Urban growth, climate change, and freshwater availability

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Nearly 3 billion additional urban dwellers are forecasted by 2050, an unprecedented wave of urban growth. While cities struggle to provide water to these new residents, they will also face equally unprecedented hydrologic changes due to global climate change. Here we use a detailed hydrologic model, demographic projections, and climate change scenarios to estimate per-capita water availability for major cities in the developing world, where urban growth is the fastest. We estimate the amount of water physically available near cities and do not account for problems with adequate water delivery or quality. Modeled results show that currently 150 million people live in cities with perennial water shortage, defined as having less than 100 L per person per day of sustainable surface and groundwater flow within their urban extent. By 2050, demographic growth will increase this figure to almost 1 billion people. Climate change will cause water shortage for an additional 100 million urbanites. Freshwater ecosystems in river basins with large populations of urbanites with insufficient water will likely experience flows insufficient to maintain ecological process. Freshwater fish populations will likely be impacted, an issue of special importance in regions such as India's Western Ghats, where there is both rapid urbanization and high levels of fish endemism. Cities in certain regions will struggle to find enough water for the needs of their residents and will need significant investment if they are to secure adequate water supplies and safeguard functioning freshwater ecosystems for future generations.

general circulation model | global warming | Intergovernmental Panel on Climate Change | Global Rural–Urban Mapping Program

In the next 40 y, the number of urban dwellers in the developing world is forecast to grow by nearly 3 billion (1). While this urban demographic transformation is unfolding, climate change is expected to affect the global hydrologic cycle. Anthropogenic emissions of greenhouse gases will likely raise average global temperatures, with temperature changes expected to be greater near the poles than the equator. Climate change will also likely alter precipitation patterns, with some areas becoming wetter and others becoming drier (2). For some regions, climate and demographic trends will present a fundamental challenge: how will water be provided on a sustainable basis for all those new urbanites?

Freshwater provision to urban residents has three components: water availability (is there enough water nearby?), water quality (how much treatment is needed before it is clean enough to use?), and delivery (are systems in place to bring water to users?) (3). This article examines only the water availability component, recognizing that for many cities challenges of water quality and delivery are paramount. Throughout this article, "water availability" and "water shortage" refer solely to the amount of water physically available, not accounting for issues of water quality and delivery. In a sense, our estimates of water shortage are conservative: we assume cities can use all nearby water and map where problems of water shortage are likely to remain.

This article models how population growth and climate change will affect water availability for all cities in developing countries with >100,000 people. These cities had 1.2 billion residents in 2000, 60% of the urban population of developing countries and, according to our demographic projections, will account for 74% of all urban growth globally from 2005 to 2050 (1). We describe the magnitude and general patterns of the global challenge of water availability for urban residents, recognizing that such a global approach cannot account for each city's particular circumstances.

We used data on population distribution (30 arc-second resolution) from the Global Rural–Urban Mapping Project (GRUMP) (4), as well as demographic forecasts for our study cities (5). Two demographic scenarios are explored: the "Basic Demographic" scenario, which predicts a city's population growth according to its size and national-level urban fertility and mortality trends; and the "Ecological Factors" scenario, which in addition allows cities in specific biomes (e.g., arid regions) to have different rates of population growth, all else being equal. Hydrologic data (6-min resolution) on monthly sustainable surface and groundwater flows are taken from the Water Balance Model (6–10). Four scenarios of climate and land use change, driven by consistent scenarios of global economic development, are based on the Millennium Ecosystem Assessment (11) scenarios as implemented by Fekete et al. (12): Adaptive Management; Global Orchestration; Order from Strength; and Technogarden.

We first calculate whether a city has sufficient sustainable surface or groundwater within the urban extent delineated by GRUMP. The GRUMP urban extents used to spatially delineate a city are relatively large and include many suburban and exurban locations surrounding a given city center. Water shortage is defined as 100 L per person per day, a rough measure of the amount an urban resident needs to live comfortably long-term, including water for drinking, bathing, cleaning, and sanitation including flush toilets (13–16). If an urban area does not meet this minimum standard, nearby areas are evaluated using a series of buffers (Fig. S1), out to 100-km distance. The underlying assumption is that cities with a water shortage within the 100-km buffer will have to obtain water by other means, such as long-distance transport, extracting groundwater faster than aquifer recharge, or desalinization.

Results

In 2000, 150 million people lived in cities with perennial water shortage (i.e., annual water availability <100 L per person per

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day) within their urban extent. Many more people—886 million—lived in cities with seasonal water shortage (i.e., monthly water availability <100 L per person per day), with insufficient flows occurring in at least 1 mo of the year. If water in buffer zones adjacent to an urban extent is considered available to the extent's residents, fewer urban dwellers are under perennial or seasonal water shortage. For instance, a 100-km buffer reduces the number of urban dwellers facing perennial or seasonal shortage to 24 million and 312 million, respectively.

Population growth will greatly increase the number of urban dwellers who live with water shortage (Fig. 1). In 2050, we forecast that 993 million people will live in cities with perennial water shortage within their urban extent. At the 100-km buffer distance, this number would fall to 145 million. In 2050, similarly, 3.1 billion urban residents would confront seasonal water shortage within their urban extent, or 1.3 billion at the 100-km buffer distance. There is little difference between our two demographic scenarios (indicated by the lines on the bars in Fig. 1), with numbers for perennial and seasonal water shortage in the Basic Demographic scenario being approximately 3.3% and 0.7% less, respectively, than those in the Ecological Factors scenario.

Climate and land use change (hereafter referred to simply as "climate change") will further increase the number of urban dwellers facing water shortage (Fig. 1). In some cities, water availability will decrease owing to climate change, whereas other cities will see increases, with more cities having less water than having increased flows. Averaging across all climate change scenarios, ≈100 million more urbanites will live under perennial shortage under climate change conditions than under current climate. At the 100-km buffer difference, the equivalent figure is 22 million. Climate change does not greatly change the aggregate number of urban residents facing seasonal shortage, although the effect for particular cities may be large. Our hydrologic model does not fully account for water storage through glaciers and snowpack, an important source of water for many cities (17–19),

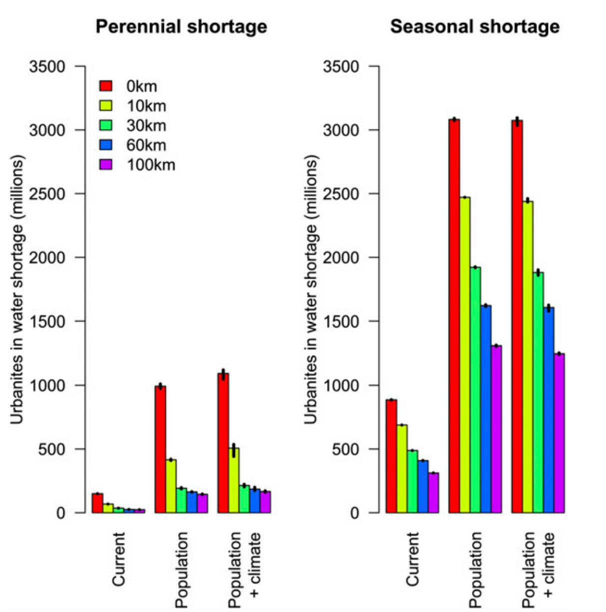

Fig. 1. Number of people living in cities with either perennial or seasonal water shortage (<100 L per person per day). Shortage numbers are shown for current conditions (*ca.* 2000), with projected population growth (2050), and with both population growth and climate change (2050). Errors bars are the range across various scenarios of population growth and climate change. Shortage numbers are shown for water available within the urban extent (0 km) as well as varying buffer distances, with a large spatial area over which water can be obtained necessarily reducing water shortage.

and aggregate effects might emerge if this issue could be investigated in greater depth. Interestingly, there is relatively little variation among the impacts on water shortage of our four scenarios of climate change. At the 100-km buffer distance, the coefficient of variation of perennial and seasonal water shortage across all four climate change scenarios and both demographic scenarios was only 2.7% and 0.3%, respectively.

Fig. 2 shows water shortage status for cities of more than 1 million people in 2000. Perennial water shortage is generally confined to cities in the Middle East and North Africa. Seasonal shortage is much more geographically widespread, occurring on all continents and in many different climates. Rapidly urbanizing China and India will have a large number of cities with seasonal water shortage by 2050.

Urban population can be usefully divided into three categories reflecting their perennial water shortage status (Table 1). A total of 162 million people will live in cities that will have perennial water shortage in 2050. The majority of people in this category will be in Asia (94 million), although Africa will have a greater percentage (7.7%) of total urban dwellers under perennial water shortage. A second category is people in cities that will not have perennial water shortage by 2050 at the 100-km buffer distance, but the buffer distance needed to avoid perennial water shortage will increase from 2000 to 2050. This potentially implies infrastructure investment to enable short-scale (<100 km) water transport to satisfy the needs of a projected 2050 population of 720 million. Again, the majority of people in this category will be in Asia (338 million), but Africa will have a greater percentage (36.3%) of total urban dwellers in this category. Finally, a third category is people in cities that do not seem likely to have problems with perennial water shortage, whose population will grow from 1.0 billion to 2.9 billion from 2000 to 2050. Many city dwellers who fall into this residual category will, however, face seasonal water shortage.

One useful way to visualize the cumulative impact of urban water consumption by the thousands of cities in our study area is to examine them relative to freshwater ecoregions. Freshwater ecoregions are areas with similar ecological characteristics and are often defined relative to major hydrologic units (20). Freshwater ecoregions with high numbers of urbanites with insufficient water (Fig. 3, *Upper*) will potentially have flows inadequate to maintain biodiversity, because by our definition of water shortage there will be at least 1 mo per year in which some rivers in an ecoregion have essentially all water withdrawn for urban use. These freshwater ecoregions with substantial urban water shortage populations vary widely in ecological context, from wet river basins like the Ganges Delta and Plain (119 million people in water shortage by 2050) to the endorheic basins of the Arabian Interior (40 million people). Even some of West Africa's tropical river basins with substantial precipitation will have extensive water shortage by 2050, including the Bight Drainages of Nigeria, Benin, and Togo (92 million people).

Potential ecological impacts vary depending on the freshwater ecoregion and the taxonomic group considered. Fig. 3 (*Lower*) shows the number of species of freshwater fish in each freshwater ecoregion, a taxonomic group especially vulnerable to water withdrawals. The Arabian Interior has fewer than 50 freshwater species, perhaps not surprising given its dry climate, whereas the Ganges Delta and Plain has more than 250 species of fish (20). Of particular conservation concern is the Western Ghats of India, which will have 81 million people with insufficient water by 2050 but also houses 293 fish species, 29% of which are endemic to this ecoregion and occur nowhere else in the world.

It is difficult to quantitatively predict how many fish species globally will be imperiled by increased future urban water use, simply because the current relationship between urban water use and imperilment is unknown, because the current conservation status of many fish species has not been assessed. One exception

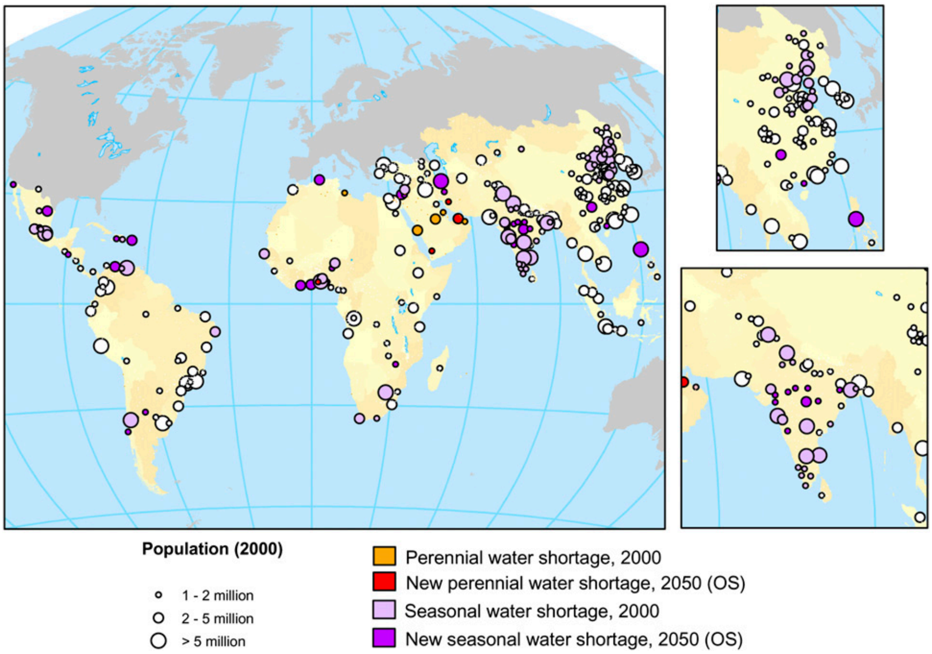

Fig. 2. Spatial distribution of large cities (>1 million population in 2000) and their water shortage status, in 2000 and 2050. Circle size is proportional to city population in 2000. Countries within our study area are shown in beige, whereas countries not studied are shown in gray. *Insets:* Maps of India and China.

that serves as a useful case study is in the Mediterranean. An International Union for Conservation of Nature survey of all fish species in the Mediterranean Basin found 253 endemic fish species (21). The Basin is highly urbanized, with many cities that experience problems of water shortage (22). In part because of excess water extraction, more than half (56%) of these endemic fish species are listed as "critically endangered," "endangered," or "vulnerable" (21). The Mediterranean case indicates the potential for urban water withdrawals to negatively impact endemic fish species.

Discussion

Our modeled results suggest that population growth will have a large effect on urban water shortage. Climate change will cause an additional increase in water shortage on top of these demographic effects. Population growth and climate change together pose a significant challenge for urban water managers, but one that can be foreseen and planned for well in advance.

Of course, significant uncertainties cloud all forecasts, and ours present no exception. Long-term demographic forecasts can be rendered misleading by inadequate data or made inapplicable by unforeseen events. Nevertheless, in the next few decades we expect the effects of urban growth to be stronger and generally less uncertain than climate change in most settings. Climate change forecasting is inherently more difficult than demographic forecasting, because climate modelers must predict the consequences of a novel experiment on the Earth's atmosphere. Precipitation, of obvious importance for a city's water balance, is particularly difficult to forecast. Some impacts of climate change on hydrology, such as more frequent flooding, could impact (positively or negatively) local water supply; our analysis does not account for phenomena in the hydrologic cycle that occur more quickly than the monthly time-step of our models, such as flooding. Similarly, our analysis does not fully account for changes in snowpack or the timing of snowmelt, which can significantly impact some cities' seasonal water supply.

Despite these uncertainties, predictions of water shortage based on the best available data can and should inform planning by water managers. For cities that find themselves in a state of water shortage, there are two types of solutions.

First, water shortage can be viewed as an engineering challenge, with an infrastructure solution. For cities with seasonal water shortage, more water storage from dams or other impoundments may be the solution, although changes in the seasonal distribution of water availability due to climate change may complicate matters. For perennial water shortage, long-distance transport from somewhere beyond the 100-km buffer may be a solution. For cities near the coast, desalination may be an option. Finally, cities on top of a large aquifer may choose to unsustainably mine groundwater, removing water faster than aquifer recharge and putting off water shortage by a few years or decades.

Second, water shortage can be alleviated through landscape management and more efficient use of this resource. Agriculture

Table 1. Geographic distribution of water shortage for our study area

	Africa		Asia		N. America		S. America		Total	
Category	2000	2050	2000	2050	2000	2050	2000	2050	2000	2050
Water scarcity (at 100 km)	6	66	18	94	0	0	0	2	24	162
Water demand met by expanding buffer	62	313	105	338	4	10	23	58	195	720
No perennial water scarcity (at 100 km)	135	483	634	1,760	71	184	168	459	1,009	2,886
Total population in region	203	862	757	2,192	75	195	192	519	1,227	3,768

For three categories, each requiring different responses to water shortage, the population (millions) in 2000 and 2050 is shown by continent. Note that because of rounding column and row totals may not equal the sum of the numbers shown. See text for details.

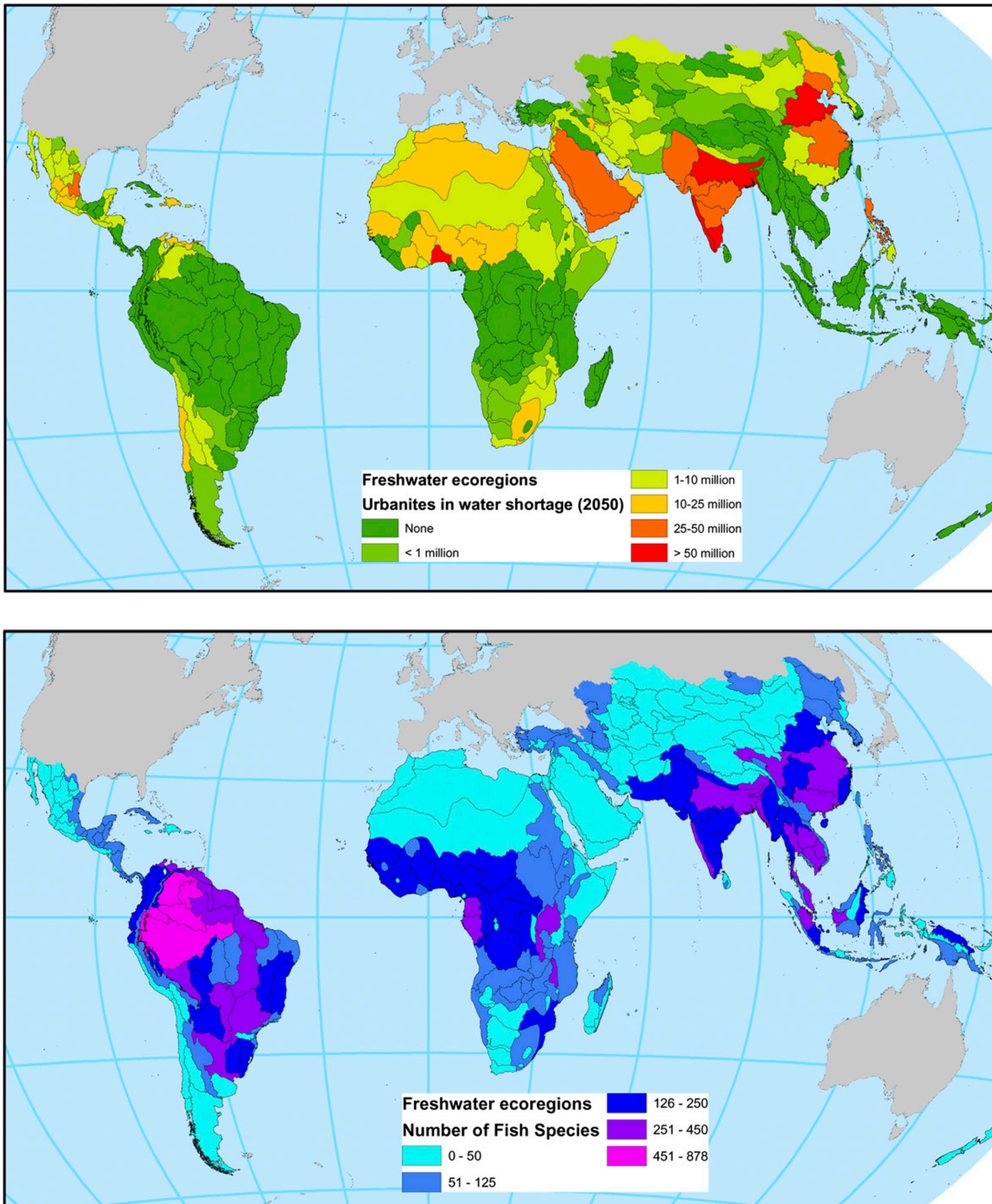

Fig. 3. Urban water shortage by freshwater ecoregions. *Upper:* Population of cities with perennial or seasonal water shortage in 2050. *Lower:* Number of fish species, a taxonomic group potentially impacted by water withdrawals.

is the major consumptive use of water globally, and even small gains in agricultural water use efficiency might save substantial quantities for urban dwellers. Similar efficiency gains in the industrial or residential sector may also save significant quantities of water. More generally, changes in land use or land management may free up water for urban dwellers or for the environment. In part of the southwestern United States, for instance, cities sometimes pay farmers to purchase the water the farmers have traditionally put on their fields, in effect freeing up water for cities by reducing the area of irrigated agriculture (23, 24). Another example is in South Africa, where tree plantations of nonnative water-hungry species are being removed to increase groundwater recharge (25).

Regardless of which strategies are used, there will be costs. For instance, one study estimates that long-distance transport costs approximately $0.06 to transport a cubic meter of water 100 km (26). Desalinization takes more money and energy, costing between $0.61 and $0.81 per cubic meter for production, depending on the technology. Water efficiency gains are often cheaper and can even save money (27). For instance, one study for California found that 2.5 billion cubic meters of water could be saved for less than $0.50 per cubic meter and 810 million cubic meters could be saved for less than \$0.05 per cubic meter (28). Although a full accounting of the costs of addressing water shortage is beyond the scope of this article, Camdessus et al. (29) estimated that from 2003 to 2025 necessary investments to keep up with water needs would exceed \$180 billion per year. This study assumed a specific mix of projects to alleviate water shortage, focusing mainly on infrastructure solutions rather than landscape management, and different assumptions would yield different cost estimates.

Beyond the financial costs of meeting the urban water shortage challenge, there is the risk of endangering wildlife and the natural systems on which they depend. Freshwater systems are already one of the most altered habitat types (30). Without careful planning, the demands of urban dwellers may threaten many more freshwater species. Of the two broad strategies outlined above, landscape management and water efficiency are probably less likely to impact freshwater biodiversity than further infrastructure development. The lack of adoption of revenue-positive water-saving techniques points to incomplete or perverse incentives for water-use efficiency and suggests that work to realign these incentives might help alleviate urban water shortage.

Supplying the world's urban dwellers with adequate water in 2050 will pose a challenge. More than 1 billion people will live in cities without sufficient available water within their urban extent, and these cities will need to invest in other ways to get water. It is a solvable problem but one that will take money, time, political will, and effective governance. For countries with moderate to high per-capita income, domestic investments seem likely to be adequate to find solutions to water shortage if sufficient political will can be found. However, for countries with low per-capita income, domestic investment is likely to be inadequate, and new financing institutions and commitments by the international community will be needed. These kinds of commitments are crucial if the world is to ensure that all urban residents can enjoy their fundamental human right to adequate drinking water.

Materials and Methods

Demography. Base demographic data on cities were taken from GRUMP (4, 31). GRUMP urban extents are spatially defined primarily on the basis of satellite imagery of night-time lights. The extents are then linked with information from censuses and gazetteers containing population information on hundreds of thousands of urban settlements, including those with quite small populations. The algorithm that defines urban extents, especially for large urban agglomerations, typically gathers contiguous urban and suburban areas into one urban extent. For our study, we evaluated the water availability and population for the entire urban extent as measured by GRUMP; this assumes water sharing among constituent municipalities that may or may not occur in practice.

Demographic projections for the urban areas to the year 2050 were taken from Balk et al. (5). For these cities, a time series of population at the city level was obtained from the United Nations (UN), using all information available; for most countries this means a series from 1970 onward. Panel-data regression models (with an allowance for city-specific features captured statistically through random or fixed effects) were used to estimate the historical drivers of city growth and to forecast city populations to 2050. We examined two sets of control variables in these regressions. The first set, producing what we term the Basic Demographic scenario, is based solely on national-level urban rates of fertility and child mortality, city size, and some correction factors to account for how the implicit spatial boundaries of a city have changed over time (using the UN's definitions of city proper, urban agglomeration, and metropolitan region). We augment these controls to produce the Ecological Factors scenario, adding multiple categorical variables for ecosystem (using definitions from the Millennium Ecosystem Assessment (32) and a low-elevation coastal zone (33). This scenario allows the population of cities in specific biomes (e.g., arid regions) to grow slower or faster to the extent that observed population dynamics have consistently correlated with biome in the past. Note that these demographic projections—which are attached to a spatial reference for 2000—do not include estimates of how urban spatial extents will change by 2050.

Hydrology. The water balance calculations were carried out at 6′ (longitude × latitude) spatial resolution using version 6.01 of the Simulated Topological Network (STN30p), a modestly updated version of the dataset presented in Vörösmarty et al. (6). The water balance/transport model applied in the present study (WBMplus) is an updated version of the global water balance model that was developed by Vörösmarty et al. (7, 8) and subsequently modified by Wisser et al. (9, 10). Input data on precipitation and temperature use are fed into the model, as well as a hydrologic network based on a digital elevation model. Evapotranspiration is calculated as a function of local land use, including consumptive water use by agriculture.

We use four scenarios of future hydrology, based on the four scenarios in the Millennium Ecosystem Assessment: Adaptive Management; Global Orchestration; Order from Strength; and Technogarden. More detail on the assumptions behind these four scenarios can be found in the volume of the Millennium Ecosystem Assessment on their scenarios (11). Importantly, each scenario represents a spatially explicit model of economic development, greenhouse gas (GHG) emissions, and land-use change, including agricultural expansion. For each of the four scenario's GHG emissions timeline, a climate model was used to simulate the climate in 2050. Changes in precipitation or temperature then impact the modeled hydrologic cycle. The variation in hydrology among our four scenarios is thus due to variation in the extent of land-use change and GHG emissions.

We have chosen to use the Millennium Ecosystem Assessment scenarios because of the spatially explicit and logically consistent forecasts of land-use change and GHG emissions embedded with them. However, the most recent GHG forecasts of the Intergovernmental Panel on Climate Change (IPCC) have changed somewhat. To give readers a sense of the assumptions underlying our scenarios, our four scenarios emissions pathways are shown next to the current IPCC scenarios (Fig. S2).

Analysis. Using river network topology, we calculated the available water for each urban extent. Cities on small islands (e.g., Comoros Islands) that were not modeled in our hydrologic network are excluded from the analysis. Available water included local runoff generated within the city extent and water flowing into the city. In one sense, this is a very optimistic number: all water is assumed available for use, even water than ends up falling on rooftops or city streets. Moreover, we are assuming that water use among cities in the same watershed is nonconsumptive and that water can be reused several times as it flows down the river. Urban water use is generally nonconsumptive in this sense, except that water quality issues may make some water unusable for downstream users without expensive treatment plants. Our treatment of urban water use as nonconsumptive is a different perspective from many water availability indices calculated at a watershed level, whereby dividing watershed available water by watershed population water use is implicitly defined as consumptive.

Various standards have been used for the minimum amount of water for daily needs, depending on what needs are considered in the estimate (14). We define water shortage as <100 L per person per day, following the World Health Organization definition of "optimal" water for all domestic needs, including drinking, cooking, bathing, cleaning, and sanitation (15). If a city's average water availability is less than this standard it is defined as having perennially water shortage. For cities that did not satisfy their water requirements within their urban extents, a series of buffers was used in an iterative process (Fig. S1). First a buffer of 10 km was used, and if the water shortage standard was not achieved then buffers of 30 km, 60 km, and 100 km were used. Because the population of the urban extent did not change during this buffering process, available water per capita by necessity stays the same or increases as buffer distance increases.

Because our hydrologic model outputs data on a monthly time step, it is relatively easy to incorporate seasonal variability into our analysis. An urban extent is defined as having seasonal shortage if there is at least 1 mo per year in which it does not have 100 L per person per day. Note that many cities meet this criterion for seasonal shortage and may in practice avoid problems simply by having sufficient water storage to make it through the dry month or months.

To examine how urban water use might affect freshwater biodiversity, we intersected our map of cities with insufficient water and a map of the freshwater ecoregions of the world. Freshwater ecoregions are spatial areas of similar ecology, often in the same major hydrologic drainage or of similar geology. If a city with insufficient water is located in a freshwater ecoregion, this means there is at least one stream in the ecoregion that is being fully used by urban residents. When an urban extent or its buffered area of water acquisition crossed the boundary of two freshwater ecoregions, in our calculation the population of the city with insufficient water was partitioned between the two ecoregions according to the volume of water available within that portion of each ecoregion. Population with insufficient water by freshwater ecoregion was graphically related to freshwater fish richness and endemism, because freshwater fish are one of the taxa most likely to be affected by water withdrawal.

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