectivity (hydrological linkages) and environmental flows, while water pollution input by humans is minimized through the management of the impacts of imperviousness on flow together with the environmentally friendly infrastructure development such as wastewater treatment plants and the artificial water recycling basins (see details for Section 4 and 5).

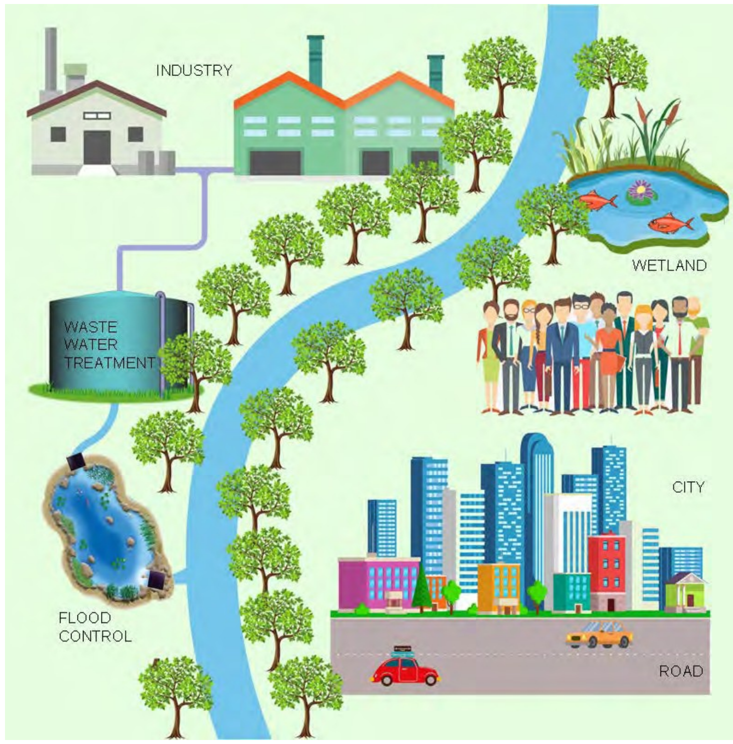

FIGURE 2. Artistic impression of the concept of the healthy waterways and ecologically sustainable cities in northern China.

The IPCC (2008) state: 'water and its availability and quality will be the main pressure on, and issue for, societies and the environment under climate change'. In the BTH region, this is manifested as extreme weather events including droughts and floods, which are urgent water governance issues. For example, the people living in cities in arid and semi-arid climatic zones often face unprecedented shortages of surface and groundwater flows (<100 L per person per day) and these areas are highly prone to droughts and floods (McDonald et al., 2011). Considering the pressures of rapid urbanization and climate change, a recent collaborative water resources strategy of the Chinese government is making a significant difference with regards to developing ecologically sustainable cities, including healthy waterways, in the region (Zhang et al., 2017). Large-scale infrastructure development projects such as the South-to-North Water Diversion Project (SNWDP) and the Yellow River water diversion project (YRWDP) have increased household water supplies, revived ecosystems and decreased the depletion rates of groundwater tables (through recharge and supply substitution), and enhanced food self-sufficiency by integrating agricultural production and improved water quality (Kattel et al., 2019, Dalin et al., 2015). For example, by the end of 2019, five years after the instigation of the Middle Route Project (MRP) of the SNWDP, a total of 25.8 billion m^3 water was supplied to BTH and its buffer zones including some areas of Henan province. The project helped to reduce groundwater withdrawal and led to a rise in groundwater levels by up to 2.88 m in Beijing (Chen, 2019), an outcome that benefits communities and ecosystems by fostering economic prosperity and improving the health of the local watershed. A long-term water quality monitoring program has been set up in the region for wetland ecosystem restoration and groundwater replenishment with a view to both short-and-long-term achievement of social, economic and environmental goals.

The use of improved scientific knowledge and technology not only enhances water resources but also the broader environments. For instance, the water-saving irrigation technology is beneficial to mitigate climate change impacts by offsetting regional CO_2 emissions in drier regions as this minimizes the use of fossil-fuel operated water pumping (Zou et al., 2011). However, the scientific community working for water resources development in the region has indicated a gap in addressing the key water security and ecosystem health issues. The potential exploration of water innovation in the context of efficient use of quality water to nurture environment and society is not well examined. In addition, some of the evolving scientific ideas and approaches in water sectors are not well disseminated (Kattel, 2019). Given the significance of the issues, the role of sustainability science, is not well conceived and articulated in the region. Sustainability science is thought to transform the system dynamics of urban center into transdisciplinary enterprise with expertise that addresses the complex problems of culture, institutions, and human behaviour in cities (Shrivastava et al., 2020). For example, there are instances of failure in water diversion projects such as the YRWDP as a result of a knowledge limitations and limited use of emerging technologies in water resources system such as mapping water distribution and security (Yuan et al., 1989, Li et al., 2019a). This requires concerted efforts from all sectors through research, dialogue, and exchange of ideas with the use of evolving scientific approaches and knowledge of environmental change and infrastructure technology (Pohlner, 2016, Lin, 2017).

With the aim of identifying some of the key challenges of healthy waterways and ecologically sustainable cities (Box 1) in the BTH region, this study has compiled data from northern China by inviting a panel of experts on water security, pollution and ecological health issues of urbanized landscapes, and by facilitating interactive discussion forums with different stakeholders including resource managers, engineers and decision makers. Direct field observation of built environment including wastewater systems, constructed wetlands and inter-basin water transfer projects were also required (Annex 1). The evidence-based knowledge and information derived from this study have been utilized to develop the social-ecological framework for the city's sustainable development program.

BOX 1

Healthy Waterways and Ecologically Sustainable Cities with Green Infrastructure Designs

"Healthy waterways and ecologically sustainable cities" are characterized by good environmental flow regimes with strong habitat networks, highly functioning ecosystems and an absence of eutrophication and pollution due to the use of green infrastructure designs (Figure 2). The increased connectivity of green space enables development of a multifunctional and innovative city with better abiotic, biotic and cultural interactions and human health and wellbeing, in other words, empowers a city's sustainability. Green infrastructure designs focusing on sustainability provide low-impact urban development with conventional, cost-efficient use of stormwater management and wastewater recycling scheme that integrate plants, animals, soils, and natural landscapes including flow regimes and wetlands that minimize or control pollution and enhance healthy urban landscapes and promote health for humans.

Here, we identify four key challenges facing the development of healthy waterways and sustainable cities in BTH: i) water security; (ii) surface water pollution and ecosystem degradation; (iii) groundwater hydrology and (iv) water governance. To address these challenges in the BTH region, the Government of

China has recently made a concerted management effort to protect Baiyangdian Lake (BYDL) as an area of healthy waterways for the proposed future city, Xiong'an New Area (XNA) (Zou and Zhao, 2018). The XNA will be the subsidiary administrative center of the government and is to be established as a green, smart and ecologically friendly eco-city balanced among nature, people and infrastructure (Sun and Yang, 2019). The BYDL hydrosphere complex, extending over 350 km^2 in area, generates important goods and ecosystem services including drinking water supply, ecological habitats, climate and nutrient regulation, all of which enhance the green spaces and wellbeing of people of the XNA in future. However, climatic and anthropogenic repercussions have endangered the BYDL water resources system and increased the challenge of planning and developing eco-cities in BTH, including the XNA. Within this context, this paper also highlights the key drivers that shape future research directions for the water security program of this eco-city.

2. KEY CHALLENGES OF WATER RESOURCE MANAGEMENT IN BEIJING-TIANJING-HEBEI REGION

The BTH urban agglomeration needs an effective water management solution for resolving the conflicts between water demand and supply in future eco-cities, so that those cities including the Xiong'an New Area will meet the economic, environmental, and social goals of being a model sustainable city. Today, BTH faces four key overarching challenges: water security; surface water pollution and ecosystem degradation; groundwater hydrology management and water governance. Solutions to these challenges which were identified during the symposium will profoundly contribute to the sustainability program of the eco-cities and improve the long-term viability and prosperity of the northern dry region of China including BTH.

2.1. Water security

The symposium identified regional water security vulnerability and uncertainty involved in the sustainability of waterways and ecosystems in BTH. Per capita water resources available in China is already very low as a result of uneven temporal and spatial variations and inconsistent distributions of water, and fragile water ecology and environment (Wang et al., 2017a). These are emerging challenges in water resources in the region due to unprecedented population growth, rapid economic development and climate change (Wang et al., 2017b, Cao et al., 2019). Water security is the adequacy of water availability (Srinivasan et al., 2017), both in quantity and quality terms, for health, livelihoods, ecosystems and production. Water security assumes that it is managed under an inclusive, integrative, transparent and evidence-based institutional setting (Pahl-Wostl et al., 2013). Water security is a complex issue as it embraces challenges related to physical and societal nature of water use in both policy and academic discussion fora (Cook and Bakker, 2012).

However, urban water supply in the regional urban hubs of northern China is in crisis. The water supplies of Beijing–Tianjin–Hebei are largely controlled by upstream environmental flows and groundwater aquifers (Li et al., 2017b, Li et al., 2012b). Rapid urbanization and industrialization have caused substantial impacts on waterways and groundwater aquifers in the region (Li et al., 2017b). The expansion of BTH urban agglomeration has increased household water consumption substantially from 9.4% to 13.6% of total water use from 1997 to 2016, respectively (Li et al., 2017b). The increased water use by households and industries has put additional pressures on environmental water flows. During water shortages, agricultural productivity has been maximized by using phosphorus and nitrogen fertilizers and by adopting low water use efficiency (WUE) and nitrogen use efficiency (NUE) agricultural practices (Kong et al., 2019). In BTH, areas integrating water saving and wastewater treatment technologies with the use of an 'adaptive management' approach promises to increase water security in the future. However, areas without good management plans are likely to suffer water insecurity (Figure 3). Intensive nitrogen fertilization, wastewater irrigation, leakage, and pollutant discharges from livestock and poultry farms have not only polluted surface water but also increased nitrate and nitrite concentrations in groundwater representing additional impacts of agricultural development on regional water security (Wang et al., 2019). Groundwater pollution (see groundwater hydrology section for more details) is further enhanced by rapid industrial growth, which has disturbed naturally occurring fluoride and arsenic sources, leading to the abandonment of numerous supply wells and creating further pressure on stressed water resources in the region (Currell et al., 2012).

Climate change has intensified the conditions of water insecurity in BTH (Pan et al., 2018). Changing temperature and precipitation affect water resources directly and indirectly. Urbanization, land use/land cover change, irrigation and water pollution also impact resource demand, availability and condition. For instance, the urban heat island increases a city's water demand (Wang et al., 2017b). Land erosion and subsequent sedimentation of river channels and saltwater intrusion in some coastal areas have worsened the conditions of water quality in waterways. For example, the loss of natural coastal wetlands and river channels in Bohai Bay is caused by increased land conversion for industrial development as well as inbound discharge of riverine and oceanic pollutants including salts resulting in coastal erosion, sedimentation and water resource degradation (Lin and Yu, 2018). These changes have also significantly influenced the use of irrigation water and subsequently affected agricultural productivity and economic growth (He, 2013). Another fact is that around 70% of the water for irrigation in northern China (BTH and surrounds) is abstracted from groundwater aquifers as surface water supplies are inadequate (Zhu et al., 2019). Overuse of water resources and agricultural demand under changing climatic conditions has resulted in dry rivers and wetlands, diminished groundwater supply and many aquatic and agri-ecosystems have either collapsed or on the verge of collapse (Wang et al., 2019). For instance, from 2000 to 2015 about 30% rivers, 23% channels and canals, and 16% swamps were lost from BTH due to changes in land use activities (Zhang et al., 2019). The projected 30 billion m^3 water shortages by 2030, is causing $20 billion regional financial losses due to low grain production (Kattel et al., 2019). Water demand from direct and indirect consumption poses critical challenges of water security in BTH (Currell et al., 2012).

2.2. Surface water pollution and ecosystem degradation

Surface waters in BTH account for a very small proportion (2.90%) of the total land area of the region. However, surface water plays an important role in maintaining biodiversity and sustaining ecosystem products and services that are also critical for human well-being (Zhang et al., 2019). The symposium discussed degraded surface water quality and ecosystem decline. The symposium participants and the expert panel inspected the urban wetland complex in Shijiazhuang in order to appraise water quality and ecosystem health and evaluate surface water pollution. This presents a serious threat to the sustainability of BTH. Water quality is classified as below national standard i.e. Class III in 27.9% of the waterbodies in the BTH region (Yang et al., 2017). A concern was raised in the discussion forum that water quality standards (WQS) initially adopted from the WHO are problematic locally, due to the unique geographic, environmental and ecological characteristics of BTH. Specifically, the sub-humid continental monsoonal climate with relatively low annual precipitation (543 mm) occurring in the Bohai Rim transitional zone between the Taihang and Yanshan Mountains in northeast China (Zhao et al., 2018, Zhang et al., 2019) significantly reduces flushing and recycling of nutrients and causing increased concentration of chemicals in water bodies. Increased populations, rapid growth of socio-economic conditions, use of commercial fertilizers, nitrogen discharge from agricultural, domestic and industrial sources have all contributed to deteriorating regional water quality (Strokal et al., 2016). More than 15 megatons of nitrogen is reported to be discharged into waterways every year in the northern dry region alone (Strokal et al., 2016). This is three times the estimated 'safe' level of nitrogen discharge (Yu et al., 2019). As a result, most waterways have become eutrophic, hindering economic growth and efforts to achieve sustainable development goals (SDGs) (Shao et al., 2006, Jiang, 2009, Desa, 2016). Reduction in dissolved oxygen levels due to increased water pollution and fish kill episodes in rivers and wetlands are classic signs of the collapse of aquatic ecosystems (Han et al., 2020). Eutrophication has also inflicted tremendous damage to water supplies, fisheries, transportation and tourism, resulting in significant economic losses in the region

(Xu et al., 2018). Outbreaks of cyanobacterial and toxic algal blooms in reservoirs and drinking water reservoirs demand more sophisticated technologies for treatment, at higher costs (Liu et al., 2016). Drinking water treatment processes are increasingly challenged by persistent organic pollutants (POPs) from industrial, municipal, and agricultural sources (Schwarzenbach et al., 2010). The presence of antibiotics and antibiotic resistance genes (ARGs) in both water and sediments of natural and constructed rivers and wetlands have further challenged the functionality of wastewater treatment plants in BTH (Li et al., 2019b).

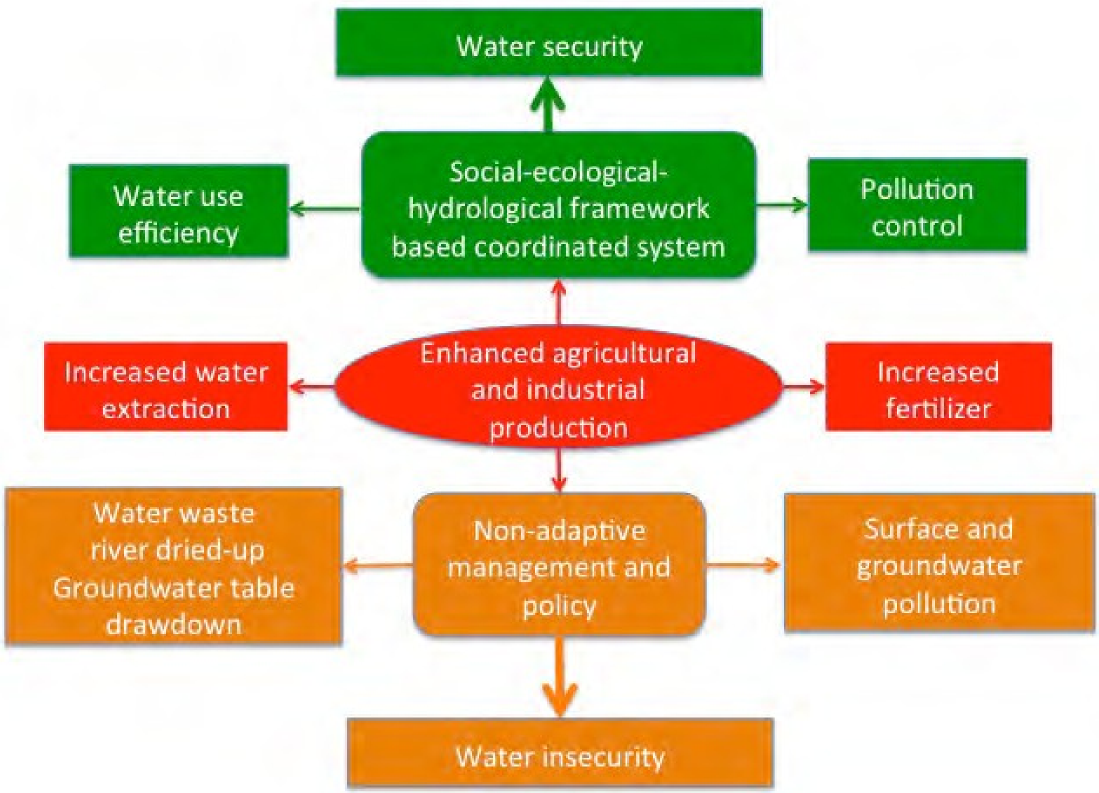

FIGURE 3. Current water security framework of waterways and ecosystems in BTH urban agglomeration under rapid climate change and industrialization. The food production in the region is dependent on over-extraction of surface and groundwater resources as well as excessive use of fertilizers. There is a trade-off: water security improves when there is a use of adaptive management approach such as advancement of water saving irrigation and wastewater treatment technologies and the use of knowledge, while water insecurity increases at absence of adaptive management.

2.3. Groundwater hydrology

The symposium identified issues associated with the maintenance of groundwater supply and associated water quality and its impact on a city's health and the well-being of the people. Adequate groundwater, free from hazardous contamination is necessary for drinking water security. Supporting groundwater dependent ecosystems (GDEs) and supporting irrigated agriculture for food, and energy security is pivotal (Dalin et al., 2015). For example, riverine systems where groundwater mixes with surface water (the hyporheic zone), have highly active ecosystem processes with heterotrophic respiration and elevated abundances of microbial taxa that have ability to mobilize or utilize organic compounds effectively and maintain ecosystem goods and services (Stegen et al., 2016). Increased spatial and temporal variability of anthropogenic inputs including nutrients (e.g., total phosphorus, total nitrogen), toxic metals (e.g., cadmium) and organic and inorganic pollutants (NH_4^+-N) to rivers across BTH have increased hazards to surface water-groundwater interactions (Figure 3) and also impacts irrigated water systems (Kattel et al., 2019). Irrigated agriculture in the BTH region is dependent on a continental monsoon climate, which is increasingly unreliable due to climate change (Tao et al., 2003). Massive development of irrigation systems in the region has increased crop production 6.6-fold between 1960 and 2000 but has caused a 70% increase in groundwater withdrawal (Tao et al., 2003) In the same period, the water table in some areas of BTH has lowered by about 12 m (Xu et al., 2010). Problems associated with over-pumping of groundwater have been known for a significant period of time with Xu et al. (2005) reporting a decrease in the groundwater level of 0.62 m per year over 10 years (Xu et al., 2005). In deep aquifers, the groundwater levels have declined throughout the region in the last three to four decades by up to 3 m per year (Currell et al., 2012). The groundwater aquifer that extends over 320,000 km^2 in the northern dry region is heavily used for wheat and maize production. The rapid decline of the groundwater level has critically threatened agriculture and groundwater dependent ecosystems (Aeschbach-Hertig and Gleeson, 2012). The declining groundwater levels have significantly impacted the sustainability of urban ecosystems. There are cases of increased groundwater contamination with nitrogen and heavy metals due to regional land use intensifications and related public health concern (Liu and Ma, 2020, Han et al., 2017, Chen et al., 2007). Further, groundwater hydrology is influenced by seawater intrusion, riverbank habitat destructions across the coastal zones, which have triggered water shortage and environmental degradation with negative impact on socio-economic development (Xu et al., 2005).

2.4. Water governance

Water governance was identified as an important component of an eco-city, as this plays a key role in attaining ecologically sustainable cities. There is increasing recognition that the "water crisis" is mainly a crisis of governance (Castro, 2007). Water governance across BTH is characterized by an inadequate legal framework, weak enforcement and the unsatisfactory implementation of integrated water resources management (Ching and Mukherjee, 2015). Successful implementation of Integrated Water Resource Management (IWRM) in the region requires both the formal integration of water infrastructure and operations, and joint deliberation and participation with local stakeholders (Leong and Lejano, 2016). However, in the absence of appropriate measures of IWRM practices, emerging stressors (e.g. heavy metals) in conjunction with existing water issues such as poor water quality caused by nutrient loading, have driven water resources quality to below the acceptable level of consumption, presenting a fundamental challenge to water governance for both water quality and quantity in the region (He, 2013).

The idea of "water security systems" in BTH is not new and sits within the framework of the centralized national water governance regime (Sheng and Webber, 2019, Jiang, 2015). However, there are ongoing issues regarding both policy and implementation (Barnett et al., 2015). Despite the policy driving balanced regional equity, inclusive of development needs and environmental protection, the issue of fragmented authoritarianism (overlapping and separated management) has greatly hindered the practice of integrated water resources management (Pohlner, 2016). Reflected in the BTH urban agglomeration, the interactions between local and regional interests have influenced government initiatives through the reallocation of water resources with increased attention from multiple sectors (i.e. social, cultural, environmental) in development and mobilization. The outcome of the current mutual consultations of authorities in BTH has seen low efficiency in water governance and decision-making. Controlling over-allocation of water through the use of different institutional approaches in these cities has added further complexity in water governance (Wang and Li, 2019). For example, recently instituted cooperative management efforts between the central and local governments within BTH have been viewed as a promising administrative approach. Yet the collaborative efforts of these agencies at regional and local scales remains unclear.

Along with the increased pressure from the central government to work on the philosophy of "ecological civilization" (Hu, 2012), a concept of integrated social-ecological system, where ecological resilience is translated into social resilience with the aim to empower the people and the nation is promoted (Davoudi et al., 2012). However, the increasing demand on water resources has posed further challenges to the governance of water allocation among the institutions and their vested interests. Externalities, complexity and diversity of the regional water issues remain with the emerging responses largely focused on engineering solutions. Long-term synergistic, socially-aware sustainable systems and practical governance mechanisms have been mostly sidelined (Kattel et al., 2019). Sustainable socio-economic development where, water demand and supply can be adjusted by changing water prices is only partly successful and often problematic at global scale. Administrative-controlled water prices can alter demand and supply curves and destabilize water saving (Jiang, 2009). Hence, allocating water rights and allowing a water rights trading system can resolve some water scarcity issues while mitigating the negative impact of water pricing but must be carefully managed. Identifying the trajectories of policy gaps is particularly significant for minimizing the cascading effects of those complex interactions between engineered solutions, social equity and other drivers such as water pricing. Incorporation of water rights and trade in the policy frameworks improves economy, and supports future water reforms including the improvement of water infrastructure and water use efficiency (Kattel, 2019).

3. SYNTHESIS OF FRAMEWORK AND RECOMMENDATIONS

The collective views of participants at the symposium have been synthesized and provided as recommendations for urban water resource development in BTH.

1. Develop and implement an integrated water-quality and ecosystem monitoring network that incorporates both surface and groundwater-associated physical, chemical and biological parameters.

Many participants raised concerns over availability of limited monitoring networks on surface water and groundwater resources including ecosystems and physical and chemical parameters of waterways in the region. For instance, the Huai River basin (174,000 km^2 area), one of the important waterways within the Yellow River basin (see Figure 1), has only 10 national routine monitoring sites along the main channel and an additional 42 sites along its major tributaries (Yang et al., 2017). Many irrigation projects in BTH have diverted water from the lower reaches of the Yellow River for more than 50 years. This has caused severe nitrate (NO_3^-) pollution in both surface water and groundwater resources across the Yellow River alluvial fan (Li et al., 2014). However, limited water quality and ecosystem monitoring networks in the region have significantly undermined the water resources development program and consequently hindered the distribution of adequate good quality water in the region (Ma et al., 2020). Development of an integrated network of water quality monitoring in BTH coordinated by scientists, resource managers, irrigators, engineers and decision makers is urgently needed. Regularly collected data by research organizations and universities over time have become useful to track major deviations of water quality and ecosystem trends. For example, incorporation of some key groundwater metrics in long term monitoring programs has identified the change and reduced uncertainty on the vulnerability of groundwater dependent ecosystems (GDEs) and consequently assisted management decisions (Rohde et al., 2017). Supplementing monitoring with effective methodologies has also been found to help identify point pollution sources (Townsend et al., 2018, Halim Moss et al., 2017, Ta et al., 2016) over large areas like BTH, which can be a cost-effective way of focusing management efforts. Similarly, citizen science (or conservation volunteer programs) engages individuals living in or near an aquatic ecosystem to play a complementary role in reporting the changes of temporal and spatial distribution of local and regional water resources (Krabbenhoft and Kashian, 2020). The use of water resource development and information systems in conjunction with citizen science has proven to be significant for spatio-temporal monitoring and decision making of water resources systems (Thakur et al., 2016), as well as increasing community understanding and sense of environmental stewardship (Toomey and Domroese, 2013). However, a unified information system with measurement and quality standards that records water quality and quantity has not been advanced in the region (Jiang, 2009). Hence, a transparent geo-located information system needs to be set up by government authorities so that the scientific communities can freely access the water related information for research. To enable the continued advancement of the economy, the government can invest in cutting-edge scientific research in developing and maintaining complete information systems in water resources, and transfer of information to policy design and management is essential (Jiang, 2009).

2. Identify water pollution sources, regulate compliances and enhance mitigation

Participants advised that identification of non-point sources of water pollution, regulation of compliance and pollution mitigation measures are urgently needed in BTH. In many cities in the BTH region, there is a disparity between the existing urban storm water drainage network and newly developed sewage system undermining the water pollution mitigation efforts (Xu et al., 2019)**.** The Chinese Government has adopted the UN's sustainable development goals (SDGs) of 'clean water and sanitation' and 'life below water' which include controlling pollution, eliminating dumping and minimizing the release of hazardous chemicals and materials, halving the proportion of untreated wastewater and substantially increasing the recycling and safely reuse of water in the region by 2030 (Xu et al., 2019, Desa, 2016).

However, no such progress in compliances have been made towards the national SDGs for water quality and ecosystem health in BTH. There are ongoing debates on enhancement of domestic wastewater treatment and improvement of cropland nitrogen management, which may partially reduce surface water pollution, but comes with higher capital costs. Serious transformational changes of the management paradigm and modernization of city infrastructure are needed to boost recycling and reuse within the context of comprehensive water quality metrics (Yu et al., 2019, Zhao et al., 2018). Adaptive management and the role of a water resource leadership program are thought to be capable of mitigating water pollution and improving water security with benefits for both the environment and people (Kenward et al., 2011). Such a management program should consider sustainable use of water resources through a broad range of approaches including governance and science at local and international levels (Vollmer et al., 2018, Liu et al., 2019b, Sun et al., 2016). Improved water governance mitigates pollution and positively impacts on climate change to minimize uncertainty. Hence, integration of climate change adaptation with improved water governance is urgently needed for a water pollution mitigation program in BTH (He, 2013).

3. Increase efficiency of water and energy use

The necessity for a strong policy on the efficient use of water and energy in BTH was discussed in the symposium. Including energy is important as water security is strongly impacted by energy uses. Water harvesting is often achieved in the short term at the expense of the environment with harmful implications in the long run (Pahl-Wostl et al., 2013). Secure water resources sustain agriculture, increase food supplies and empower people. The Chinese government has adopted the strictest water resource management (SWRM) policy in 2009 to cope with the increasing water stress by complying with three red lines: (i) reduce the total amount of water use, (ii) enhance water use efficiencies and (iii) control water pollution (Wang et al., 2017a). Setting a quota for water consumption can improve water security but alone this is insufficient. There is a need to fully understand the connectivity between distant freshwater ecosystem service provision and local freshwater ecosystem service consumption. This approach may also help managers to choose more sustainable strategies for critical freshwater resource management in the region (Li et al., 2017b). Inadequate surface water supply in BTH has led to an increased abstraction of groundwater resources followed by deepening of groundwater aquifers. Groundwater can play a significant role and contribute to a sustainable water-food-energy balance. In some areas, groundwater depletion in shallow aquifers has been exacerbated by climate warming. After the 1970s, even the reduction in irrigation has not minimized the deepening of groundwater table levels (Aeschbach-Hertig and Gleeson, 2012) possibly due to the sustained effect of climate warming and increased drought. The use of renewable energy such as solar and wind energy is devised to optimize WFE rather than reduce deepening of groundwater table (He et al., 2019). The large water infrastructure exemplified by the south to north water diversion project (SNWDP) in BTH does contribute to groundwater recharge (Aeschbach-Hertig and Gleeson, 2012, Kattel et al., 2019), reduces drawdown rate of the water table, improves GDEs and subsequently elevate water efficiency (Ye et al., 2014). The selection of water-saving irrigation technology and crop varieties is advised for soil conservation and sustainable use of groundwater in the region (Xu et al., 2005, Zou et al., 2011). Water conservation approaches such as the adoption of sprinkler irrigation, regulation of pumping restrictions (including restrictions on the diameter and depth of wells), construction of industrial waterworks and regulation of water tax policies are important for groundwater recharging and water saving programs (Endo, 2015). Groundwater governance comprising the promotion of responsible and collective actions to ensure socially sustainable utilization, control and protection of GDEs for the benefit of humankind is thought to be highly beneficial (Foster and van der Gun, 2016). This is a requirement for good human health outcomes and is consistent with the SDG of the WHO (Desa, 2016).

4. Determine integrated industrial, agricultural, domestic and environmental water requirements at catchment scale and enable a framework for water allocation and trading

Participants made strong arguments on the balance of water resources across the industrial, agricultural, domestic and environmental sectors. Equitable water allocation is crucial for food security, environmental maintenance, people's livelihoods, and socio-economic development, particularly in the face of extreme climate changes. Otherwise conflicts will arise between various stakeholders and sectors over water use and allocation. Effective inclusive governance of water use is critical for relieving water use conflicts. Reliable deterministic models can predict the requirement of water use for each sector by effectively investigating the internal structure of water resources system dynamics (Wei et al., 2018). Incorporation of good framework modelling approaches in water use efficiency and urban planning is strongly urged. Formation of water rights institutions, market-based approaches in water allocation, and capacity building programs are governmental priorities to address severe water disparity among various water sectors (Jiang, 2009, Cheng and Hu, 2011). However, the definition of water rights, how the water is distributed as per the stakeholders' rights, is not yet clear and the approach has not been well articulated (Jiang et al., 2020). A holistic, integrated, scientific approach with long-term, coordinated efforts for equity in water allocation is essential. One such tool to enhance decision making and transparency is water trading. If done well, this enhances reallocation of water across the domestic and agricultural sectors that increases access and water use efficiency and maximizes the economic values. Consequently, the water market could become a potential tool for reviving water rights and irrigation services and support safe and balanced water supplies in the cities and other sectors (O'Donnell and Garrick, 2019). However, institutional coordination of the relationship among water resources, food production, and the environment is considered to have greater significance for regional sustainability of water resources system (Wang et al., 2019). Particularly, a strategy of an integrated framework of social-ecological-and-hydrological system of science and management addressing climate, land-use, energy and water, together with resource assessments is essential to improve water use efficiency and allocation across various water sectors including industrial, agricultural, domestic and environmental.

5. Share knowledge among stakeholders including academia, resource managers, engineers, decision makers and local community in water governance

Knowledge of regional urbanization and external drivers such as globalization on water resources and the use of innovative methods and tools such as Integrated Water Resource Management (IWRM) are not adequately deployed in BTH (Leong and Lejano, 2016, Kattel, 2019). The symposium strongly recommended to diagnose IWRM as part of the combined social-ecological-and-hydrological system and within such system how current urban policies would relate to waterways and ecosystems in the region through an exchange of knowledge and ideas among academia, resource managers, engineers and policy makers. Innovation in water resources can strengthen the linkage of geo-spatial, socio-ecological, political and financial systems and shape healthy waterways. However, constant flow of capital investment in water-related industries appears to have fragmented the society by increasing income disparity and resource allocation in the region (Tian et al., 2019). Incorporating the sustainable policies in urban planning can bond the city's environmental, socio-cultural and economic development (Tian et al., 2019). Further, it can enhance the health of humans in the area. Cities adopting an IWRM approach, for example, can offer better sustainable solutions to water resources systems if the process is aligned with the prevailing management paradigms and institutions. In BTH, institutions and stakeholders are not fully aware of the data and complexity of water governance. Water governance addresses the human dimension by focusing on the analysis of regulatory processes that influence the behavior of actors in water management systems. Integrated analysis of water resource management and the governance system builds on a Management and Transition Framework that allows the examination of structures and processes underlying water management and governance (Halbe et al., 2013). The linking of participatory modeling and research on complex governance systems allows the transfer of knowledge between the science, policy, engineering and community, facilitates assessment and implementation of transformation processes towards IWRM that require adoption of adaptive management principles (Halbe et al., 2013). Failure in water governance can lead to resource conflicts. Under climatic extremes current governance regimes face complexities to deal with present and future challenges. Hence, multi-level learning exercises, memory and knowledge are emphasized to influence the institutional framework modelling of water management (Pahl-Wostl, 2009). The linkages between central, provincial and local governments strengthens the relative importance of bureaucratic hierarchies, marketing and networks that also improves water governance. Complex and diverse governance regimes have higher adaptive capacity. Shared conceptual frameworks among national and global scientific community particularly generate knowledge base needed to advance current understanding of the state of art in water governance in BTH (Pahl-Wostl, 2009). The issues addressed here play out in many countries and shared knowledge provides the most effective vehicle to deliver solutions.

4. FUTURE DIRECTIONS

The symposium identified two fundamental drivers: scientific research and institutional co-ordination as important in shaping future directions in water resources in the region (Figure 4a). Evidence-based scientific research defines challenges and finds solutions to water security issues of future eco-cities. Scientific research detects and characterizes how water systems are transformed by humans and climate change and assists better urban planning and water policy designs. Mounting scientific evidence of environmental changes, including water quantity, quality and ecosystem integrity in Baiyangdian Lake and its catchment indicates that BTH has undergone water-related shocks (drought, flood and pollution) over the past few decades more frequently than ever before with serious implications for future water insecurity (Wang et al., 2018, Han et al., 2020, Song et al., 2018). Analysis of the complex interactions and feedback mechanisms of these changes across and between scales is urgently needed with broader assessment of social-ecological-and-hydrological system dynamics (Sivapalan et al., 2014, Wilkinson, 2011). Evidence suggests that incorporating the system thresholds and feedback responses of biotic and abiotic interactions can contribute to water resource management as it would identify the state of system resilience when exposed to various environmental changes including land use and climate change (Kattel, 2019).

The other essential driver for future direction of the city's sustainability is a coordinated institutional effort among universities, governmental and nongovernmental research organizations towards water resource management goals. Attempts have been made to manage the inherent complexity of water resources systems under rapid climate by coordinated efforts of scientists decision makers and stakeholders (Liu et al., 2015). Collaboration finds avenues for setting up warning and prevention system as well as addressing climate change adaptation strategies (Liu et al., 2015). International research cooperation is required as water resources system knowledge has become increasingly globalized (Hoekstra and Mekonnen, 2012). Integrated social-ecological-and-hydrological programs on sustainability sciences can reshape the university research, influence funding agencies, improve science communication, policy, and decision making. This work empowers sustainability, increases engagement with society and induces an environment of employing all available sources of knowledge in favor of creating ecologically sustainable cities (Shrivastava et al., 2020).

The ideal eco-city that we proposed in Figure 2 represents the use of novel approaches in water resources systems integrating perspectives of experts from a broad range of disciplines, including ecology, hydrology, geochemistry, social sciences, economics and climate change in BTH. Integration of novel approaches of water resources systems can result in a successful eco-city. Integration of the assessment and framework modelling of various components including hydrology, groundwater flow, social-ecological system, and stakeholders' behavior (e.g. water consumption, water pollution) and participation in identifying the water-related issues as well as agricultural productivity, point and diffuse source pollution all have become significant to minimize future uncertainties of water scarcity and water quality risks (Gain and Giupponi, 2015, Gaiser et al., 2008). The use of information sciences, such as the integration of remote sensing, geographic information system and location services are essential research tools contributing to managing surface and groundwater hydrology as well as developing emergency response models in eco-cities to combat natural and man-made disasters (e.g. floods) (Thakur et al., 2016). Exploring key challenges and mitigation options of water security issues and communicating research outcomes based on the mechanism set by water experts that translates science into better urban planning and policies. Strong scientist-manager collaborations are required to achieve water resource management goals of an eco-city on a timely fashion. Proactive scientific measures including the use of rigorous data and experimental designs are significant. Inputs from stakeholders and policy makers result in rapid transformation of water resources information across the urban communities (Seastedt et al., 2008). Citizen science-led solutions should be made a part of the water resource development program of cities which lack local professional and scientific support (Hibbett et al., 2020).

The Baiyangdian Lake complex, one of the prime wetland ecological habitats and water supply sources, of the future 'eco-city' (Figure 4b), such as Xiong'an New Area in BTH (Nagai, 2017), has been made a priority for researching healthy waterways and ecologically sustainable cities through national and international collaboration from both central and provincial governments of China (Jun and Chen, 2001). The BYDL and its extended catchments within the Yellow River Basin provide an important example for rapidly changing water resource systems including the hydrology and ecosystems and can be the best collaborative research platform among universities and research organizations in the future for the eco-city development program in northern China. The scope of international collaboration is particularly important as the issues of ecosystem degradation and water shortages in dry regions are common threats to humanity in cities across the arid and semi-arid regions of China and elsewhere.

a. Future Direction Framework

b. Proposed Eco-city Xiong'an

FIGURE 4. (a) Future direction framework for (b) an eco-city (e.g. Xiong'an). Two fundamental drivers play a key role for functioning of the eco-city. Research drivers (horizontal axis) strongly influences the water policy and planning of the future cities through evidence-based scientific research and peer-reviewed publications, and the institutional drivers, such as the coordinated efforts of universities, governmental and non-governmental organisations (vertical axis) ease the water resource management practices and intensify water efficiency in the future cities.

Ecosystem function and the associated products and services of the BYDL are controlled by climate-induced hydrological alteration of incoming river flow, lake level fluctuation and the mixing of anthropogenically-originated nutrients, heavy metals and other industrial and agricultural contaminants consequently threatening the societal efforts in managing water resources (Zhang et al., 2013, Liu et al., 2019a). After the 1980s, the social and ecological system dynamics of the BYDL have transformed rapidly along with the expansion of cities in BTH (Bai et al., 2016, Wang et al., 2018). Hence, the development of social-ecological-and-hydrological system resilience of BYDL is a fundamental goal for an eco-city. A rapidly changing nature of the large cities (e.g. Baoding) in BTH (Li et al., 2017a) also suggests that long-term hydrological, ecological and social (e.g. public health) risks need to be assessed urgently through a joint national and international research coordination (Ji et al., 2019, Liu et al., 2019a). Collaboration not only maximizes the innovative environmental research outcomes (Han et al., 2020, Cui et al., 2010), but also leads to policy-oriented research outcomes in water resource technologies supporting sustainability of future eco-cities (Li et al., 2017a). While long term records of water and sediment and information science is essential for tackling climate change and other human-induced issues in the BYDL (Bai et al., 2016), the fundamental role of social-ecological-and-hydrological system resilience should be planning the future eco-cities (e. g. XNA) in BTH and ensuring the health of its citizens. The social-ecological-and-hydrological framework modelling has successfully integrated ecosystem functions with social and hydrological system dynamics and enhanced resilience of cities (Pickett and Zhou, 2017, Srinivasan et al., 2016).

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CONFLICT OF INTEREST

The authors have declared no conflicts of interest for this article.

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ANNEX 1

This study compiled a vast amount of data and information on healthy waterways and ecologically sustainable cities in northern China using various approaches such as, reviewing relevant scientific reports and peer-reviewed journal articles, organizing the international research symposium and running an interactive discussion forum on the "Healthy waterways and ecologically sustainable cities in Beijing-Tianjin-Hebei urban agglomeration (Northern China): Challenges and future directions" among various stakeholders including water resource engineers, aquatic ecologists, sociologists and water resource managers in local and provincial governments of northern China and also making a direct field observation of research areas. About 100 delegates were invited for the symposium in which a quarter of them contributed their research as oral presentations to the symposium (see below). At the end of the oral presentation, a Q & A discussion forum was organized by inviting the three prominent water scientists in the region as the panel members to answer the questions raised by participants. The detailed conversations among the stakeholders and scientific communities were noted during the discussion. In the following day, delegates visited the nearby urban waterways to gain the knowledge of urban ecology and how the local people are interconnected with the complex waterways in the area. The interactions among the delegates and local people were also organized as a part of this study. The firsthand information and evidence-based knowledge derived from this study were then utilized to develop the framework for the sustainable development program on ecologically healthy cities (eco-cities) in the BTH region.

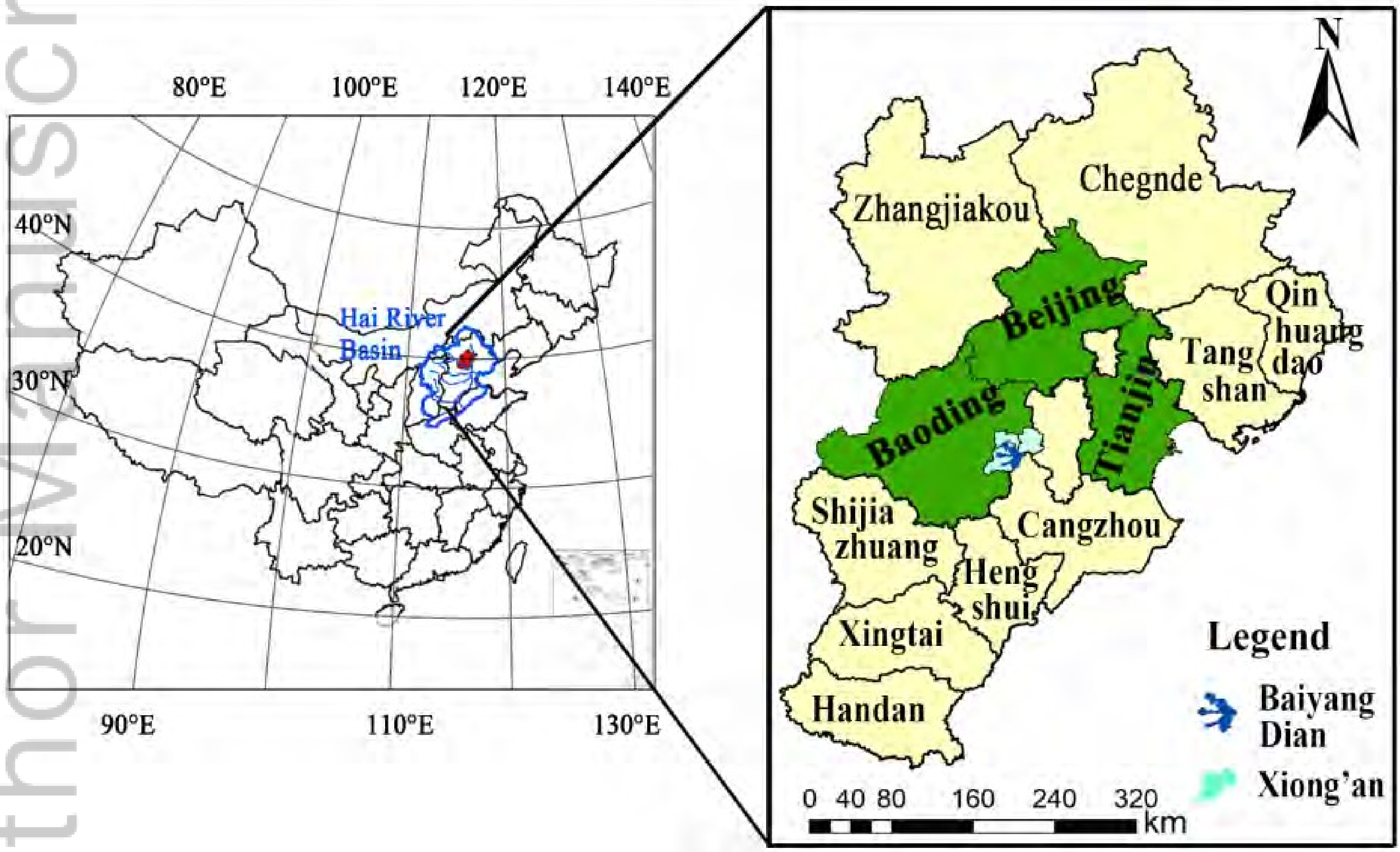
International Research Workshop

1-3 November 2019

"Healthy waterways and ecologically sustainable cities in Beijing-Tianjin-Hebei urban agglomeration (Northern China): Challenges and future directions"

DAY 1 (1 November 2019)	
Registration/Reception	
6:00-8:00 Banquet Reception and Dinner	
DAY 2 (2 November 2019)	
8:45-8:50 WELCOME: HEBUST PRESIDENT	
8:50-9:00 HEBUST Water Research Program, DEAN, School of Environment	
Morning Theme: Ecology, water quality and social-ecological resilience	
Session I	**Aquatic ecosystems and food web dynamics in past, present and future and social-ecological resilience (Chair: Qiang He)**
9:00-9:15	Suzanne McGowan (Nottingham University, Nottingham, United Kingdom): Combining palaeoecological and archival datasets to assess the causes of ecological change in Yangtze Delta lakes
9:15-9:30	Ke Zhang (NIGLAS, Chinese Academy of Sciences, Nanjing, China): Dynamics of linked social-ecological systems: learning from the past
9:30-9:45	Samantha Capon (Riverine Institute, Griffith University, Brisbane, Australia): Restoring urban riparian ecosystems in the Anthropocene: challenges and opportunities
9:45-10:00	Lulu Zhang (Hebei University of Science & Technology-HEBUST, Shijiazhuang, China): Quinolones antibiotics in the Baiyangdian Lake China: Distribution, bioaccumulation, and ecological risks
10:00-10:15	Giri Kattel (University of Melbourne, Melbourne, Australia): Unraveling the long-term eutrophication issue of regulated river systems by integrating the past and present ecosystem and food web dynamics in Australia and China
TEA BREAK (10:15-10:30)	

Session II	**Water pollution, eutrophication, quality control, modelling and management (Chair: Suzanne McGowan)**
10:30-10:45	Andrew Western (The University of Melbourne, Australia): Identifying catchment water quality controls in Australia through statistical modelling of large data sets
10:45-11:00	Qiang He (University of Tennessee, USA): Source tracking of contamination in impaired surface water
11:00-11:15	Kim Dowling (Federation University Australia, Ballarat, Australia): Waterways in the Victorian Goldfields: Rivers of gold and heavy metal mobility
11:15-11:30	Chun Liu (Hebei University of Science & Technology-HEBUST, Shijiazhuang, China): Application of microbubble ozonation for pre-treatment and advanced treatment of refractory industrial wastewater
11:30-11:45	Dejun Wan (China Geoscience Academy, Shijiazhuang, China): Sedimentary record of biogeochmical changes in a typical lake in North China (absent)
11:45-12:00	Chuanyu Gao (IGACAS, Chinese Academy of Sciences, Changchun, China): The impacts of land reclamation and regional human activities on the accumulation of key elements in wetland soils in typical wetland distribution regions in northeast China
LUNCH BREAK (12:00-14:00)	
Afternoon Theme: Climate change, urban water shortages, distribution and management	
Session III	**Climate change, surface and groundwater management (Chair: Peter Scales)**
14:00-14:15	Sun Feng (The Yellow River Conservancy Commission, Zhengzhou, China): Climate change and societal response in Yellow River Basin, China
14:15-14:30	Wenjing Zhang (The University of Melbourne, Melbourne, Australia): Which way forward? Water security for China's city of the future
14:30-14:45	Lei Wang (ITPCAS, Chinese Academy of Sciences, Beijing, China): Large lake water storage change over Tibetan Plateau caused by climate change and its associated cryosphere melts
14:45-15:00	Zaifeng Tian (Hebei Environmental Science Institute, Shijiazhuang, China): Water standards in Hebei under the rapidly changing climatic environments.
15:00-15:15	Lan Cuo (ITPCAS, Chinese Academy of Sciences, Beijing, China)): Warming induced changes in the Yarlung Tsangpo basin of the Tibetan plateau and their influences on streamflow
TEA BREAK (15:15-15:30)	
Session IV	**Future city, green infrastructure, citizen science and minimizing risks in water resource management (Chair: Andrew Western)**
15:30-15:45	Peter Scales (The University of Melbourne, Melbourne, Australia): Future water in our cities and integrated urban water management
15:45-16:00	Jing Wei (Tsinghua University, Beijing, China): Transition of societal value in water resources in Australia and China
16:00-16:15	Pan Zenghui (Groundwater Hebei Hydraulic Institute, Shijiazhuang, China): Groundwater Resource and Governance in Hebei
16:15-16:30	Jessica Reeves (Federation University Australia, Ballarat, Australia): Developing community-led environmental stewardship
16:30-16:45	Luo Xiao (Hebei University of Science & Technology -HEBUST), Shijiazhuang, China: Simulation of urban water supply using EFDC model to minimize the risks of source pollution
16:45-17:30	**Q &A Synthesis of workshop + conclusion**
18:00-21:00	**Dinner**
DAY 3 (3 November 2019)	
Excursion	**Visit to a lake/river basin or a local reservoir in Hebei Province**



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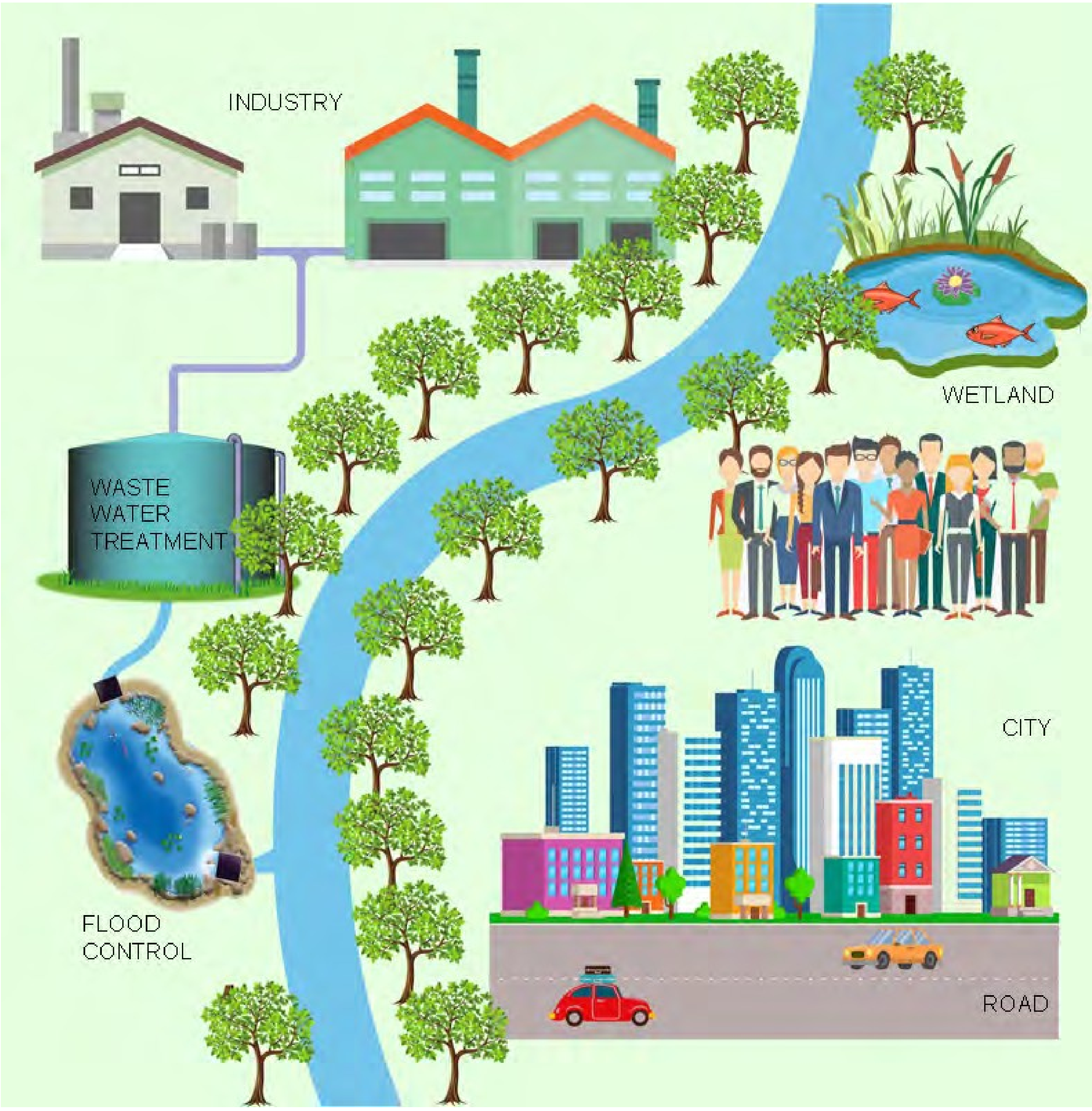

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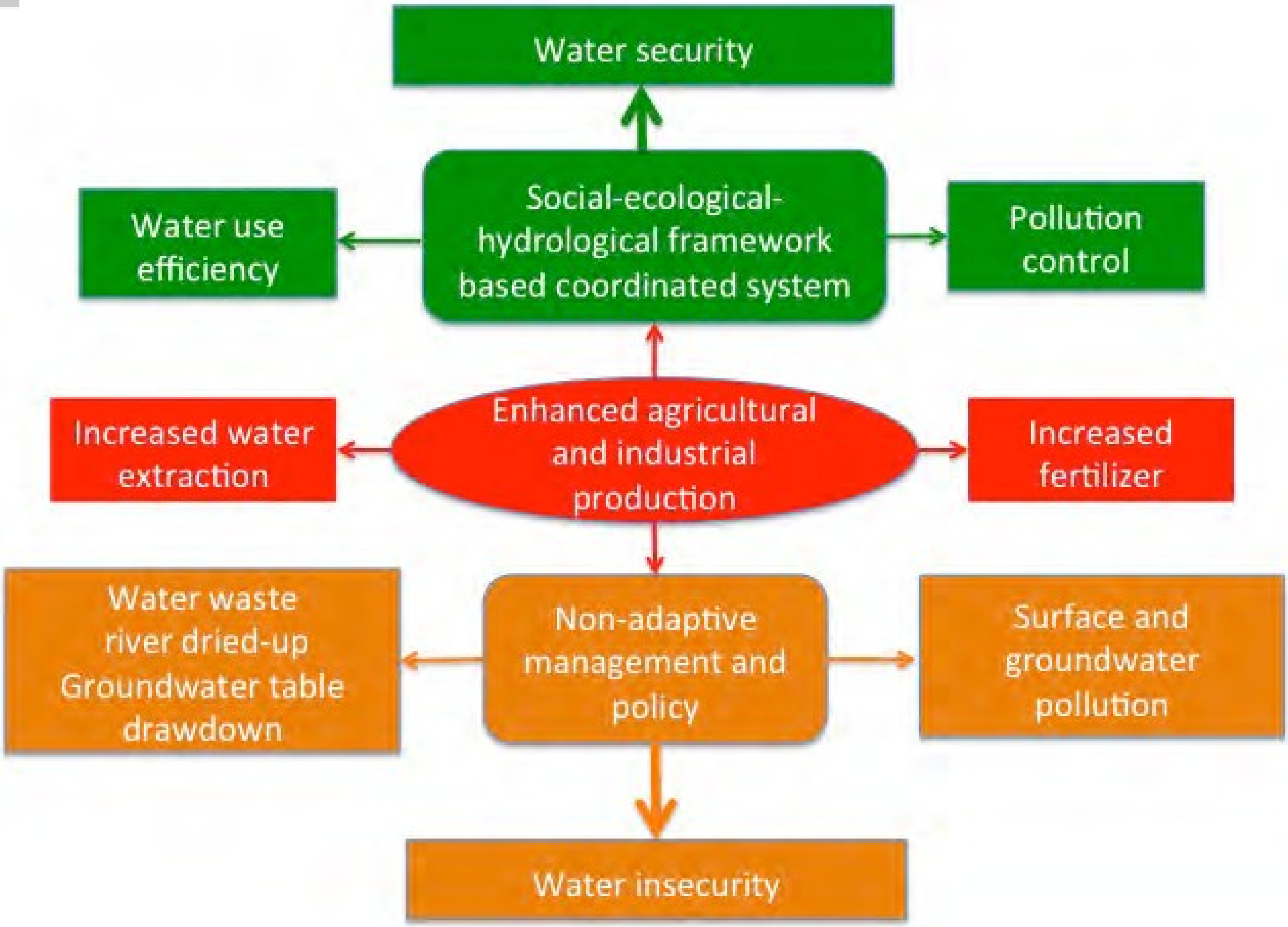

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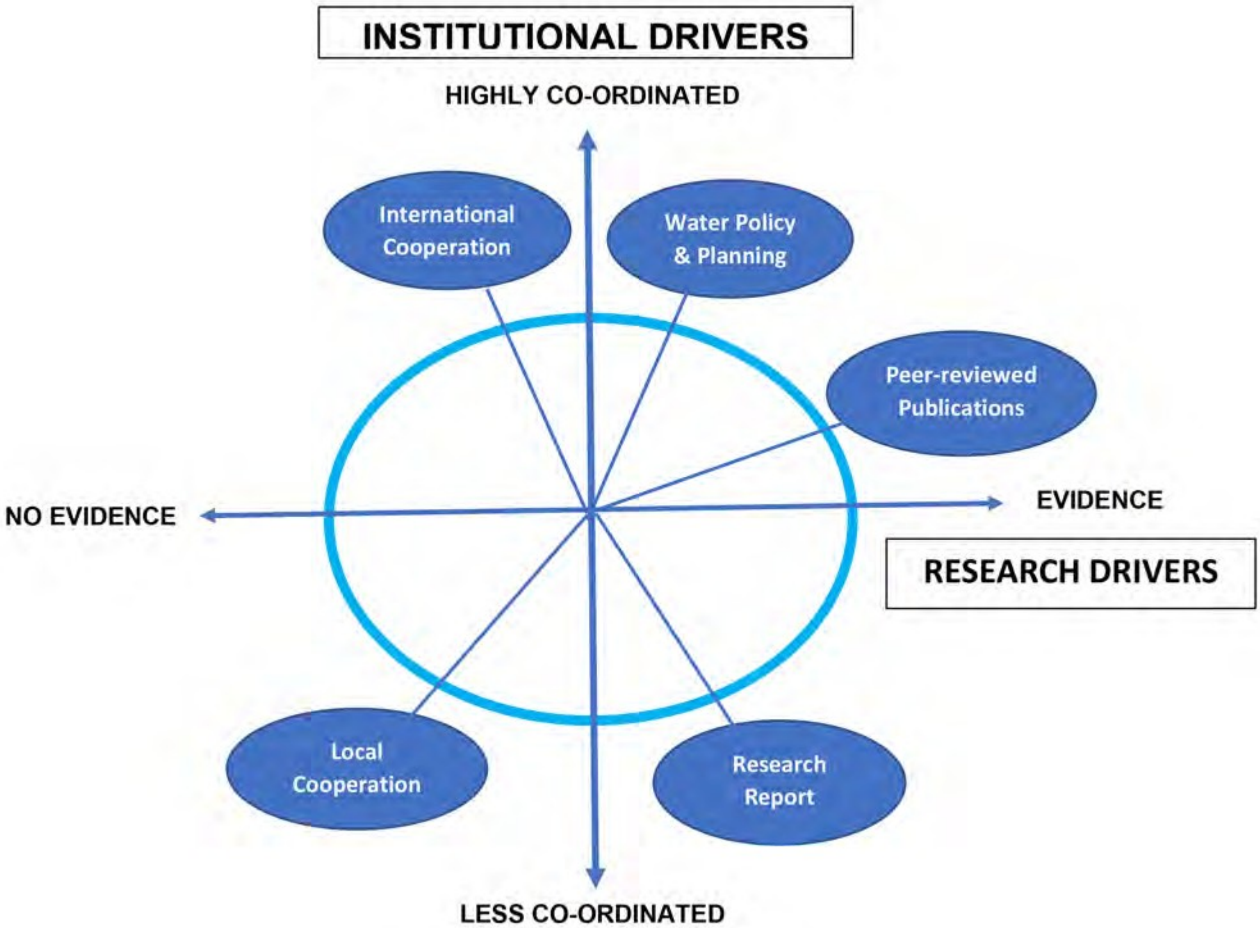

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