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Telecoupling in urban water systems: an examination of Beijing's imported water supply

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ABSTRACT

Urban centres increasingly have difficulties meeting water needs within their hydrologic basins. To sustain urban water supply, cities and water source regions have increased telecouplings (socio-economic and environmental interactions over distances). To analyse these complex interactions, we apply the new telecoupling framework to the water-stressed megacity of Beijing's imported water supply. We found that Beijing's remote water sources have lower risk than local supply, but connections impact the sending systems. The telecoupling framework provides a standard, systematic and flexible tool for evaluating the sustainability of urban water supply. It also identifies a number of research gaps for future quantification efforts.

Introduction

Achieving sustainability in urban water systems is of immediate concern globally. Currently 3.9 billion people (54% of the global population) live in cities, and this number is expected to increase to 6.4 billion (66%) by 2050 (United Nations Population Division, 2014). As dense population centres with highly concentrated water demands, cities are finding it increasingly difficult to meet their water needs within their municipal boundaries or hydrologic basins. Estimates using the water footprint approach found that, on average, cities with populations higher than 750,000 require areas 27–621 times their urban extent to meet water needs (Jenerette & Larsen, 2006). Large cities source water from 41% of global land area while occupying only 1%, resulting in aggregate transport of surface water over approximately 27,000 km (McDonald et al., 2014).

Given burgeoning urban populations and the associated geographical expansion of urban water sources, current methods of assessing urban water systems are inadequate. Sustainably managing urban water demand increasingly will require integrating spatially distant sources and impacts into urban water accounting. A novel approach is needed that can consistently integrate components of water systems over distances, including spatially disjoint areas. Traditional methods such as local hydrologic water

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balance models often overestimate urban water stress. In about one-third of cases, however, additional water infrastructure and transfers alleviate this stress (McDonald et al., 2014). For example, Padowski and Jawitsz (2012) examined 225 cities in the United States and found that estimates of water scarcity decreased from 47% to 17% when extracted, imported and stored water were considered in addition to typical local renewable water flow assessments. This reliance on infrastructure and distant water sources, however, also means that the impact of urban water demand is spread farther. Urban water demand negatively impacts freshwater biodiversity and ecosystem services via dam construction, water diversions, surface water depletion and contamination (Fitzhugh & Richter, 2004).

In addition to physical water supplements, many cities import a considerable amount of water through virtual water embedded in traded goods. Virtual water is the total amount of water required to produce goods, including food and industrial products (Allan, 1993; Hoekstra & Chapagain, 2008). In the context of a municipal water budget, importing virtual water through goods is analogous to the physical water that would otherwise be needed locally to meet demand and is thus a method of transferring water between regions (Chapagain, Hoekstra, & Savenije, 2006; Dalin, Hanasaki, Qiu, Mauzerall, & Rodriguez-Iturbe, 2014). In 2004, virtual water trade accounted for 30% of global freshwater withdrawals, thus playing a large role in global water redistribution (Chen & Chen, 2013). However, virtual water flow does not always flow from water rich to water poor areas (Kumar & Singh, 2005; Zhang, Shi, & Yang, 2012) and can provide both economic gain and additional water stress in source areas. With increasing globalization and trade, virtual water connections are almost certain to increase (Chapagain & Hoekstra, 2008).

It has been suggested that these external water footprints transfer burden to other regions, but more detailed cost–benefit analyses on source regions would be needed for assessment (Zhang et al., 2012). Similarly, many water management strategies involving engineering, infrastructure or landscape management at source regions (McDonald et al., 2011) require a broader scope to evaluate. Given that urban water infrastructure is likely to continue to expand in coming years (McDonald et al., 2014), a new framework is warranted to evaluate systems interacting through water exchanges over distances.

Here we apply the emerging telecoupling framework (Liu et al., 2013) to urban water systems. The framework provides a consistent methodology to evaluate socio-economic and environmental interactions in linked systems across distances. In order to demonstrate the efficacy of the telecoupling framework to sustainable urban water management, we apply the framework to the megacity of Beijing as a proof of concept and to highlight research gaps needing further study to evaluate fully urban water sustainability. Beijing is an ideal demonstration city for several reasons. First, it is one of the world's 28 megacities (cities with populations topping 10 million), and there are expected to be 41 megacities by 2030 (United Nations Population Division, 2014). Currently, one in eight urban residents live in the megacities. As dense population centres, megacities amplify urban water challenges. Furthermore, Asia currently holds 53% of the world's urban population (Europe follows next with only 14%), and 90% of urban population growth through to 2050 is expected to be in Asia and Africa (United Nations Population Division, 2014). Thus, Beijing's status as an Asian megacity makes

it relevant for ongoing and future water challenges. Second, Beijing is the fifth largest city under water stress globally (McDonald et al., 2014). Third, like many other cities, Beijing relies on external sources of water, including contributions from China's South-to-North Water Transfer Project (SNWTP), the world's largest inter-basin water transfer to date. It is also a net importer of virtual water (Zhang, Yang, & Shi, 2011).

We synthesize the literature to apply the telecoupling framework to three telecouplings used in Beijing's water supply: (1) inter-basin water transfers; (2) virtual water imports; and (3) payments for ecosystem services (PES) to upstream regions in order to increase water supply quantity and quality. We then investigate the relative water risk in Beijing and telecoupled source regions to determine if Beijing has lowered its vulnerability to water shortage through these telecouplings. Because this proof-of-concept demonstration is based on existing literature, it also identifies research gaps in need of further study to capture the complexity of modern urban water systems.

Methods

Conceptual model for applying the telecoupling framework

Growing populations, variable and changing climate patterns, evolving socio-economic water demand, institutional policies, and land-use transitions all interact to determine available water supply and use, potentially with nonlinear effects and feedbacks. Thus, urban water systems are coupled human and natural systems (CHANS; Liu et al., 2007) where socio-economic and environmental components interact in complex ways, often with emergent properties, feedbacks and surprises. Urban water frameworks, therefore, need to take a systems approach.

The new integrated telecoupling framework (Liu et al., 2013) emphasizes linked CHANS over distances ('tele' means distant). In this way, the telecoupling framework can be complementary to existing frameworks while crucially expanding their scope to address multiple interacting systems more fully, thus addressing key features of modern urban water systems. The telecoupling framework aims to integrate analyses of socio-economic and environmental flows among interacting systems in order to evaluate holistically sustainability, particularly when systems are physically distant (Liu, 2014; Liu et al., 2013). According to Liu et al. (2013), there are five major components in telecoupled systems: (1) connected CHANS that fulfil roles of sending, receiving and spillover *systems*; (2) *flows* of material, energy and information among these CHANS which produce effects; (3) *agents* who facilitate or hinder flows; (4) *causes* that produce the telecoupling; and (5) *effects* generated. The telecoupling framework has been applied to issues such as forest sustainability in China (Liu, 2014), soybean trade (Garrett, Rueda, & Lambin, 2013), energy trade (Liu et al., 2015a), and land change science (Eakin et al., 2014; Liu et al., 2014).

In Figure 1, we develop a conceptual model for applying the telecoupling framework to urban water systems. As noted in item 1 above, there are three roles that any system can fulfil: sending, receiving and spillover. In the case of urban water telecouplings, the receiving system is primarily the urban entity receiving water from the sending system or systems. These sending systems could be nearby in the case of short physical water transfers, or distant and spatially disconnected in the case of long inter-basin water
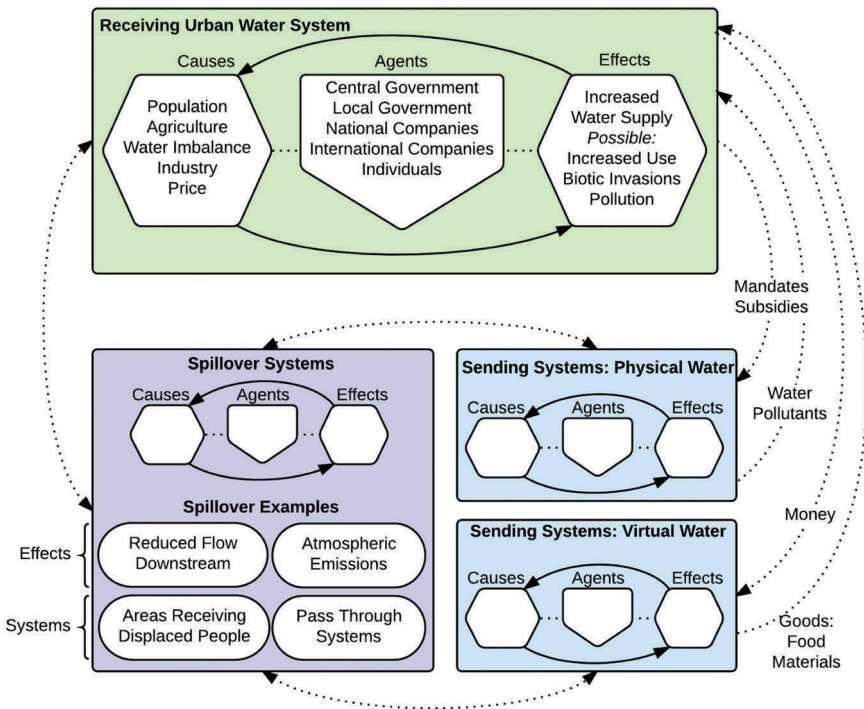
Figure 1. Telecoupling framework applied to urban water systems. Conceptual diagram of the five telecoupling elements (systems, agents, causes, effects and flows) in urban water systems. Flows are depicted with dashed arrows. Agents or causes can span multiple systems, and systems can have reciprocal roles as sending and receiving systems depending on the directions of the focal flows. Causes, agents, effects and flows listed are examples.

transfers or virtual water flows embedded in global trade. The receiving urban system may or may not contribute compensatory flows, such as payment, back to the sending water system. Spillover systems are systems that receive byproducts from the connection of the sending–receiving systems (Figure 1) (Liu et al., 2013) and tend to be the most overlooked in traditional assessments. Agents, causes and effects are attributes found in each system or acting over several systems, while flows are the material exchanges among the systems. Figure 1 provides examples of agents, causes, effects and flows in telecoupled urban water systems. It should be noted that systems can have reciprocal sending and receiving roles (depending on the flows of interest), and cross-scale interactions or agents affecting multiple systems are possible.

Applying the telecoupling framework to urban water management allows researchers and planners to expand their consideration beyond the urban receiving system to include the sending and spillover systems. This provides an immediate advantage over existing methods. For example, Integrated Water Resources Management (IWRM; United Nations – Water, 2008), Integrated Urban Water Resource Management (IUWRM; United Nations Environment Program, 2003), and urban ecohydrology (Jenerette & Alstad, 2010) are existing frameworks seeking to manage sustainably and holistically and/or account for urban water. Though each has particular nuances and even outstanding challenges (Biswas, 2004), all three attempt to capture

the full urban water cycle and incorporate social dynamics of human water use. All three frameworks, however, are focused on the city itself and do not extend beyond the hydrologic unit in which the city is found, except perhaps to quantify incoming or outgoing water flows. By considering agents, flows, causes and effects both within and among interacting systems, the telecoupling framework provides a comprehensive way to integrate consistently components of existing water management frameworks over distances, as necessitated by the increasing long-distance connections in the global water cycle and urban water supply.

Case study area: Beijing, China

The municipality of Beijing has provincial status under China's administrative system. It lies in north-east China (Figure 2(a)) and encompasses the urban core as well as rural outlying districts. In this study, we refer to the full municipality of Beijing, unless otherwise stated. Over the last several decades, Beijing's rapid population growth, land-use changes and associated increases in water demand have greatly stressed its water supply. Approximately 90% of Beijing's surface water originates in the Hai River Basin (Zhang, Yang, & Fath, 2010), where almost half of the rivers are dry more than 300 days per year (Duan et al., 2004). Surface water is largely stored in the Miyun and Guanting reservoirs. Poor water quality in the Guanting Reservoir has prevented its use as drinking water since 1997 (Probe International Beijing Group, 2008). Therefore, the Miyun Reservoir, located 100 km from downtown Beijing, is the city's main source of domestic tap water (Ma, Yang, Tan, Gao, & Hu, 2010).

Due to the limited amount, uneven temporal distribution, and degraded quality of surface waters, Beijing is dependent on groundwater for approximately two-thirds of its physical water needs (Probe International Beijing Group, 2008). Though the city has utilized groundwater for over 2000 years, extraction increased rapidly from 0.05 billion m^3 in 1949 to 2.7 billion m^3 in 1981, reaching 50% of the water supply by the 1980s (Zhang & Kennedy, 2006). The Beijing Water Bureau estimates the sustainable yield of groundwater to be between 2.0 and 2.45 billion m^3 annually, depending on rainfall, but the pumping rate often exceeded this. As a result, average groundwater levels in the Beijing plain have dropped by 21.7 m since 1960 (Beijing Water Bulletin, 2010). The six water works in Beijing city drawing groundwater have created a depression cone in the water table that extends up to 2000 km^2 in the Beijing plain, causing land subsidence and damaging municipal infrastructure (Wang & Wang, 2005).

Total annual water use in Beijing has declined since its peak in the mid-1970s largely due to decreased agricultural area, increased efficiency and reuse. However, the rapidly rising population has greatly stressed supply (Figure 3). As a result, per capita physical water availability has declined from 1000 m^3 in 1949 (Probe International Beijing Group, 2008) to 470 m^3 in the early 1980s and 107 m^3 by 2010 (Zhang et al., 2012). As a commonly used measure of water stress, per capita resources below 500 m^3 are typically considered 'absolute water scarcity' (World Water Assessment Programme, 2012). To address this water crisis, Beijing uses several measures to supplement its water supply from distant sources. At a broad scale in China, more abundant water resources tend to be in the south, while its
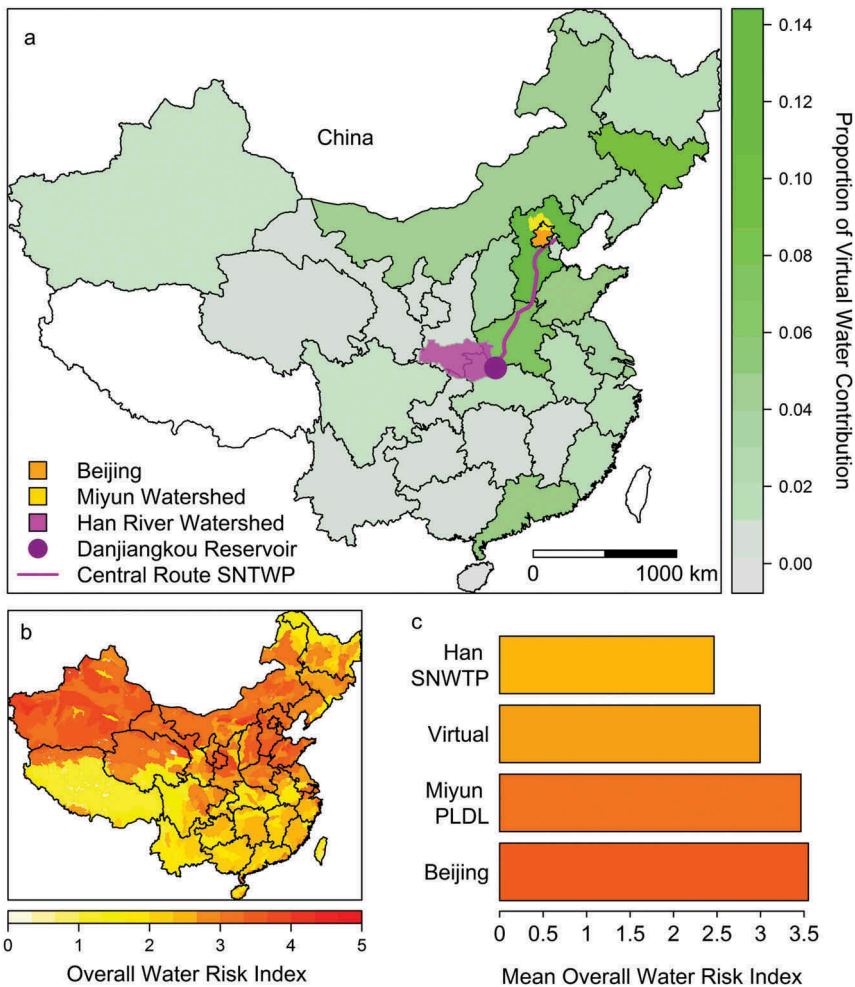
Figure 2. The demonstration city, Beijing, and its water sources. (a) Receiving and sending systems. SNWTP, South to North Water Transfer Project. Provinces are symbolized by the relative contribution to Beijing's virtual water; Tibet and Taiwan, in white, indicate no data (Zhang et al., 2011). (b) Water risk data extracted from the World Resources Institute's Aqueduct Water Risk Atlas (Gassert et al., 2013). The water risk index has five categories: low risk (0–1), low to medium risk (1–2), medium to high risk (2–3), high risk (3–4), and extremely high risk (4–5). (c) Mean water risk for the source region of each sending system in Beijing's water supply (PLDL, Paddy-Land to Dry-Land payment for ecosystem services scheme in the Miyun watershed). Areas used to extract risk values are shown in (a). Virtual water means were weighted by provincial contribution to Beijing based on Zhang et al. (2011).

economic and agricultural centres tend to be in the north (Zhang & Anadon, 2014). Because of this, interregional coordination and exchanges are important to Beijing and will continue to play a role going forward (Zhang et al., 2012).

Application of the telecoupling framework to Beijing's water supply

To demonstrate the efficacy of the telecoupling framework to urban water supply, we chose three types of water telecouplings in Beijing: (1) inter-basin water transfers; (2)
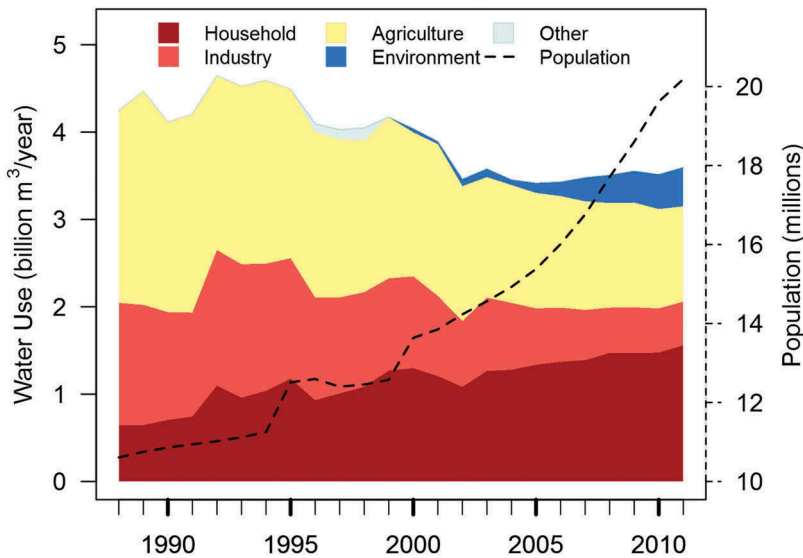
Figure 3. Physical water use by sector and population, 1988–2011. Total water use has declined to 3.5 billion m³ per year, largely due to decreased agricultural area and irrigation and industrial efficiencies. Household use, however, has steadily increased. Population is shown with the dashed black line and represents permanent resident population in the full municipality. Data are from the *Beijing Statistical Yearbook* (2012).

virtual water imports; and (3) PES to upstream regions in order to increase water supply quantity and quality. We then used the existing literature to identify and describe elements of the telecoupling framework in each telecoupling to facilitate synthesis and comparison across multiple linked systems. Further, we compared the volume of water contributed by each telecoupling with Beijing's water supply. The large scope and complexity of the telecoupling analysis required the use of multiple sources to obtain quantitative estimates. Although these sources likely use different methodologies and may not be always directly compatible, comparing the relative volumes can still be informative. Table 1 provides a summary of sources used for each component of our analysis. When specific numbers were not available in the literature but shown in the form of plots, we used WebPlotDigitizer v. 3.3 (Rohatgi, 2014) to extract numbers from plots (figures).

Inter-basin water transfers

Inter-basin water transfers tend to be engineered works of massive size and costs, indicative of the economic and political importance of the receiving systems (Gupta & Van der Zaag, 2008). While Beijing has several local water transfers from reservoirs in the adjacent Hebei province initiated during an extended drought in the early 2000s, these were relatively small scale, covering distances between 75 and 185 km and transferring on average 0.29 billon m³ of water per year between 2005 and 2011 (Figure 4) (Beijing Bureau of Statistics, 2012). For the telecoupling analysis in this paper, however, we focus on the larger inter-basin water transfer, the South-to-North Water Transfer Project (SNWTP).

Table 1. Summary of data sources and literature synthesized by analysis.

| Analysis	References
Inter-basin Water Transfer	Chen & Wenger, 2014
	Hubacek et al., 2009
	Liu et al. (in press)
	Li 2003
	Pittock et al., 2009
	Qian et al., 2002
	Yang et al., 2012
	Zheng & Han, 2012
Virtual Water	Dalin et al., 2014
	Huang et al., 2010
	Wang & Wang, 2009
	Wang et al., 2013
	Zhang & Anadon, 2014
	Zhang et al., 2011
	Zhang et al., 2012
Payments for Ecosystem Services (PES)	Liu & Yang, 2013
	Zheng et al., 2013
Beijing's local supply	Beijing Bureau of Statistics, 2012
Vulnerability assessment	Gassert et al., 2013
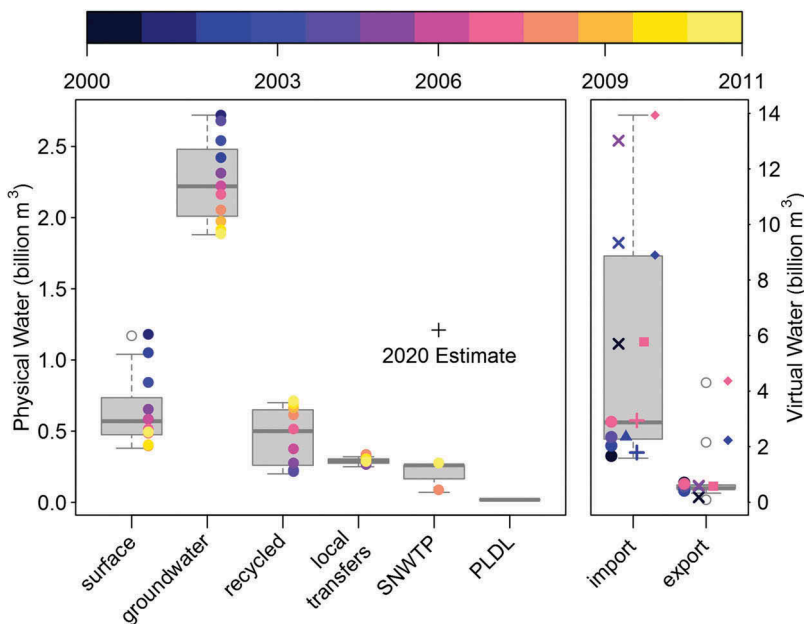
Figure 4. Relative contributions of physical and virtual water to Beijing's water budget from 2000 to 2011. (left) Data for annual surface water, groundwater, recycled water, local water transfers and current South to North Water Transfer Project (SNWTP) from the Beijing Bureau of Statistics (2012). SNWTP estimate for 2020 is from Hubacek et al. (2009); Paddy Land-to-Dry Land (PLDL) payment for ecosystem services programme is the annual amount gained between 2006 and 2010 (Zheng et al., 2013). (right) Mean estimated virtual water import between 2000 and 2007 is 2.874 billion m^3 compared with the mean local physical supply (surface water and groundwater) of 2.79 billion m^3 between 2001 and 2011. Virtual water literature sources are given by the following coloured symbols: (solid circle, Wang & Wang, 2009; ×, Huang et al., 2010; triangle, Zhang et al., 2011; Zhang et al., 2012; square, Zhang & Anadon, 2014; diamond, Wang et al., 2013).

The SNWTP is the largest inter-basin water transfer in the world to date. The full project includes three diversion routes that bring 44.8 billion m^3 of water (Chen & Wenger, 2014) from the Yangtze River watershed in southern China to water-stressed regions in the north at a projected cost of 486 billion yuan (Probe International Beijing Group, 2008). We summarized telecoupling components for the Middle Route, which began serving Beijing in December 2014 (Figure 2(a)). This route brings water from the Danjiangkou Reservoir on the Han River, a tributary of the Yangtze River, to Beijing, Tianjin and Hebei province, covering a distance of 1246 km (Chen & Wenger, 2014).

Virtual water imports

China's four largest cities, including Beijing, are all net virtual water importers and rely on these imports for over half of their water consumption (Zhang & Anadon, 2014). Virtual water is expected to play an increasing role in Beijing's water plans, even though there have been no explicit policies recognizing its contribution or planning its future role (Zhang et al., 2011). We apply the telecoupling framework to virtual water imported to Beijing in 2002 from within China using province specific data from Zhang et al. (2011). To assess the total volume of water that virtual water contributes to Beijing, we used additional literature sources that provide virtual water estimates for Beijing but do not identify source regions to an appropriate level of specificity (Table 1).

Payments for ecosystem services (PES)

PES are programmes that aim to compensate agents for opportunity costs resulting from land management decisions that increase ecosystem services but may not benefit the agents (Engel, Pagiola, & Wunder, 2008). In 2006, Beijing worked with Chengde and Zhangjiakou municipalities in Hebei province to implement the Paddy Land-to-Dry Land (PLDL) PES programme, which aims to improve water quality and quantity in the Miyun Reservoir by compensating upstream farmers in Hebei for lost revenue if they convert their fields from rice paddy to corn (Zheng et al., 2013). Although the Miyun Reservoir is located within Beijing, 80% of its source watershed lies in Hebei province to Beijing's north (Figure 2(a)). Ma et al. (2010) estimate that human land use and vegetation changes in its watershed caused 18% of the decreased flow into Miyun between 1956 and 2005; similarly, Wang, Xia, and Chen (2009) attributed 68% of the runoff decrease between two periods before and after 1980 to human activities. Moreover, nutrient loading from agriculture has polluted the reservoir, increasing the nitrogen concentration 430% between the 1978–88 and 2003–05 periods (Zheng et al., 2013).

Overall, growing dryland corn is less water intensive than flooded paddy rice fields. Replacing rice with corn, then, should decrease upstream water withdrawal and leave more water for downstream users in Beijing. Further, while corn is more nutrient intensive, it exports smaller nutrient quantities than flooded rice fields. Thus, the PLDL system was implemented to increase not just water quantity but also water quality, aiming to prevent Miyun from following Guangting Reservoir's fate. The telecoupling approach can help elucidate systemic social and environmental impacts, in addition to the typical economic accounting in PES evaluations (Liu & Yang, 2013).

Vulnerability assessment

Today's biosphere is characterized by ongoing global change. Water resources vary with both space and time, making it important to consider vulnerability introduced through supply variability. As noted above, Beijing lies in a water-stressed region. Here, we asked, 'Do Beijing's water telecouplings increase or decrease the city's water vulnerability through variation or uncertainty in water supply?' We use the term 'water risk' to encompass baseline water stress, quality and temporal variability. We evaluated this question by comparing the water risk in each source region and Beijing itself.

To find the overall water risk in each of the telecoupled systems examined, we extracted areal means from the World Resources Institute Aqueduct Water Risk Atlas Global Maps 2.0 dataset (Gassert, Landis, Luck, Reig, & Shiao, 2013) (Figure 2(b)). This dataset incorporates 12 indicators describing quantity (including temporal variability), quality and regulatory risk based on global data collection and modelling efforts. Contributing datasets include both point and time-series data; among datasets, the most recent data range from 2000 to 2012, and the earliest time-series begins in 1901. From these variables, Gassert et al. (2013) generate overall water risk scores for individual watersheds ranging from 0 to 5. This scale is categorized into five categories: low risk (0–1), low to medium risk (1–2), medium to high risk (2–3), high risk (3–4), and extremely high risk (4–5). These mean water-risk composite scores were then extracted for each region of interest. We used the municipality of Beijing to obtain the city's baseline water risk. To quantify the risk for the SNWTP and PLDL telecouplings, we used the Han River basin upstream of the source Danjiangkou Reservoir and the watershed of the Miyun Reservoir, respectively (Figure 2(a)). For inter-provincial virtual water, we used a weighted-sum approach where we scaled the areal mean of each source province by the proportional contribution of each region to Beijing through virtual water based on Zhang et al. (2011) (Figure 2(a)). Analyses were performed in R (R Core Team, 2014) using the 'rgdal' (Bivand, Keitt, & Rowlingson, 2014), 'raster' (Hijmans, 2014), and 'rgeos' (Bivand & Rundel, 2015) packages.

Results and discussion

Relative water contributions

The SNWTP is expected to contribute a substantial amount of water to Beijing's physical water supply by 2020. Of the total 13 billion m^3 projected yearly transfer for the middle route (Qian, Lin, Zhang, & Sun, 2002), 1.2 billion m^3 of water will go to Beijing by 2020 (Hubacek, Guan, Barrett, & Wiedmann, 2009). This is approximately 43% of Beijing's mean annual renewable water supply (surface water plus groundwater) of 2.79 billion m^3 between 2001 and 2011 (Figure 4) (*Beijing Statistical Yearbook* 2012). In contrast, the PLDL programme has made only a marginal contribution to Beijing's water supply. It increased water quantity flowing into Miyun Reservoir by only 18.2 million m^3 during the 2006–12 period (Zheng et al., 2013), or 0.65% of Beijing's mean annual renewable water supply (Figure 4).

Literature estimates for annual imported virtual water had a mean of 2.874 billion m^3 for years between 2002 and 2007. This volume far surpassed contributions of the SNWTP and PLDL and even exceeded Beijing's annual renewable water supply

(Figure 4). Estimates of virtual water volumes varied by publication and ranged from a low of 1.587 billion m^3 in 2000 (Wang & Wang, 2009) to 13.935 billion m^3 in 2007 (Wang, Huang, Yang, & Yu, 2013). Studies that examined multiple years found increases in virtual water import ranging from 14.5% to 63.9% between 1997 and 2002 (Huang, Song, & Chen, 2010; Wang & Wang, 2009; Zhang et al., 2012), and from 44.2% to 67.9% between 2002 and 2007 (Wang & Wang, 2009; Wang et al., 2013; Zhang et al., 2012). Analysis of Beijing's water footprint, the combined total of virtual water and local water use, found an increase from 4.342 to 5.748 billion m^3 between 1997 and 2007; over 98% of this increase was attributed to virtual water importation (Zhang et al., 2012). Figure 4 further details the range of virtual water estimates by year and study.

Methodological differences can greatly affect the magnitude of virtual water estimations. The most common method utilizes input–output analysis (Leontief, 1936), relying on economic input–output tables and transforming the exchange of goods into water equivalents, often by sector. The direct water-use coefficient (DWUC), or the amount of water necessary for one monetary unit of production, is used to translate monetary amounts into water volumes. Varied results can occur for several reasons. First, there are multiple approaches for determining the DWUC of goods. Estimating water needs over the full supply chain is difficult and place specific, depending on water-use efficiency of the production zone. For example, Zhang et al. (2011) and Wang and Wang (2009) both base DWUC on Beijing-based calculations and apply these numbers to all imported goods. In contrast, Zhang and Anadon (2014) calculate DWUC by source province. Second, studies that aim to perform a provincial-level analysis must compile their own input–output tables, or use previously generated tables (Zhang & Anadon, 2014), all of which can have methodological discrepancies. Because of this, however, analyses tend to concentrate on years in which these tables have been assembled, such as 2002 and 2007. Finally, estimates can vary based on the scope of water or goods considered, which is not always made explicit. For example, many studies focus on blue water, the surface and groundwater consumed, while others do not specify or may consider green water as well, the consumption of soil moisture in agricultural products. Due to the wide variation in estimates, we preserved literature source information in Figure 4 for transparency and comparison.

Vulnerability analysis

We found that the overall water risk within Beijing is 3.550 on the water-risk scale, indicative of a 'high water risk'. This is higher in magnitude than all water sources of the telecoupling processes examined (Figure 2(c)). The PES scheme within the Miyun Reservoir watershed had a marginally lower score of 3.464, still solidly within the 'high water risk' range. The weighted mean for virtual water sources, however, falls within the 'medium to high risk' category at 2.995, and the SNWTP's middle-route source in the Han River basin had the lowest risk value at 2.465.

Our analysis indicates that Beijing's telecoupled water sources do decrease the city's vulnerability by having lower water-risk scores than Beijing (2.465, 2.995 and 3.464 compared with Beijing's score of 3.550) similar to a 'portfolio effect' where diversifying water sources among multiple regions with lower risks reduces Beijing's overall risk.

Still, each source falls in the 'medium to high risk' range or higher, indicating that Beijing remains vulnerable to water shortages even with these telecoupled sources. Note, however, that full vulnerability analyses should examine not only just the stressors, as done here, but also the system's sensitivity and response (Turner et al., 2003). Further analyses could also expand upon our indicator of water risk or quantify the change in water-risk scores in each region as a result of water telecouplings with Beijing.

Telecoupling synthesis

Tables 2–4 summarize telecoupling components for the three water telecouplings examined. This common approach allows comparative evaluations of these different water importation strategies in large cities such as Beijing. For example, each telecoupling has different primary agents driving the water supply connection. The SNWTP is a massive, costly undertaking conceived and implemented through China's strong central government (Table 2). Here, the central government determined the water allocation along the three transfer routes, financed the project and coordinated this national-scale project. On the other hand, the PLDL PES programme was developed and implemented among the municipal governments of Beijing, Chengde and Zhangjiakou, reflecting its smaller scale (Table 4). In contrast to both these connections, which involved a strong role of central planners, agents in the virtual water supply are

Table 2. Telecoupling of Beijing and South China via the South-to-North Water Transfer Project (SNWTP). Systems are classified based on their primary role. Figure 2 provides additional geographical information.

	Sending system	Receiving system	Spillover systems
System description	Danjiangkou Reservoir on the Han River, a tributary to the Yangtze River	Beijing	Resettlement areas; pass-through ecosystems; agricultural systems near Beijing
Causes	Abundant water in southern China; industrial and agricultural centres in northern China which is more arid; water shortage in Beijing		Reservoir impoundment; aquifer construction; water diversion
Agents	Central and local governments of China; government organizations and companies inside and outside China; involved and affected individuals inside and outside China (Liu et al., in press)		
Flows	Water, building materials, money, pollutants, biotic organisms, people		
Effects (+)	Flood control, employment (Liu et al., in press)	Increase physical water supply by one-third; reduce water shortage, groundwater over-extraction, subsidence (Liu et al., in press; Yang et al., 2012)	Agricultural systems near Beijing may have more access to water once municipal and industrial needs are alleviated through the SNWTP
Effects (–)	Decreased flow, particularly in dry years when half the Han River's runoff will be diverted (Pittock et al., 2009); 330,000 displaced people due to reservoir expansion (Pittock et al., 2009)	Receive pollution from the source region, particularly high nutrient loads (Chen and Wenger, 2014; Zheng & Han, 2012; Liu et al., in press)	Resettlement areas for 330,000 displaced individuals (Pittock et al., 2009); 1200 km of pass-through ecological systems may experience eutrophication due to high nutrient loads in the Danjiangkou (Zheng & Han 2012; Liu et al., in press) and soil salinization (Li 2003)

Table 3. Telecoupling of Beijing and virtual water suppliers within China. Systems are classified based on their primary role. Figure 2 provides additional geographical information.

	Sending system	Receiving system	Spillover systems
System description	Twenty-two Chinese provinces, three municipalities and four autonomous regions; order of magnitude follows a gravity model, where the nearest provinces (i.e., Hebei) and economically developed provinces contribute the most (Figure 2) (Zhang et al., 2011)	Beijing	Atmospheric systems (carbon emissions from shipping); ports along the trade path may receive harmful invasive species spread by trade; opportunity for further research to define fully
Causes	Water shortage in Beijing, land use, globalization, diet and material preferences; explicit policy is not a cause at this point (Zhang et al., 2011)		Necessities of shipping goods
Agents	Businesses; individuals; local, regional and national governments		
Flows	Over half of Beijing's water footprint, excluding global virtual water imports, via food, material and money		Carbon emissions, species in trade
Effects (+)	Income and economic productivity	Reduces demand on local water resources, particularly when importing primary goods such as agriculture (Zhang et al., 2011); decreases vulnerability to water shortages by expanding portfolio of source regions	Positive benefits are likely but unknown
Effects (–)	Provinces near Beijing, such as Hebei, are also water scarce, further stressing their resources	Increasingly reliant on imports to meet food needs	Increased climate forcing; impacts via invasive species

much more diverse. Here, agents tend to be dispersed among businesses and individuals, and the connections are largely driven by market forces (Table 3).

The telecoupling analysis can also provide additional context to compare the relative benefits of water connections. For example, although the SNWTP will contribute far more water to Beijing's water budget (Figure 4), the PLDL PES programme is more cost-effective compared with large infrastructure projects like the SNWTP. Furthermore, the PLDL positively affects stakeholders in the sending system by providing return flows of adequate financial compensation (Zheng et al., 2013). The effects of the SNWTP are more negative, including the displacement 330,000 people due to reservoir expansion in the sending system (Table 2) (Pittock, Meng, Geiger, & Chapagain, 2009). The PLDL also improved water quality, a major issue in Beijing's water supply, by reducing both nitrogen and phosphorus loading to the Miyun Reservoir (Zheng et al., 2013). In contrast, the SNWTP is expected to convey pollutant flows such as high nutrient loads from the sending system (Chen & Wenger, 2014; Liu, Yang, & Li, in press; Zheng & Han, 2012) These additional benefits of the PLDL programme may encourage continued development of PES schemes despite the relatively small contribution to Beijing's water supply.

The SNWTP does have substantial benefits for Beijing. Estimated water transfer from the SNWTP in 2020 will import a significant amount of physical water to the city

Table 4. Telecoupling of Beijing and Hebei via the Paddy Land-to-Dry Land (PLDL) programme. Systems are classified based on their primary role. Figure 2 provides additional geographical information.

	Sending system	Receiving system	Spillover systems
System description	Hebei province	Beijing	Not yet identified; further research is warranted (Liu & Yang, 2013)
Causes	Decline in surface water flows to Miyun Reservoir, Beijing's primary surface water source; history of Guanting Reservoir, which became unusable for drinking water due to nutrient and pollutant loads		
Agents	Beijing, Chengde and Zhangjiakou municipalities in Hebei, farmers		
Flows	Money, water, nutrients		
Effects (+)	Financial compensation that adequately replaces opportunity costs of switching from paddy rice to corn; increased educational opportunities due to livelihood changes (Zheng et al., 2013)	Increased water quality and quantity (18.2 million m^3); extremely cost-effective with a benefit–cost ratio of 1.5 (Zheng et al., 2013)	
Effects (–)	Nutrient quantity applied increases with corn, but less is transported off fields. Full environmental impacts may need to be further assessed (Liu & Yang, 2013)	Full environmental impacts may need to be further assessed (Liu & Yang, 2013)	

(43.0% of the annual mean of surface and groundwater for 2001–11; Figure 4) that will directly supply municipal and industrial users and is expected to have positive spillover effects in agricultural areas by relieving pressure on current water resources (Table 2). We also found that the source region for the middle route has the lowest water risk among Beijing's sources (Figure 2(c)), an important factor in resource planning. Liu et al. (2015b) analyzed the probability of water demand exceeding supply in Beijing during 2015–30 and found the SNWTP lowered probabilities from 70–80% to 26–36%, further highlighting the role the SNWTP will play in meeting Beijing's water demand. In this case, it might be best to mitigate harmful effects on sending and spillover systems.

The telecoupling framework also allows side-by-side examination of physical and virtual water transfers, which often are studied separately. Placing them in the same framework may help analyze trade-offs and synergies between them. For instance, all three routes of the SNWTP combined are expected to deliver 43 billion m^3 of water to northern China. Virtual water, however, flows from water-limited northern China to southern China (Zhang & Anadon, 2014) and is estimated to be of larger magnitude (52 billion m^3) than total SNWTP flows (Ma, Hoekstra, Wang, Chapagain, & Wang, 2006). While this can seem counterintuitive, this trend is likely driven by crop productivity patterns (Dabrowski, Masekoameng, & Ashton, 2009; Ma et al., 2006), uneven economic development and the distribution of arable land suitable for large-scale agriculture (Dalin et al., 2014; Kumar & Singh, 2005; Zhang & Anadon, 2014). From this perspective, the SNWTP and virtual water trade allow China spatially to match water resources and crop production.

In contrast to static infrastructure investments such as the SNWTP, virtual water strategies have the benefit of being low cost, flexible and able to be scaled up or down in response to demand (Hoekstra & Chapagain, 2008; Pittock et al., 2009). Moreover, in Beijing, its evident virtual water contributes the most to the water supply budget despite the wide range in estimates (Figure 4). Beijing's reliance on virtual water is typical of many large cities, and highlights how large cities are often dependent on imports for food and other necessities (Varis, 2006). While this can have real physical water savings and is often hailed as a flexible alternative to physical transfers (Dalin et al., 2014; Hoekstra & Chapagain, 2008; Wang et al., 2013), it can also undermine food security. At national scales, it has been suggested that water-rich nations are likely to reduce or eliminate virtual water exports as their populations and dietary demands grow, leaving import-dependent nations unable to meet their needs (Suweis, Rinaldo, Maritan, & Odorico, 2013). Planning agencies seeking to utilize virtual water as a long-term sustainable solution to water scarcity should therefore use caution, as such virtual water use can allow populations to overshoot limits in local water resources (Kumar & Singh, 2005; Suweis et al., 2013). Given current land-use trajectories in Beijing, however, reliance on virtual water in primary sectors is likely to continue growing (Zhang & Anadon, 2014). Still, improvements in water-use efficiency at the national level in China are achievable via reorganization of flow in agricultural trade (Dalin et al., 2014), and given the strong role of the central government in China, these sub-national strategies may be more secure than international trade.

There are ample research opportunities for further investigation across all three telecouplings. For virtual water, increased geographic specificity for sources both within China and internationally would help identify impacts from Beijing's consumption of traded goods. It is likely that sending systems profit from the sale of goods, but they can also deplete their own water sources to do so. For example, the province of Hebei is the largest provincial contributor to Beijing, but is itself highly water stressed (Zhang et al., 2011). It would also improve risk assessment for Beijing's food security, since agricultural goods consume large quantities of water for production and importation is essential to meet Beijing's food needs as local agriculture declines (Figure 3). For the PLDL PES programme, the current literature does not document the spillover effects. Because the programme has induced socio-economic, livelihood and hydrologic changes, spillover effects are a research gap ripe for exploration (Liu & Yang, 2013). Impacts of the SNWTP on sending and spillover systems have already gained research attention but should continue to be studied and quantified as the full project is completed and begins full-scale operation.

Conclusions

Net flows of ecosystem services such as clean water into cities are increasing in both magnitude and distance travelled (Liu et al., in press), often at even higher rates than urban population growth due to increased living standards (Engel, Jokiel, Kraljevic, Geiger, & Smith, 2011; McGranahan et al., 2005). Many cities, particularly megacities, can no longer supply their full water needs within their jurisdiction or even river basin (Lundqvist, Tortajada, Varis, & Biswas, 2005). The use of distant water sources adds considerable complexity when evaluating the sustainability and impact of urban water

systems. For example, because cities occupy just 1% of the Earth's land surface but source water from 41%, land-use across large, disjunct areas can affect the quantity and quality of the water supply (McDonald et al., 2014). Similarly, cities are subject to changing hydrology due to climate change across wide areas. Further, the involvement of multiple jurisdictions involved in water planning can result in a complex hierarchy of agents and decision-making (Jenerette & Alstad, 2010), often requiring national intervention or oversight (McDonald et al., 2014). The impacts of urban water demand are also spread further and felt in both sending systems and spillover systems.

Sustainably managing urban water needs increasingly will require integrating spatially distant sources into urban water accounting. Doing so holistically to avoid outsourcing water stress beyond city borders necessitates a framework that can address ecological and socio-economic flows, causes and effects in distantly coupled systems. As demonstrated in our application to Beijing, telecoupling analyses result in the identification of many research gaps. Filling these gaps requires a large amount of data and knowledge about a range of systems in spatially distant places, but is necessary for a full-scale, in-depth analysis of the telecoupled urban water system. As distant connections and impacts increase due to human population growth and globalization, identifying and addressing these research gaps is vital to setting and achieving sustainability goals.

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