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Natural infrastructure in sustaining global urban freshwater ecosystem services

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Rapid urbanization throughout the globe increases demand for fresh water and the ecosystem services associated with it. This need is conventionally met through the construction of infrastructure. Natural infrastructure solutions have increased to provide freshwater ecosystem services, but little global research has examined the intricate relationships between built and natural infrastructure for providing freshwater ecosystem services to cities across the globe. Using network analysis, here we examine the interrelationships between built and natural infrastructure in 2,113 watersheds for 317 cities worldwide, focusing on four key freshwater ecosystem services: freshwater provision, sediment regulation, flood mitigation and hydropower production. Our results indicate that protected wetlands contribute to sustaining freshwater provision to cities. Forest cover in protected areas can improve the capacity of large dams in reducing sediment loads and producing hydropower, but cities mainly depend on reduced impervious surfaces and more green spaces within urban areas for flood mitigation. Improved understandings of the role of natural infrastructure in urban water networks must underpin strategic decision-making to sustainably provide freshwater ecosystem services to global cities.

Over the past few decades, rapid urbanization has been causing water-related problems for cities worldwide including water shortages, low water quality, floods and energy shortages. With increased urban population and income levels, built (or grey) infrastructure—that is, human-engineered constructs for water resources such as dams and treatment facilities[1]—has been routinely constructed to meet cities' increased freshwater demands[2–4]. Modifications of natural river systems through built infrastructure increase water security for residential users[5] but cause loss of freshwater biodiversity, poor water quality and habitat degradation[3,4,6,7]. Since the early twentieth century, almost 90% of watersheds providing water to cities have experienced a reduction in water quality, including increases in nitrogen and phosphorous due to anthropogenic activities (for example, changes in agricultural land use)[8]. This degraded water quality directly affects water for drinking and recreation in cities[7].

However, nature-based solutions have continuously provided freshwater ecosystem services (ES) to help meet the Convention on Biological Diversity Aichi targets and the United Nations Sustainable Development Goals (SDGs)[9–11]. Natural (or green) infrastructure is an application of nature-based solutions that uses a network of natural and semi-natural features to provide multiple benefits for both human and natural systems[1,11]. Since water originates from natural and semi-natural features, natural infrastructure for water is already in existence across cities and their source watersheds[11]. For example, increased watershed conservation activities (such as protected areas (PAs) and investments in watershed services (IWS)) in designated areas can act as a natural infrastructure to potentially reduce the negative effects of built infrastructure that degrade freshwater biodiversity, damage fisheries and displace local people[12–14]. For this research, a PA refers to a legally designated area actively managed by national or subnational institutions that has a spatial boundary informed by the World Database on Protected Areas[15]. IWS are broader conservation strategies to provide and enhance freshwater ES with incentive-based mechanisms between the beneficiary and the owners of the areas providing ecosystem services[9,16]. Water storage from forests and wetlands in PAs may increase the capability for freshwater provision, flood protection and hydropower production[10,14,17]. The capacity of watershed conservation areas under IWS can also help meet the increased freshwater demands of cities by maintaining high freshwater ES and biodiversity[9,18,19]. Additionally, in cities, increases in natural infrastructure such as urban green space and green roofs, by reducing impervious surface area, can provide benefits for freshwater provision and flood mitigation[11,20].

With rapid increases in PAs and IWS worldwide, the networks of watershed conservation areas that act as a natural infrastructure may complement built infrastructure by providing various freshwater ES to cities. The relationship warrants attention because maintaining the benefits of built infrastructure while conserving healthy freshwater ecosystems is a complex challenge[21,22]. These relationships between built infrastructure and natural infrastructure become more complicated as cities are increasingly reliant not only on surrounding watersheds but also on distant watersheds through built infrastructure construction (for example, dams and aqueducts)[8,23]. Although natural infrastructure for water is a sustainable and cost-effective alternative to conventional built infrastructure[12], natural infrastructure requires more space, and the capacity of natural infrastructure may not meet the increased freshwater ES demands in cities[24]. Yet, little is known about the global relationships between built infrastructure and natural infrastructure for providing freshwater ES to cities. Consequently, natural infrastructure is often neglected in water resource management and planning for cities[11].

To fill this important knowledge gap, we seek to answer two questions: (1) What are the relationships between built and natural infrastructure in terms of freshwater ES supplies for global cities? and (2) Which socioeconomic and environmental factors of source

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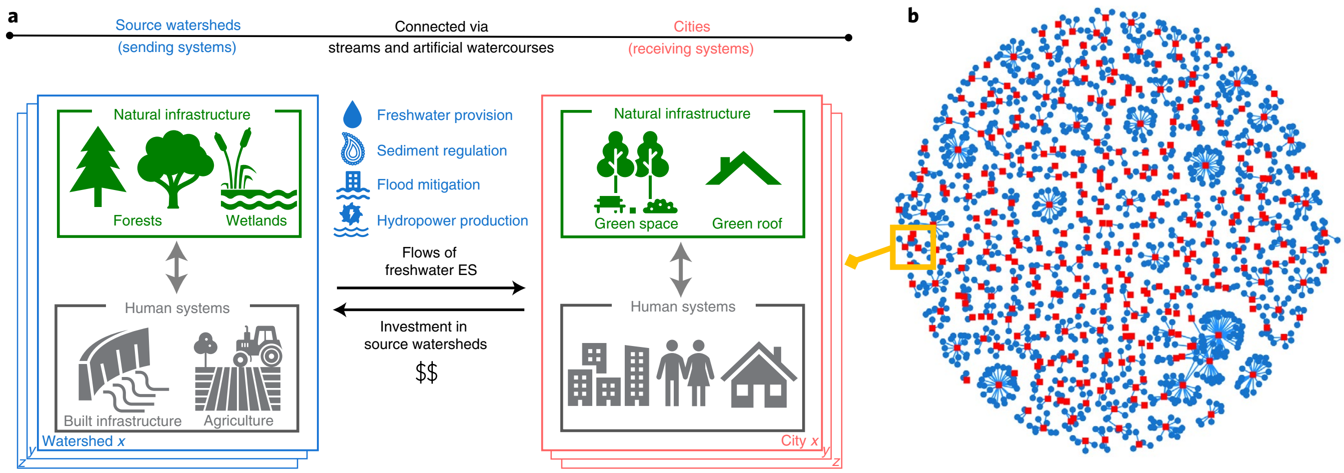

Fig. 1 | Conceptual framework of freshwater ES flows between cities and source watersheds. a, The flows of freshwater ES from source watersheds to cities. Both source watersheds and cities have interactions between natural infrastructure and human activities. Cities are connected with source watersheds and receive freshwater ES through streams and/or artificial watercourses. *x*, *y* and *z* indicate city *x*, *y* and *z*, and watershed *x*, *y* and *z* in an example of urban water supply networks. **b**, Water supply networks between cities (receiving systems of freshwater ES) and freshwater source watersheds (sending systems of freshwater ES). Red squares indicate cities and blue circles indicate freshwater source watersheds. The yellow box indicates an example of water supply networks between cities and source watersheds. Five icons (wetland, built infrastructure, agriculture, green space and green roof) are from The Noun Project (https://thenounproject.com).

watersheds and cities contribute to the changes in freshwater ES supplies to cities? Our working hypotheses related to these questions are (1) that existing natural infrastructure in many cases helps enhance freshwater ES flows to cities by improving the capacity of built infrastructure, and (2) that environmental and socioeconomic factors in cities and source watersheds modulate such benefits, acting differently across different cities and source watersheds. This study focuses on four freshwater ES—freshwater provision, sediment regulation, flood mitigation and hydropower production in source watersheds—that have exponentially increased to meet cities' water demands. We used data for freshwater provision[25], sediment regulation[26], flood mitigation[27] and hydropower production[28]. Our indicators for built infrastructure are dam density in source watersheds and fractional impervious surface in cities. Our measures of natural infrastructure solutions are watershed conservation activities that included PAs in source watersheds[15] and IWS programmes in cities[9].

On the basis of the framework of metacoupling (environmental and socioeconomic interactions within and across adjacent and distant systems)[29], we developed a conceptual framework of freshwater ES flows between source watersheds and cities to understand the relationship of natural infrastructure approaches with urban water supply networks (Fig. 1). The flows of freshwater ES from source watersheds (sending systems) to cities (receiving systems) form a water supply network as cities generally have more than one source watershed for freshwater ES supplies (Fig. 1). This conceptual framework combined with our multilevel analysis enables us to model effects at the level of the watershed and at the level of the city simultaneously. This allows us to identify at what level, and which components, are most strongly related to ecosystems services. The particular multilevel model we use here is an egocentric network model in which characteristics of the multiple watersheds linked to each city as well as their relationship to a city (for example, distance) are modelled at level 1 (sending systems) and characteristics of the city are modelled at level 2 (receiving systems). The set of variables available to us at sending and receiving systems allows us to examine how built and natural infrastructure in source watersheds can be integrated to enhance the provision of freshwater ES for global cities (317 cities and 2,113 watersheds worldwide) while controlling for the net of geographic factors, watershed characteristics and city characteristics. Additionally, the network analysis allows us to include diverse types of neighbouring and distant source watersheds together if these watersheds provide freshwater ES to cities through stream flows, aqueducts and/or interbasin transfers. Our study provides evidence to inform decision-making in pursuit of sustainable urban water management in a time of rapidly growing urban water demands.

Results

The role of natural infrastructure. The relationships between built infrastructure (dams) and conservation activities (forest cover and wetland cover in PAs) varied with types of freshwater ES (Table 1). Our results indicate that forest cover in PAs complemented dams for sediment reduction and hydropower production. Watersheds with high dam density had low sediment flows and flood risks while having high hydropower production. Dam density did not have a statistically significant association with freshwater provisioning to cities, but, in the alternative models that considered reservoir storage capacity instead of dam density, watersheds with large reservoir storage capacity had more freshwater provisioning to cities (Supplementary Table 1). Watershed conservation activities did not provide the same level of freshwater ES as built infrastructure. For instance, forests and wetlands in PAs of source watersheds did not have a statistically significant association with flood mitigation for cities.

Conservation activities had different links to the supplies of freshwater ES for cities than built infrastructure did. Forest cover in PAs of source watersheds had a negative association with the amount of sediment flux but was positively associated with hydropower production (Table 1). Protected forests in source watersheds help decrease sediment flows because forest cover reduces soil erosion due to tree root systems, high infiltration rates and low overland flows[1,30]. High evapotranspiration rates in protected forests can reduce overland runoff and therefore reduce sediment generation and transport[31,32]. Upstream protected forests may enhance the longevity of dams with the reduction of sediment flows to a reservoir[33]. Furthermore, protected forests can provide additional water sources for hydropower production by influencing stream flow via rainfall and soil moisture[17,34]. Our results also

Table 1 | Multilevel coefficients predicting four freshwater ecosystem services

	Variable	Water supply	Sediment flow	Flood risk	Hydropower
Watershed	Forest cover in PAs (%)	0.012 (0.027)	−0.109** (0.035)	0.022 (0.085)	0.206* (0.090)
(Level 1)	Wetland cover in PAs (%)	0.095* (0.045)	0.124* (0.058)	0.067 (0.111)	0.039 (0.172)
	Dam density (number per km of river length)	0.013 (0.042)	−0.149** (0.054)	−0.541 (0.288)	1.482** (0.353)
	Irrigation area (%)	−0.056 (0.030)	0.041 (0.037)	0.006 (0.046)	−0.072 (0.082)
	Watershed area (km^2)	0.161** (0.024)	0.312** (0.031)	−0.077 (0.062)	0.220 (0.119)
	Urban–watershed distance (km)	0.243** (0.055)	0.166* (0.070)	−0.038 (0.122)	0.550* (0.216)
	Elevation (m)	−0.132** (0.042)	−0.288** (0.052)	−0.153 (0.090)	−0.315** (0.108)
	Slope (°)	<0.001 (0.042)	0.203** (0.053)	−0.200** (0.065)	0.418** (0.125)
Urban	IWS programme (0, 1)	−0.633 (0.326)	0.219 (0.350)	−0.051 (0.342)	0.483 (0.390)
(Level 2)	Impervious surface (%)	−0.459* (0.214)	−0.290 (0.233)	0.708** (0.210)	0.181 (0.299)
	Urban population (1,000 persons)	0.281* (0.094)	0.219* (0.101)	−0.002 (0.086)	−0.027 (0.128)
	Urban GDP-PPP (2005 constant billion US$)	−0.196* (0.087)	−0.270** (0.094)	−0.010 (0.081)	−0.155 (0.124)
	Temperature (°C)	0.155 (0.248)	1.606** (0.268)	0.422* (0.209)	0.798* (0.329)
	Precipitation (mm)	0.868** (0.126)	0.010 (0.138)	0.151 (0.121)	−0.044 (0.180)
	Intercept	−3.126** (1.307)	−4.922** (1.433)	−0.382 (1.515)	−1.941 (2.241)
	Random effect				
	City (intercept)	1.538**	1.655**	0.506**	0.835**
	Residual	0.716**	1.201**	1.102**	2.051**
	N (watershed)	1,249	1,249	664	454
	N (city)	317	317	189	189

Standard errors in parentheses: **$P<0.01$, *$P<0.05$.

showed that watersheds with larger wetland cover in PAs had larger freshwater provisioning (Table 1). This implies that protected wetlands can help provide surface water to cities. Protected wetlands retain water in wetland soils and vegetation, and the water gradually flows into streams and rivers[35]. Thus, the extent of forests and wetlands in PAs increased freshwater ES to cities except for flood mitigation. In the alternative model that included forest and wetland cover in non-PAs as well as overall watersheds, forest cover in non-PAs and overall forests did not have a statistically significant effect on sediment reduction and hydropower production (Supplementary Tables 2 and 3). Wetlands in non-PAs and overall wetlands still had a positive relationship with the amount of freshwater provisioning to cities.

In cities, the presence of IWS programmes was not associated with any of four freshwater ES at the significance level of $P<0.05$, and only negatively associated with freshwater provisioning at the level of $P=0.053$. Many cities adopted IWS programmes while experiencing low freshwater provisioning, partly because of water resource conflicts with source watersheds[8,9,18,25]. The IWS approach in high water conflicted cities might be a useful tool for improving freshwater provisioning to cities, but further research is needed to establish more firmly the effects of IWS programmes.

Urban and watershed characteristics. Many urban and watershed characteristics were associated with the flows of freshwater ES. Cities with larger impervious surface had higher flood risks and lower freshwater provision from source watersheds (Table 1). Cities with large amounts of impervious surface generally have small green spaces for natural infrastructure[11]. This would be consistent with the explanation that a higher proportion of impervious surface leads to reduced evapotranspiration and soil infiltration and increased runoff peaks and total volumes with shorter lag times between the beginning of precipitation and peak flows[20,36]. Our results also showed that increased temperature tended to increase sediment load and flood risk for global cities (Table 1). For instance, high temperature may increase sediment flows from source watersheds because of the reduction of vegetation cover as well as the loss of ground aggregates[37]. Many studies also supported the result that a warmer climate may also increase flood risks worldwide[38]. If this cross-sectional relationship holds with temporal changes, climate changes could exacerbate these problems.

A larger city population size was positively associated with more freshwater provisioning and sediment flows, while urban gross domestic product based on purchasing power parity (GDP-PPP) was negatively associated with these two ES. Increased urban populations had a positive relationship with the amounts of freshwater provision and sediment loads from source watersheds. However, increased affluence in cities was negatively associated with both freshwater provision and sediment loads. Cities with low affluence may have to use low quality fresh water, partly because of the lack of water infrastructure and conservation activities in their source watersheds[2,9]. New PA designations in such cities' freshwater source watersheds may be crucial to reduce sediment flows because high sediment levels in source watersheds create additional costs for urban water treatment[8,30,33]. Such PA designations, however, need to consider other social, economic and political contexts to avoid potential conflicts with local communities[39–41].

Although our network analyses included geological characteristics (that is, watershed size, distance to cities, elevation and slope) largely to avoid spurious effects, the results indicate that these geological characteristics played an important role in freshwater ES supplies. Geological characteristics of watersheds also

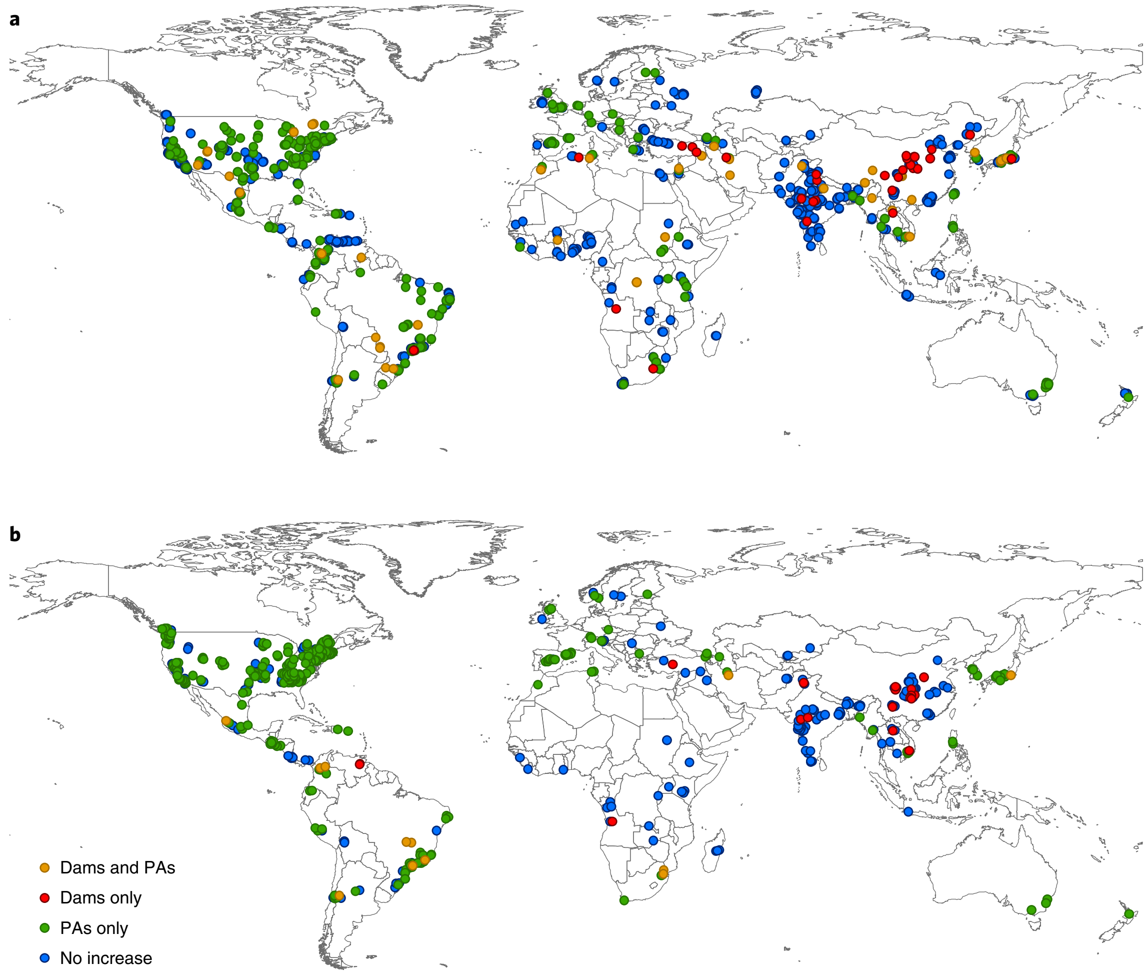

Fig. 2 | Spatial changes in the numbers of dams and sizes of PAs from 2000 to 2016. a,**b**, Changes in freshwater source watersheds (**a**) and hydropower watersheds (**b**). Orange indicates an increase in the number of dams and size of PAs, red indicates an increase in only dams, green indicates an increase in only PAs and blue indicates no increases in dam numbers or PA sizes in each watershed from 2000 to 2016.

contributed to the flows of freshwater ES to cities. Watersheds with larger areas and greater distances between watersheds and cities had a positive relationship with more freshwater provisioning, sediment flows and hydropower production. Watersheds at lower elevations provided less fresh water and fewer sediments. Steeper watersheds had larger sediment flows and hydropower production but lower flood risks.

Spatial priorities for natural infrastructure solutions. Our analyses can help target areas where natural infrastructure solutions might improve the flows of multiple freshwater ES to cities. Globally, there was uneven spatial distribution of new large dams and PAs at the watershed level from 2000 to 2016 (Fig. 2). We concentrated on freshwater source watersheds and hydropower watersheds, as both dams and PAs positively contributed to sediment reduction and hydropower production. From 2000 to 2016, new PAs were designated in 34.1% of freshwater source watersheds and 56.1% of hydropower watersheds without new large dam constructions. These watersheds were mainly located in North America and Europe (Fig. 2). In the same period, areas in 4.8% of freshwater source watersheds and 2.8% of hydropower watersheds not only received new PA designations but also underwent new large dam construction worldwide. However, in 2.9% of freshwater source watersheds and 3.8% of hydropower watersheds, of which approximately two-thirds were located in China and India, large dams were constructed without new PA designations (Fig. 2). China and India did not designate new PAs in 97.3% of freshwater source watersheds and in any hydropower watersheds over the period 2000 to 2016. In these two countries, 11.9% and 15.6% of freshwater source watersheds and hydropower watersheds, respectively, saw construction of large dams without any new PA designations.

Of course, PA designations are not the only type of natural infrastructure solution, and these alternative approaches could also act as a natural infrastructure in highly developed watersheds to sustain freshwater ES flows for cities. For example, in 2000, China implemented one of the world's largest forest conservation programmes—the Natural Forest Conservation Program—to conserve and restore forests[42]. The Natural Forest Conservation Program in China has significantly contributed to net increases in forest cover over the past two decades[43,44]. Since the Natural Forest Conservation Program bans and monitors illegal harvesting in natural forests[43], conservation and restoration of forests under this programme may provide additional freshwater ES to cities[45]. These watershed conservation activities can be expanded to other regions that experience rapid dam construction and high levels of human intervention without any watershed conservation efforts.

Discussion

Natural infrastructure strategies for freshwater ES flows. Our network approach and results pointed out that natural infrastructure in source watersheds has been widely integrated with urban water supply networks by supporting the flows of freshwater ES to global cities. The application of network analysis in freshwater ES flows helped examine dynamic interactions between source watersheds and cities as well as between natural infrastructure and human activities. The results show that PA designations in the source watersheds could add to sediment reduction and hydropower production of these dams while protected wetlands could enhance freshwater provision from source watersheds to cities. PAs in the source watersheds appear not to change the flood protection services for cities from built infrastructure because urban flood mitigation mainly depended on reduced impervious surface within cities that had more green spaces for urban natural infrastructure. It indicates that existing natural infrastructure for freshwater ES flows could support the global sustainable development agenda[46]. Integrating the two approaches can have co-benefits for multiple SDGs simultaneously[47], including freshwater sources (SDG 6, clean water and sanitation), hydropower production (SDG 7, affordable and clean energy), dams (SDG 9, industry, innovation of infrastructure), cities (SDG 11, sustainable cities and communities) and biodiversity (SDG 15, life on land)[11,46].

Our improved understanding of the role of natural infrastructure in urban water networks offers a basis to develop strategic approaches for adopting natural infrastructure solutions to cities, in response to rapid changes in global climate and urban population. The urban demand for freshwater ES has increased with rapidly growing cities worldwide[11,48], and global climate change is expected to threaten the supplies of freshwater ES (for example, flood mitigation and sediment regulation) by extreme events such as intense precipitation events, wildfire and flood[37,49,50]. To meet the increased water demand, many cities adopt a strategy that reallocates their water demand to upstream rural watersheds that provide substantial freshwater ES[8,51]. However, large-scale infrastructure projects in source watersheds are required for this strategy[48]. Emerging cities and countries have made or planned huge investments in costly built infrastructure for improving the supplies of freshwater ES[51,52]. This conventional strategy may not meet the increased demand for freshwater ES due to high costs but limited budgets while impairing freshwater biodiversity and natural habitats[3,4,6].

From a practical point of view, our integration of natural infrastructure into urban water supply networks is a step to sustainably improve the supplies of freshwater ES to cities. The results indicate that natural infrastructure such as protected forests and wetlands already plays an important role in sustaining freshwater ES flows to cities as well as enhancing the performance of existing built infrastructure. They suggest that radical changes in regulatory regimes would not be needed to promote natural infrastructure solutions for urban water sustainability that also have benefits by reducing the costs and negative impacts of built infrastructure. Armed with these findings, researchers and policymakers can establish science-based standards for sustaining freshwater ES flows on their management programmes and financing mechanisms. Since the spatial and temporal distributions of built and natural infrastructure are variable across different cities and watersheds (Fig. 2), each city or country will need to explore the optimal combination of built and natural infrastructure that sustainably provides freshwater ES flows to meet the urban demand[11]. Implementing natural infrastructure solutions requires examining causal relationships between freshwater ES supplies in source watersheds and their uses in cities, identifying how much natural infrastructure is needed to sustain freshwater ES flows during the most vulnerable seasons (for example, flooding, wildfire and drought seasons), and managing possible stakeholder conflicts between source watersheds and cities (for example, farmer–urban resident conflicts). The shift to nature-based solutions can make progress towards urban water sustainability under global environmental challenges.

Methods

City and watershed selection. We first selected cities across the globe that depend on surface water sources for more than 50% of their water using the City Water Map database[2]. For this study, we excluded cities and source watersheds that mainly extract water sources from groundwater, alluvial aquifers and/or oceans. The City Water Map also covers diverse types of water transfer such as interbasin transfers and aqueducts for cities. See ref. [2] for a more detailed explanation of data collection. Each selected city had an average population of over 300,000 people from 2000 to 2010 according to the World Urbanization Prospects data (Supplementary Table 4). For cities' urban extents, we used the Global Administrative Database that defines urban administrative areas. For cities not defined in the Global Administrative Database, we used the global urban extent map from Schneider et al.[53] based on Moderate Resolution Imaging Spectroradiometer (MODIS) satellite data. In the USA, the Cartographic Boundary File for urban areas was used to define urban extents (Supplementary Table 4).

For each city, we identified three types of source watershed: (1) freshwater source watersheds (freshwater provision and sediment regulation), (2) flood watersheds and (3) hydropower watersheds (Supplementary Fig. 1). As freshwater ES are produced in source watersheds and provide benefits to cities, source watersheds are directly and indirectly connected to cities through the flows of freshwater ES (Fig. 1). Source watersheds, river networks and flow directions were designated following the United States Geological Survey HydroSheds database at 30 arcsecond (~1 km or 0.0083° at the Equator) resolution[54].

Freshwater source watersheds provide surface water to cities. Cities depend on not only the surrounding watersheds but also distant watersheds for freshwater resources[8,23]. Surface water in freshwater source watersheds is transferred from water intake points to the city. Freshwater source watersheds and surface water intake points were obtained from the City Water Map database[2]. Freshwater source watersheds are also watersheds with sediment flows affecting freshwater quality in cities. Although the City Water Map is the best available global dataset to identify water transfers from source watersheds to cities, we note that the City Water Map covers the water sources for the principal water utility of the largest municipality in an urban area, and thus the service boundaries of the water supply areas of a utility may not always be matched with the global urban extent map and the Global Administrative Database boundaries.

Flood watersheds were delineated by the upstream watersheds of each city's urban extent. Flood watersheds have a higher elevation than cities at 30 arcsecond resolution can overlap with urban extent areas, and increase or reduce the flood risks of cities by directly draining surface water to the urban extent area. On the basis of previous research from ref. [10], we used levels 7 and 8 of the HydroBASINS[54] to select a consistent size of flood watersheds across the world.

To select hydropower watersheds, we first identified operational hydropower dams (>1 MW capacity) using the Global Power Plant Database[28]. We defined hydropower watersheds that generate and provide electricity from hydropower dams to cities and are connected with cities through high voltage power lines within 100 km from the urban extent. High-voltage power lines' linkages to the cities were obtained from OpenStreetMap (https://www.openstreetmap.org). We chose a 100 km threshold for hydropower dams providing electricity to a city. Since different countries have different territorial sizes, including different length and width of the country, which may be less than a few hundreds of kilometres, we selected 100 km as a conservative range for electricity distributions to cities. We also note that the electricity from many hydropower dams is widely distributed across provinces and countries. The role of natural infrastructure can be more significant for distant hydropower dams from cities, as many PAs are spatially further from the city[55]. Thus, our analyses may underestimate the role of natural infrastructure in hydropower production for cities. Levels 7 and 8 of the HydroBASINS[54] were used to select a consistent size of hydropower watersheds across the world.

To explore freshwater provision and sediment regulation, we selected 317 cities and 1,156 freshwater source watersheds. We also analysed a total of 637 flood watersheds across 189 cities for flood mitigation. Finally, we selected 189 cities and 454 hydropower watersheds for hydropower production (Supplementary Fig. 1).

Freshwater ecosystem services. We examined four freshwater ES that are closely linked with cities' water-related demands: freshwater provision[25], sediment regulation[26], flood mitigation[27] and hydropower production[28,52] (Supplementary Table 4). These four ES have flows from source watersheds to cities and are divided into provisioning and regulating ES. Provisioning ES include freshwater provision and hydropower production. Regulating ES are comprised of sediment regulation and flood mitigation. We used global modelling data for freshwater ES, except for hydropower production. These datasets utilized local and regional observational data to produce their output data. The resulting datasets have been widely used in peer-reviewed papers in high-impact journals[3,4,25,56,57].

Freshwater provision. In this study, freshwater provisioning that supplies cities refers to the annual average volumes of surface water flowing through a river channel. Surface water is extracted at water intake points and transferred to cities[2]. Freshwater provision data for 2001–2010 were obtained from phase 2 of the Inter-Sectoral Impact Model Intercomparison Project (http://www.isimip.org), which provides the daily outputs from five global hydrological models: H08[58], LPJmL[59], MATSIRO[60], PCR-GLOBWB[61] and Water Gap[62]. We used 15 model simulations—five global hydrological models driven by three historical climate-forcing datasets (PGFv2[63], GSWP3[64], and WFDEI[65])—to quantify the volumes of surface water supplies from source watersheds to cities. We extracted the annual-averaged values from each of the 15 simulations at the water intake locations and calculated median values for the 15 model combinations in each source watershed. We used multimodel simulations instead of results from a single model to account for uncertainties arising from both the models and input data. Such a multimodel ensemble approach is commonly used in hydrological modelling and water resource assessment[25].

The global hydrological models simulate water resource availability by accounting for a majority of natural surface and subsurface hydrologic processes (for example, evapotranspiration, surface and subsurface runoff, and upstream discharge) at 0.5° (~50 km) grid cells globally. Water management activities are also represented by accounting for various sectoral water demands including those for agriculture (irrigation and livestock), industry (manufacturing and thermal energy) and public (domestic use) sectors under time-varying socioeconomic conditions (for example, population, GDP and land-use)[25]. However, the level of process representation varies across models. For example, some models account for groundwater flow and minimum environmental flow requirements, represented as minimum flow to be maintained in river channels; others do not include such capabilities[25]. Because some of the models do not account for water withdrawn from deep groundwater in source watersheds, they might underestimate the supplies of freshwater to cities.

Sediment regulation. We obtained results from a global suspended sediment flux model based on the WBMsed global hydrology model to represent the surface water quality of cities' freshwater provisioning[26]. Cohen et al.[26] provided the amounts of suspended sediment flux in a 6 arcminute (~12 km or 0.1°) grid cell. We extracted the amounts of annual-averaged suspended sediments in water intake points for cities from 2000 to 2010. We concentrated on surface water sources, not groundwater, because built infrastructure and watershed conservation activities mainly contribute to changes in surface water quality (for example, sediment flux and phosphorous pollution)[8]. Although suspended sediments are crucial to sustain freshwater ecosystems in downstream areas (for example, creating natural habitats)[30], suspended sediments deteriorate water quality and therefore create additional costs for urban water treatment[8,33].

Flood mitigation. We used global flood hazard maps with return periods of 100 years to identify the probability of river flood magnitudes over an urban area[27]. Dottori et al.[27] used a two-dimensional hydrodynamic model to perform flood inundation simulations based on the hydrological information from the Global Flood Awareness System. This simulation model articulated water flow processes in floodplains and explained the geometry of the river channels. These flood hazard maps show flood extents and depths in a 30 arcsecond (~1 km) grid cell based on hydrological information from the Global Flood Awareness System[27]. On the basis of this model, we calculated the proportion of flood extent areas to total urban extent areas in each flood watershed, and then we predicted this proportion as a function of characteristics of the watersheds and cities. See ref. 27 for more information on the hydrodynamic model for flood hazard maps.

Hydropower production. The Global Power Plant Database provides the geolocation of operational hydropower dams above 1 MW capacity[28]. This database covers approximately 89% of global installed capacity in the hydropower sector[28]. This dataset provides point hydropower locations, and we aggregated the installed capacity of the hydropower dams in each hydropower watershed.

Source watershed and city characteristics. To examine which characteristics contribute to four freshwater ES flows from source watersheds to cities, we collected data regarding dams, watershed conservation activities (natural infrastructure solutions), environmental factors and socioeconomic factors in source watersheds and cities. These data were obtained from international organizations, online databases and peer-reviewed papers (Supplementary Table 4). Our indicators are dam density in source watersheds and fractional impervious surface in cities as a measure of built infrastructure, and natural infrastructure solutions included PAs in source watersheds[15] and IWS programmes in cities[9]. Since many PAs are located in areas distant from the cities[55], we also used three alternative models. The first alternative model included forest and wetland covers in non-PAs instead of those in PAs (Supplementary Table 2). The second alternative model included wetland and forest covers in both PAs and non-PAs (Supplementary Table 3). The third alternative model included the amounts of reservoir storage capacity instead of dam density (Supplementary Table 1).

For each of the three different types of source watershed (freshwater source, flood and hydropower), we obtained information on forest and wetland cover in PAs and non-PAs, dam density and reservoir storage capacity, irrigation areas and geographic characteristics of the watersheds. The spatial boundaries and characteristics of PAs were obtained from the World Database on Protected Areas[15]. We excluded PAs that did not have a spatial boundary informed by the World Database on Protected Areas[15]. We selected terrestrial PAs that are legally designated and actively managed at the national or subnational level. We also included all PAs that were assigned, not reported, or not assigned to the International Union for Conservation of Nature management category because many countries do not consistently apply or use the International Union for Conservation of Nature management category[66]. Since many PAs spatially overlap each other, we dissolved PA boundaries to avoid double counting problems. Then, we intersected a single PA polygon with each watershed's boundary using ArcGIS 10.3.1[67].

Forest cover data were obtained from global land cover data that provide the percentage of forest cover with 1 km resolution (Supplementary Table 4). Wetland cover data were collected from the Global Lakes and Wetlands database, which provides global wetland extents at 30 arcsecond (~1 km) resolution (Supplementary Table 4). Then, in each watershed, we calculated the proportion of forest and wetland cover in PAs and non-PAs to total watershed areas, respectively.

The attributes of dams were obtained from the Global Reservoir and Dam database (Supplementary Table 4). This database includes the name, spatial location, construction year and various characteristics of dams that are higher than 15 m and have a reservoir larger than 0.1 km^3. To estimate river length, river network data were obtained from the HydroSHEDS at 30 arcsecond (~1 km) resolution[54]. With dam numbers and river lengths, we calculated dam density (dams per 100 km of river length) in each watershed. The total amount of reservoir storage capacity (m^3) was also calculated in each watershed. We included irrigated croplands from the Global Food Security-Support Analysis Data with 1 km resolution (Supplementary Table 4). Using the size of irrigated croplands, we calculated the proportion of irrigation areas to total watershed areas. Additionally, we obtained the proportion of impervious surface in cities from the Global Man-made Impervious Surface dataset at 30 m resolution (Supplementary Table 4). In general, cities with a larger proportion of man-made impervious surface tend to have smaller green spaces that can act as a natural infrastructure for freshwater ES.

Geological characteristics of watersheds included the size of each watershed, geographic distances between cities and watersheds, elevation and slope. We calculated the size of watersheds and geographic distances between the centroids of cities and source watersheds using ArcGIS[67]. Elevation and slope data in river networks were gathered from Domisch et al.[68] at 1 km resolution.

Cities' characteristics consisted of the presence of IWS programmes, population size, the size of the urban economy and climatic factors. IWS programme data were collected from Romulo et al.[9] and Bennett and Ruef[69]. IWS, a kind of payments for ES, are broader conservation strategies to provide and enhance freshwater ES with incentive-based mechanisms between the beneficiary and provider of watershed services[9,16]. We included IWS programmes that provided freshwater resources to a city in the City Water Map database and had a specific goal for drinking water protection[9,69].

Average annual population size from 2000 to 2010 was obtained from the World Urbanization Prospects report (Supplementary Table 4). Spatially explicit GDP-PPP data in 2010 were obtained from the global dataset of gridded GDP-PPP and population scenarios at 0.5° (~50 km) resolution (Supplementary Table 4). Climatic factors (annual mean temperature and annual precipitation) came from the WorldClim database at 1 km resolution (Supplementary Table 4). Since our dataset included spatially explicit data, we extracted variables at the watershed or city level by using zonal statistics in R 4.0.3[70].

Egocentric network analysis. We used multilevel models applied to egocentric network analysis to estimate the contribution of each independent variable to freshwater ES flows from source watersheds to cities[71]. On the basis of the flows of freshwater ES, egocentric network analysis allows for the inclusion of variables in both cities and diverse types of source watershed if these watersheds provide freshwater ES to cities via built and natural infrastructure. Thus, this egocentric network analysis enables to estimate relationships at different levels of analysis—the watershed, the city and the relationship between the watershed and the city (Fig. 1). Because cities usually have more than one source watershed, they form an egocentric network: ego is the city (receiving system of freshwater ES), and alters are the source watersheds (sending systems of freshwater ES). Each tie and source watershed at the end of that tie is nested in each urban water network and the city to which that network belongs (Fig. 1). Cities form an egocentric network by environmentally and socioeconomically interacting with source watersheds that supply freshwater ES to cities.

The level 1 model includes the effects of the characteristics of watershed (i) and tie (i, j), and the level 2 model includes the effects of the characteristics of city (j). At level 1, we modelled changes in freshwater ES flows as a function of forest cover in PAs (or non-PAs and both), wetland cover in PAs (or non-PAs and both), dam density (or reservoir storage capacity), irrigation area, watershed areas, distance from city to watershed, elevation and slope. These represent key factors of source watersheds. To estimate the effects of individual cities (j) on freshwater ES flows, the level 1 model's coefficients linking changes in flows to characteristics, β_{0j}, are used as an outcome in the level 2 model. At level 2, we modelled the intercept in the level 1 model as a function of the IWS programme's presence, urban population size, urban GDP, temperature and precipitation. These represent key factors of cities. The multilevel model for the flows of freshwater ES between alter (i) and ego (j) is as follows:

Level 1 (watershed and tie):

$$\text{Freshwater ES}_{ij} = \beta_{0j} + \beta_1 \text{forest cover in PA}_i + \beta_2 \text{wetland cover in PA}_i + \beta_3 \text{dam density}_i + \beta_4 \text{irrigation area}_i + \beta_5 \text{size of watersheds}_i + \beta_6 \text{distance from urban area}_{ij} + \beta_7 \text{elevation}_i + \beta_8 \text{slope}_i + e_i$$

Level 2 (city):

$$\beta_{0j} = \gamma_{00} + \gamma_{01} \text{IWS programme}_j + \gamma_{02} \text{urban population}_j + \gamma_{03} \text{urban GDP}_j + \gamma_{04} \text{temperature}_j + \gamma_{05} \text{precipitation}_j + u_{0j}$$

For example, γ_{01} represents the effect of the presence of the IWS programme. The errors at level 1, e_i, are assumed to follow a normal distribution $(0, \sigma^2)$, and the level 2 errors, u_{0j}, are assumed to follow a normal distribution $(0, \tau_{00})$. Four freshwater ES flows were in physical units (for example, MW), but independent variables were a mix of different physical units (for example, km and US$) and percentages. To resolve this issue, we carried out natural log transformations on all dependent and independent variables. In this log–log form, the unstandardized coefficients can be interpreted as an elasticity. The multiplicative form also helps reduce potential problems of nonlinearity and non-normality, and results in a functional form typical of commonly used production functions in economics and other disciplines. We estimated multilevel models in R using the restricted maximum likelihood method[72]. We also measured variance inflation factors to check the multicollinearity of our multilevel models. Our variance inflation factor results showed that independent variables of multilevel models had no serious multicollinearity problems (Supplementary Table 5).

Our study has several limitations. We note that without panel data to capture changes in the systems we study, our multilevel models establish associations, net of other variables, but any causal interpretation would be dependent on knowing that causality flows in only one direction, from independent variables to dependent variables. While such causal assumptions may be plausible, stronger assertions of causality must await more extensive data. We also note that the interrelationships we observe may be altered with seasonal changes of freshwater ES supplies and changes in how dams are operated and in the nature of conservation activities over time. In addition, we could not identify the role of intermediate landscape between cities' water intake points and PAs within the same watershed. If unsustainable agriculture and/or withdrawals occur in the intermediate landscape, the benefits of PAs may not reach the intake points.

Reporting Summary. Further information on research design is available in the Nature Research Reporting Summary linked to this article.

Data availability

All data analysed during the current study are available from the corresponding author on reasonable request. Data that support the findings of this study are available within the paper and its Supplementary Information.

Code availability

Codes to perform our network models can be found at https://github.com/mingonchung/urbanfreshwaterES.

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Author contributions

M.G.C., K.A.F., Y.P. and J.L. designed the research. M.G.C. and Y.P. contributed the data. M.G.C., K.A.F., T.D., Y.P. and J.L. analysed the model and drafted the manuscript. M.G.C. and J.L. interpreted the results. M.G.C., K.A.F., T.D., Y.P. and J.L. conceived of the study and revised the manuscript. All authors reviewed the manuscript.

Competing interests

The authors declare no competing interests.

Additional information

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Study description

Worldwide rapid urbanization demands more freshwater. This need is conventionally met through the construction of infrastructure. Watershed conservation activities have also increased to provide freshwater ecosystem services, but little research has examined the intricate relationships between built infrastructure and watershed conservation activities for providing freshwater ecosystem services to global cities. By using network analysis, this study examines the interrelationships between built infrastructure and conservation activities in 2,193 watersheds for 333 cities worldwide in terms of four key freshwater ecosystem services (i.e., freshwater provision, sediment regulation, flood mitigation, and hydropower production). Our results indicate that wetlands in protected areas contribute to sustaining freshwater provision to cities. Forest cover in protected areas can improve the capacity of large dams for sediment reduction and hydropower production, but cities mainly depend on dams for flood mitigation. Our findings lay a fundamental basis for developing strategic approaches to integrate built infrastructure and watershed conservation activities for urban water sustainability while reducing the negative impacts of built infrastructure.

Research sample

We examined the interrelationships between built infrastructure and conservation activities in 2,193 watersheds for 333 cities in 2000s worldwide. We first identified global cities that mainly depend on surface water sources from the City Water Map database (Ref 2). For each city, we identified three types of source watersheds: (1) freshwater source watersheds (freshwater provision and sediment regulation), (2) flood watersheds, and (3) hydropower watersheds. As freshwater ecosystem services are produced in source watersheds and provide benefits to cities, source watersheds are directly and indirectly connected to cities through the flows of freshwater ecosystem services.

Sampling strategy

Built infrastructure and watershed conservation activities have a variety of impacts on natural ecosystems and ecosystem services. We examined four freshwater ecosystem services that are closely linked with cities' water-related demands: freshwater provision, sediment regulation, flood mitigation, and hydropower production. These four ecosystem services have flows from source watersheds to cities. We first identified global cities that mainly depend on surface water sources from the City Water Map database (Ref 2). For each city, we identified three types of source watersheds: (1) freshwater source watersheds (freshwater provision and sediment regulation), (2) flood watersheds, and (3) hydropower watersheds. Source watersheds were designated following the United States Geological Survey (USGS) HydroSheds database (Ref 47).

Data collection

All the data used for this study were downloaded from international organizations, online databases, and peer-reviewed papers.

Timing and spatial scale

This study included 333 cities and 2,193 watersheds in 2000s worldwide.

Data exclusions

All data are included.

Reproducibility

We have provided data source information to ensure reproducibility.

Randomization

By using network analysis, we examined how built infrastructure, protected areas, and investments in watershed services in source watersheds influence the provision of freshwater ES for global cities (333 cities and 2,193 watersheds worldwide) while controlling for the net of geographical factors, watershed characteristics, and city characteristics.

Blinding

No blinding.

Did the study involve field work? ☐ Yes ☒ No

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