Estimating watershed degradation over the last century and its impact on water-treatment costs for the world's large cities

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Urban water systems are impacted by land use within their source watersheds, as it affects raw water quality and thus the costs of water treatment. However, global estimates of the effect of land cover change on urban water-treatment costs have been hampered by a lack of global information on urban source watersheds. Here, we use a unique map of the urban source watersheds for 309 large cities (population > 750,000), combined with long-term data on anthropogenic land-use change in their source watersheds and data on water-treatment costs. We show that anthropogenic activity is highly correlated with sediment and nutrient pollution levels, which is in turn highly correlated with treatment costs. Over our study period (1900–2005), median population density has increased by a factor of 5.4 in urban source watersheds, whereas ranching and cropland use have increased by a factor of 3.4 and 2.0, respectively. Nearly all (90%) of urban source watersheds have had some level of watershed degradation, with the average pollutant yield of urban source watersheds increasing by 40% for sediment, 47% for phosphorus, and 119% for nitrogen. We estimate the degradation of watersheds over our study period has impacted treatment costs for 29% of cities globally, with operation and maintenance costs for impacted cities increasing on average by 53 ± 5% and replacement capital costs increasing by 44 ± 14%. We discuss why this widespread degradation might be occurring, and strategies cities have used to slow natural land cover loss.

ecosystem services | History Database of the Global Environment | operations and maintenance

Humanity is experiencing the fastest rate of urbanization in history. Over the 20th century, the urban population increased from 220 million to 2.9 billion, and by 2050, another 3.4-billion increase is expected (1, 2). One of the most fundamental requirements of urban existence is a source of clean, sufficient water (3, 4). Urban water supply systems are often complex, drawing water from multiple locations, some surface and some groundwater, some close and some far from the city center (5, 6). Seventy-eight percent of large cities rely on surface water sources (6), and their urban supply systems create teleconnections (7, 8) between source watersheds and the urban users who depend on them. The world's largest cities (>750,000 population), the focus of this paper, occupy less than 1% of the Earth's land surface (9) but their source watersheds occupy 41% of its surface (6).

Natural land cover in urban source watersheds provides important ecosystem services that help maintain the water quality at the city's water source, so-called raw water that will then be treated and distributed to urban residents (10, 11). Natural land cover stabilizes soil, minimizing erosion and sediment loading (12, 13). Natural land cover also has lower loading than most human land-uses of excess nutrients, such as nitrogen (N) and phosphorus (P), and other pollutants (14, 15). When humans convert natural land cover to other uses such as agriculture or housing, the loss of natural land cover decreases ecosystem service provision and the anthropogenic land uses increases pollution, which leads to a decline in water quality (16). This loss of natural land cover over time, and the resulting impacts on hydrology, is often called watershed degradation (17).

This paper focuses on the water quality at the intakes of large cities globally. This raw water quality matters because it determines the type and intensity of water treatment needed to reach drinking water standards (18–20). For instance, Alcott et al. (10) contrast the relatively minimal treatment of Boston's water supply from the largely forested Quabbin reservoir with the more extensive treatment required from Worcester's reservoir, which has had significant land development and water quality degradation in its source watershed. Better raw water quality reduces the need for sediment removal (e.g., addition of coagulants such as alum), makes filtration easier (or in cases of exceptional water quality, removes the need for water filtration), and reduces the need for additional processes (e.g., the need to remove disinfection byproducts). In addition, lower concentration of phosphorus and nitrogen reduce algal growth and the amount of organic matter in the water, simplifying filtration and reducing the prevalence of disinfection byproducts. Thus, water-treatment plants (WTPs) using raw water of high quality can be designed using simpler treatment technologies, which lead to a lower capital cost during construction and lower operations and maintenance (O&M) costs. Avoiding watershed degradation helps maintain raw water quality which reduces treatment costs, as the "natural capital" of natural land cover functions as an alternative to human capital invested in a WTP (13).

Significance

Urban water-treatment costs depend on the water quality at the city's source, which in turn depends on the land use in the source watersheds. Here, we show that globally urban source watershed degradation is widespread, with 9 in 10 cities losing significant amounts of natural land cover in their source watersheds to agriculture and development. This watershed degradation has impacted the cost of water treatment for about one in three large cities globally, increasing those costs by about half. This increase in cost matters because increases in water-treatment costs are paid for by those living in cities, so watershed degradation has had a real quantitative cost to hundreds of millions of urbanites.

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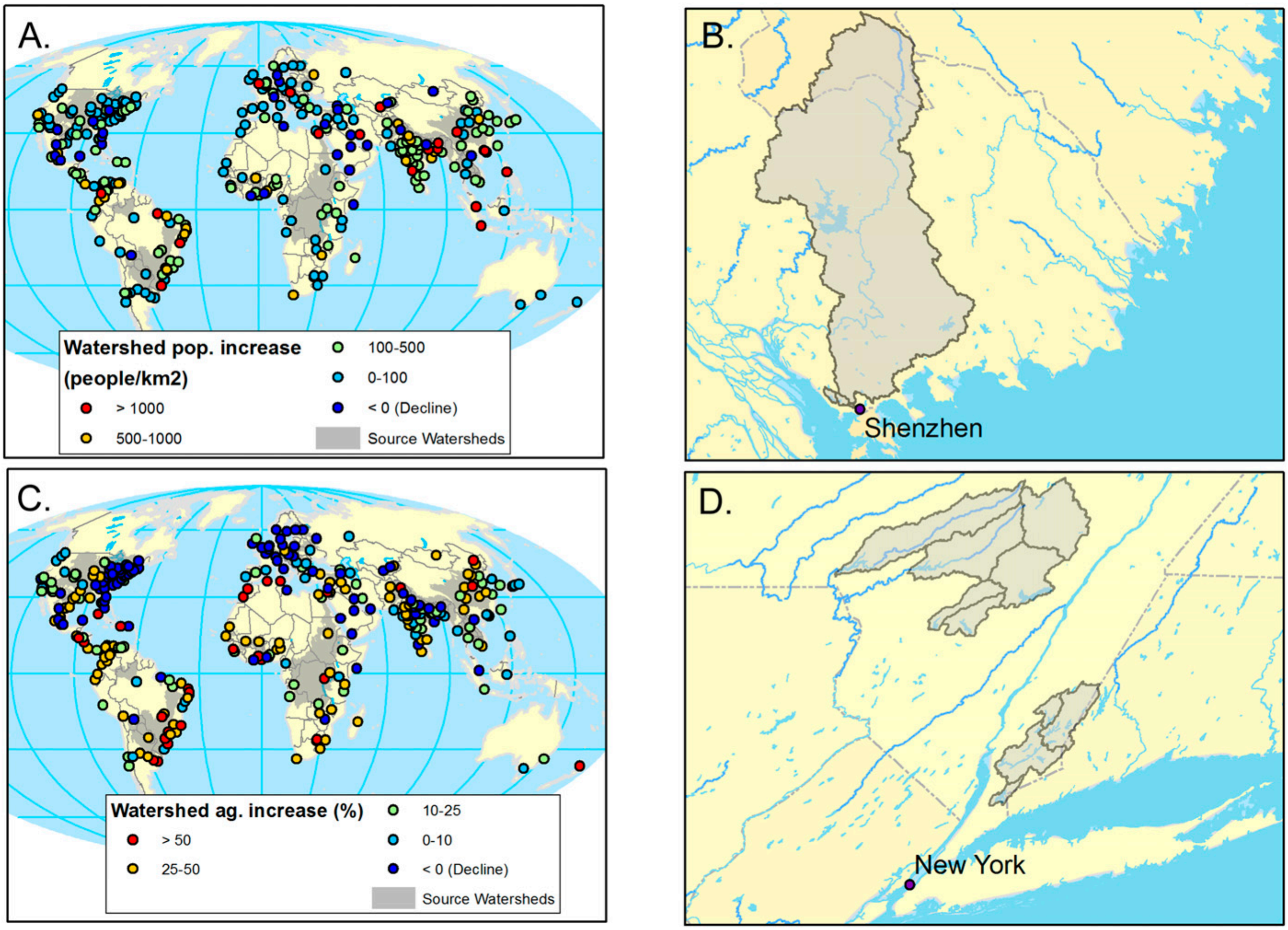

Fig. 1. Spatial variation in human activity in drinking water source watersheds of large cities. (*A*) The increase in a city's source watershed population density from 1900 to 2005. (*B*) Shenzen and its supply watersheds, including the large Dong River watershed. Note that the Dong River also supplies water to Hong Kong. (*C*) The increase in a city's source watershed agricultural use, both cropland and ranchland, from 1900 to 2005. (*D*) New York City and its supply watersheds.

Although the relationship between land cover and water quality has been measured or modeled in numerous watersheds (21, 22), the scientific understanding of the global importance of watershed degradation to urban water-treatment costs has been limited to date. Until recently (6), there has been no global dataset of where cities get their water from or of the complex teleconnections between source watersheds and cities. Similarly, although there are numerous anecdotal instances of clean water leading to reduced treatment costs, there has been relatively little global study of how financially important this proves to be for the world's water utilities. For instance, one notable study looked at 27 US water utilities and found a relationship between forest cover and O&M costs, but did not consider capital costs or changes over time in forest cover and was limited to US utilities (18).

Here, we combine our recently created global dataset of where cities get their water from (20) with datasets on the growth of human population and land use over time (23, 24), allowing us to reconstruct watershed degradation for the period 1900–2005 for the world's source watersheds. Using empirically based data for a training dataset on sediment, N, and P loading for the United States (25), we relate water quality to land use and population in the source watershed, allowing us to estimate how sediment and nutrient pollution have changed. Note that, although our statistical approach for the estimation of pollutant loading is relatively simple, it is necessitated by the long-term period of our analysis. More complex, spatially explicit models of sediment or nutrient loading and in-stream dynamics would require global maps of prior land cover and land cover transitions over the last century at high spatial resolution (<100s meters), which is not available for most watersheds globally. Finally, we assembled a unique dataset of the water-treatment technologies used in 264 WTPs and use it to estimate the statistical relationship between water quality degradation and increased treatment costs. Our two main research questions are as follows: (*i*) how has the degradation of source watersheds affected water quality for the world's largest cities; and (*ii*) how much has the decline in water quality affected water-treatment costs for the world's urban water utilities?

Results

Globally, most source watersheds have increased in population density over the period 1900–2005, but there is substantial spatial variation (Fig. 1*A*). Some places like the Ganges/Brahmaputra basin (home to cities like Dhaka) have increased dramatically in population density, whereas others have increased only slightly in population density, such as the source watersheds of Paris. Population density in urban source watersheds in 2005 varies by four orders of magnitude. Some of the highest values are in Asia. For example, the Dong watershed that supplies Shenzhen and Hong Kong, via an interbasin transfer, had a population density of 261 people/km^2 in 2005 (Fig. 1*B*). Readers who wish to see a higher-resolution image of Fig. 1 *A* and *B* should consult Figs. S1 and S2, respectively.

Agricultural expansion (cropland and ranchland) shows similarly large spatial variability (Fig. 1C). Areas like the pampas of Argentina had large increases in agricultural utilization, whereas New England had a decrease as farms were abandoned. These spatial patterns matter because they translate to spatial patterns in water quality, as we show below.

An examination of intake locations shows that cities have placed their water intakes to, in part, avoid severe water quality problems. The majority of intakes are upstream from the cities they serve. This hydrologic head of course facilitates water movement by gravity, but also potentially allows cities to source from less crowded watersheds. For instance, New York City is located along the Hudson River (Fig. 1*D*), a very urbanized river in its lower reaches, with population density exceeding 10,000 people/km^2. If New York City drew from the Hudson River, the average population density of the entire source watershed, including more rural parts of the watershed farther north, would be 123.7 people/km^2 and 14% agricultural utilization. By drawing water from two major reservoirs located an average of 151 km away, New York City can source from watersheds with an average population density of 65.3 people/km^2 and 16% agricultural utilization.

Globally, urban source watershed population density has increased significantly from a median of 22.3 to 124 people/km^2 over the study period (1900–2005), increasing by a factor of 5.4, with the fastest growth occurring in the last few decades of the

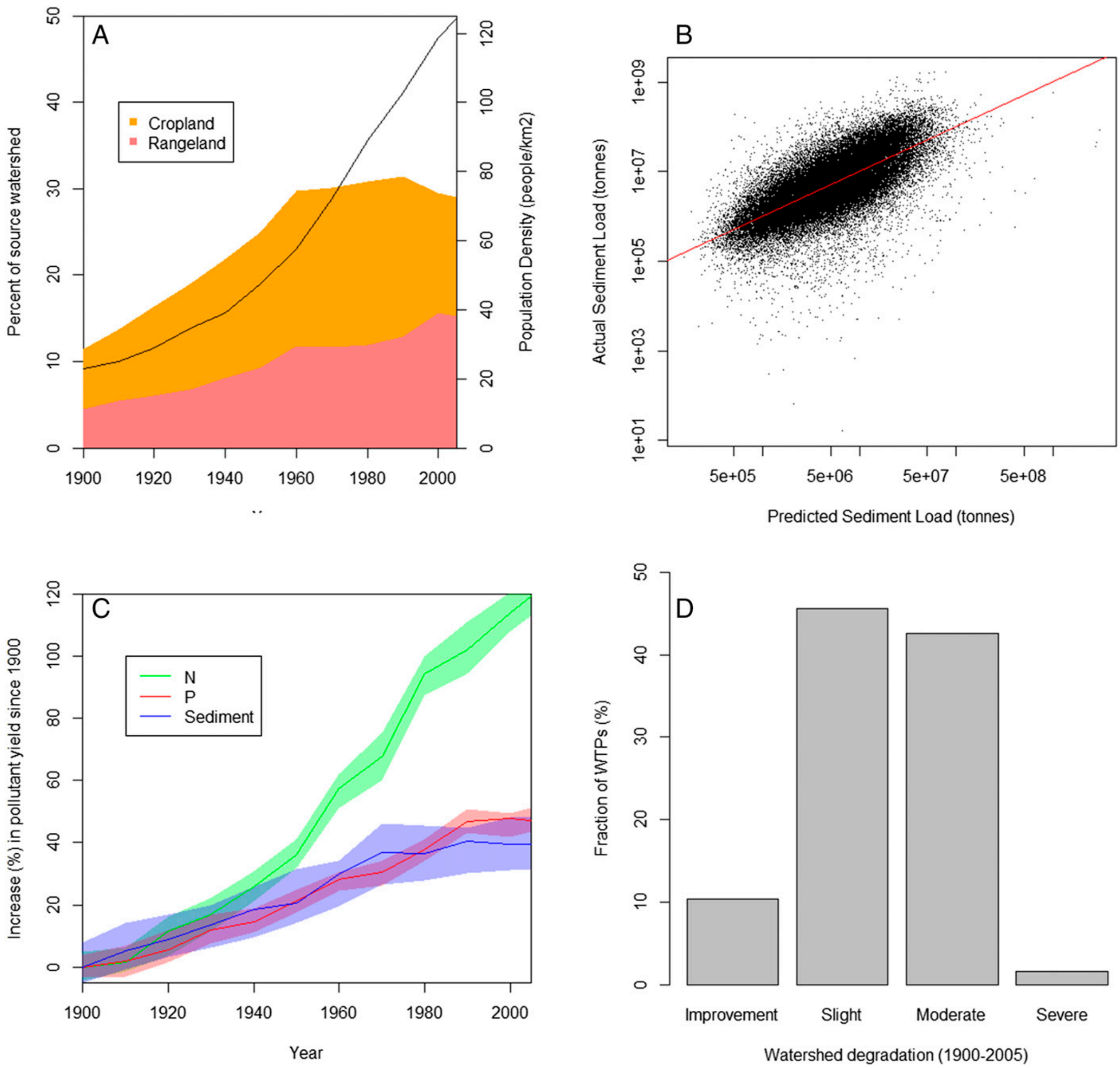

Fig. 2. Trends over time in watershed degradation and water quality in urban source watersheds. (*A*) Time series of median cropland and rangeland coverage, as well as population density. (*B*) Cropland and rangeland coverage, plus population density, predict sediment loading. Red line is the 1:1 line. Trends for N and P (not shown) are similar. (*C*) Estimated pollutant yield over time, relative to the average pollutant yield in 1900. (*D*) Proportion of WTPs by level of watershed degradation.

20th century (Fig. 2*A*). Population growth in urban source watersheds follows the exponential growth pattern commonly seen for human population globally during the 20th century, although the rate of increase in urban source watersheds is actually faster than for overall global population, which increased by a factor of 3.8 over the 20th century (1, 26).

Trends for agricultural utilization in source watersheds are more complex temporally (Fig. 2*A*). Cropland area increased dramatically until 1960 then plateaued and modestly declined from 1990 on. The slight decline in global average cropland utilization in source watershed is due primarily to declines in some source watersheds in parts of the United States and Europe (Fig. 1*C*). Use as rangeland, in contrast, continuously expanded between 1900 and 2005. Trends over time in different regions are shown in Table S1.

Population density and agricultural utilization in a source watershed can be used to predict sediment (R^2 = 0.50, P < 0.001), N (R^2 = 0.58, P < 0.001), and P (R^2 = 0.63, P < 0.001) loading. A 10% increase in population density leads on average (holding all other variables constant) to an 0.8% increase in sediment loading, a 2.6% increase in N loading, and a 1.6% increase in P loading (Table S2). Similarly, a 10% increase in source watershed utilization for cropland leads to a 1.6% increase in sediment loading, a 1.3% increase in N loading, and a 0.1% increase in P loading. Utilization for rangeland has no statistically significant relationship to sediment, N, or P loading. Note that this is likely due to the relatively coarse global data used in our study, as there are many studies that have shown important impacts of rangeland on water quality in particular watersheds or contexts (see literature review in ref. 27).

Based on the fitted regressions with empirical data in our training dataset (Fig. 2*B*), we can estimate the decline in water quality for source watersheds between 1900 and 2005. Sediment yields increased by 40% between 1900 and 2005, with a roughly linear pattern of increase (Fig. 2*C*). Similarly, P yields have increased by 47% over the study period. The biggest increase is for N yields, which increased 119% over the study period, with a more exponential pattern of increase.

Global average figures mask substantial variation among source watersheds. Because sediment, N, and P yields were correlated among one another, we used a principal components analysis (PCA) to describe the main axis of variability in watershed degradation (Table S3). Ninety percent of urban source watersheds had some degree of watershed degradation (Fig. 2*D*). Around 44% of cities had a moderate or severe decline in their source watershed. A small percentage of watersheds (10%) had an improvement in water quality over the 20th century.

Source watersheds with higher N yields are associated with more complex water-treatment technologies (Fig. 3*A*). For instance, for source watersheds in the cleanest third of watersheds globally, 42% of WTPs use two-stage filtration, direct filtration, or no filtration, technology categories that require relatively clean raw water. In contrast, source watersheds in the dirtiest third of watersheds globally have only 22% of their WTPs using these same three technologies. A similar association between water quality and technology level exists for P yield and sediment yield, and we modeled technology level as a function of the first axis of our PCA using an ordinal logistic regression (Fig. S3).

The association of lower water quality with more complex water-treatment technology classes matters because more complex water-treatment technologies cost significantly more (Fig. 3*B*). A typical 250 million liter per day (MLD) no-filtration WTP might cost $104 million in capital costs to build, plus $1.7 million per year in O&M costs, for a total annualized cost of $8.5 million. This cost is a 20% lower annualized cost than a so-called conventional filtration plant, which uses sand or gravel filtration. At the other end of the spectrum, an advanced filtration plant, such as one

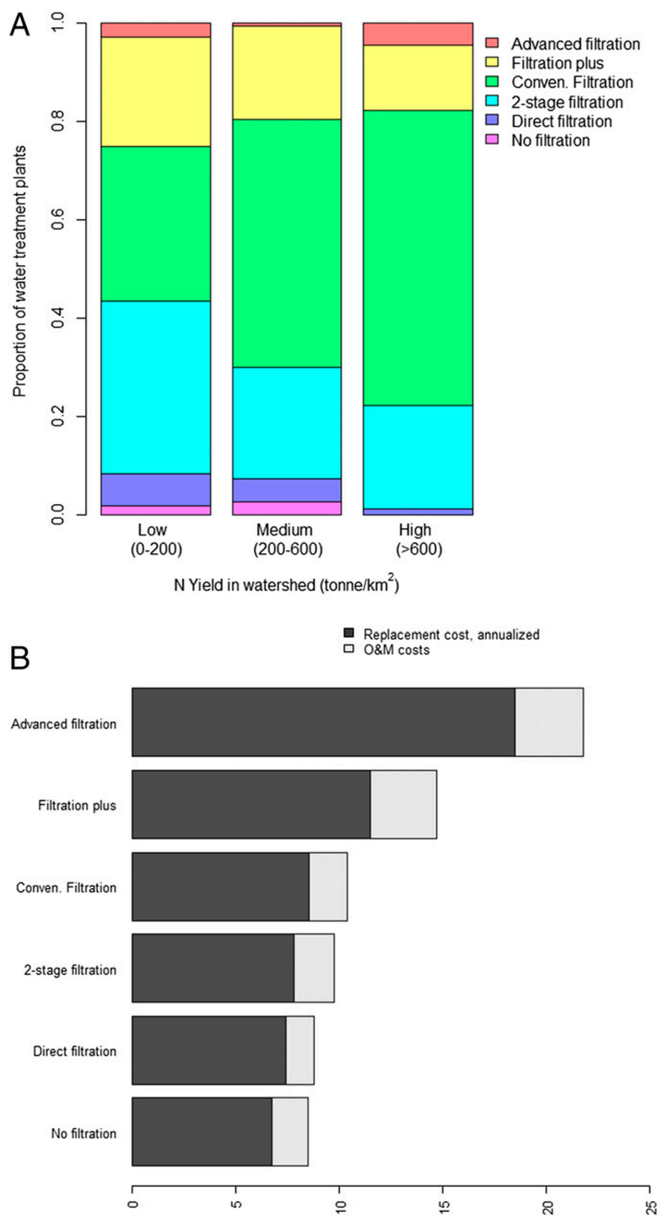

Fig. 3. Effect of water quality on treatment costs. (*A*) Treatment technology as a function of population density, empirical trends. Trends for cropland look similar. (*B*) Average operations and maintenance (O&M) and replacement cost as a function of treatment technology, for a 250 MLD plant. Replacement cost is expressed as the annual cost, assuming a 30-y bond at 5% interest rate.

using membrane filtration, would have 2.1-fold greater annualized costs than a conventional filtration plant.

We estimate that 29% of cities globally have had a significant increase in water-treatment costs due to watershed degradation between 1900 and 2005. That is, these cities would likely be using a lower technology level today if the watershed could be restored to the land use patterns of 1900. The WTPs impacted fit a specific profile. First, their source watershed has had rapid degradation, often significantly exceeding the global average rate of source watershed degradation. Second, in 1900 the watershed was relatively pristine, so a lower technology level would have been hypothetically likely.

Although only approximately one in four cities have been impacted to date, for those that are impacted, there has been a significant increase in water-treatment costs (Fig. 4). Impacted

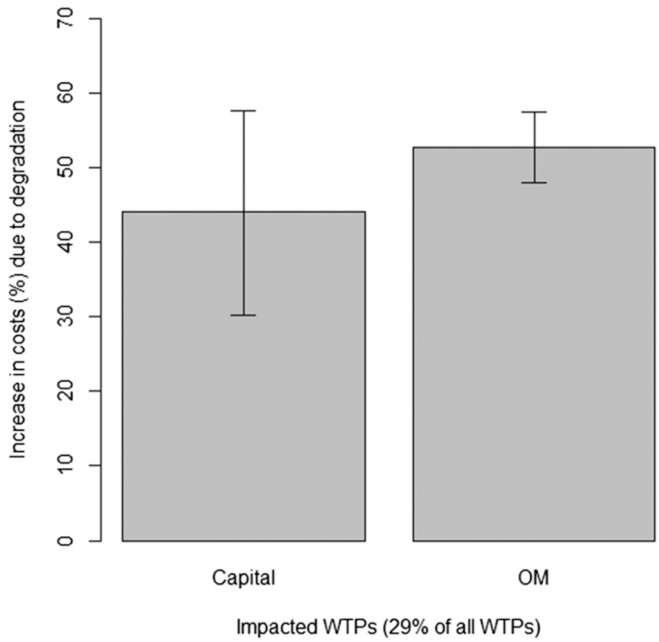

Fig. 4. Estimated percent increase in costs due to degradation for impacted WTPs. Around one in four (28%) WTPs draw water from source watersheds that have been sufficiently degraded from 1900 to 2005 to have likely required more complex water-treatment technologies. In these impacted WTPs, the average WTP is 42% more expensive in capital costs and 52% more expensive in operations and maintenance (OM) costs. Error bars are bootstrapped CIs.

cities had an estimate 53 ± 5% increase in O&M costs and a 44 ± 14% increase in capital costs. The distribution of impacts has a long right tail, with some cities having a doubling or more of treatment costs due to watershed degradation in the study period.

Discussion

This paper provides a global estimate of how much natural land cover degradation has increased treatment costs for a sample of the world's large cities. If the results from our studied cities applied across all global cities, which house 3.6 billion people (2), we would expect that 1.0 billion people are in cities whose treatment costs have been significantly impacted by watershed degradation. One study (28) estimates US $17B annually in capital expenditures for drinking WTPs, so if 29% of all cities had their capital costs impacted by watershed degradation raised an average of 44%, this implies a US $2.2B annual increase in capital expenditures due to watershed degradation. Another study estimated global WTP O&M as US $21B per year (20), so a similar calculation implies that watershed degradation over our study period (1900–2005) has increased WTP O&M by $3.2B per year. The total cost of watershed degradation to water utilities is therefore about US $5.4B annually, which represents a net present cost to urban water utilities of roughly US $108B, assuming a 5% annual discount rate. This financial impact is important to study because it is a cost imposed on urban water-treatment utilities.

By and large, land owners in source watersheds do not consider the effects of their land use on downstream water users. The ecosystem services provided by natural land cover are nonmarket goods, so landowners receive no direct benefit for allowing natural land cover to remain. Conversely, the decision to convert natural land yields benefits to landowners but imposes a large externality on urban water utilities, because of the increase in pollution that often results and the decrease in ecosystem service provision. The conversion of natural land cover to other land uses, such as housing or agriculture, has significant economic value to not just landowners but society at large. Our analysis cannot say whether the degradation of natural land cover is a net good or bad thing, because it only quantified the costs to water utilities of watershed degradation.

Our analysis focused on large cities, but it is worth noting that 1.9 billion people globally live in small cities (<750,000 people) (2). There is reason to think water supply systems are systematically different for small cities than for the large cities we studied. Small cities are much more likely to use groundwater, at least in the United States where comprehensive data are available (29). Small cities also tend to have water intakes for smaller, more local source watersheds. More study is needed to see if the trend we show for large cities holds for small cities.

Most cities, large and small, will be expanding in the 21st century. This urban growth will lead to increased demand for urban water withdrawals, a trend that is happening as surface appears likely to continue being degraded. Cities will also increasingly have to plan for the impact of climate change, which will change water supply and timing in many watersheds globally. Cities may respond to the confluence of factors by developing new water sources, whether from surface waters, groundwater, or desalination. Cities may also try to make better use of their current supply, by limiting leakage from pipes, decreasing domestic consumption, or reusing wastewater (30).

An alternative strategy for cities is source watershed planning and conservation to limit further watershed degradation (30). The goal here is to limit water pollution, often by giving economic value to the ecosystem services that natural land cover provides. This reduction in water pollution can occur through government policy, such as zoning or other land use regulations, or through a payment for watershed services scheme. Regardless the mechanism, the goal is to give value to nature to correct the market failure. Source watershed conservation may be an important strategy to safeguard urban water supplies in the next few decades.

Materials and Methods

Mapping Urban Water Sources. This study focused on a stratified sample (6) of urban agglomerations greater than 750,000 people, which were surveyed by the World Urbanization Prospects (WUP 2011) report conducted by the United Nations Population Division (2). For each target city, we geolocated freshwater withdrawal points and aligned them with the HydroSHEDS (31) digital elevation model (*SI Materials and Methods*).

The full geodatabase of urban water sources, called the City Water Map (v2.2), is publically available online at the KNB Data Repository (32).

Changes in Anthropogenic Activities over Time. Our information on population density, as well as human land use, was the History Database of the Global Environment (HYDE) version 3.1 (33). Details on the HYDE methodology are available online (34) and in *SI Materials and Methods*. We extract for each urban source watershed the HYDE predictions of population density and agricultural land use for 1900, 1910, 1920, 1930, 1940, 1950, 1960, 1970, 1980, 1990, 2000, and 2005 (Fig. S4).

Relating Anthropogenic Activities to Water Quality. There is a large literature on how anthropogenic activities affect water quality, with agricultural land uses (35) and population density (36) affecting sediment and nutrient loading. Many papers have constructed spatially explicit models of sediment (37, 38) or nutrient loading (39, 40) for the contemporary time period, based on the hydrology and mechanistic processes that lead to water pollution. However, the goal of this paper was to construct estimates of water quality over more than a century (1900–2005). More complex, spatially explicit would require detailed global maps of prior land cover and land cover transitions over this 105-y period, which is not available for most watersheds globally. Accordingly, we built a statistical model to predict sediment and nutrient loading based on agricultural land uses and population density, for which we do have estimates over the past century.

To quantify the relationship between the HYDE measures of anthropogenic activity and water quality, we related the HYDE measures to data for the United States from the SPARROW (SPAtially Referenced Regressions on Watershed attributes) database. The SPARROW models structure is described by Schwarz et al. (41). For all urban source watersheds in our sample of US

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cities, we extracted SPARROW estimates of sediment, nitrogen, and phosphorus loading, using the SPARROW national interpolated grids (42).

These empirically based water quality estimates for the United States were statistically compared with the HYDE estimates of population density, crop land use, and ranchland land use in the source watersheds, using linear regression. The total pollutant loading of sediment, N, and P was modeled as a function of the total crop area in the upstream contributing watershed, the total ranchland area in the watershed, the total human population in the watershed, and the watershed area.

In addition, for sediment we included the watershed average of the RKLS component of the universal soil loss equation (43), which represents the total erosion (not accounting for land use practices) as a product of rainfall erosivity (R), soil erodibility (K), and topography (LS). Our values for RKLS were taken from McDonald et al. (20).

Similarly, for N and P, we included information on the contemporary application rates of these nutrients on cropland and grazing. This information was taken from the global grids of the Global Fertilizer and Manure (GFD), version 1, dataset. Agricultural land was assumed to have both manure and fertilizer applied at the rates specified by the GFD, whereas grassland/pasture was assumed to have only manure applied at the rates specified by the GFD.

To validate the predictions of our statistical model, we compared for circa 2005 our estimate of N loading with that predicted by the Water Balance Model (39, 40), as downloaded from the World Water Development Report II website. The correlation between our statistical model predictions and the Water Balance Model was high ($R = 0.71$), and generally follows the 1:1 line (Fig. S5).

Please see *SI Materials and Methods* for more detail on our statistical analysis.

WTP Technologies. We collected information on treatment technologies used by 264 WTPs for around 100 cities in the United States and around 30 international cities. For more detail on the collection of this dataset, please see *SI Materials and Methods* and McDonald and Shemie (20). Table S4 lists the WTPs.

For the purpose of this project, WTPs were classified into seven categories, based on the categories in McGiveney and Kawamura (44): no filtration; no filtration with additional processing; direct filtration; two-stage filtration; conventional filtration; filtration with additional processing; and advanced filtration (e.g., membrane filtration). O&M and capital costs were estimated following McGiveney and Kawamura for all 264 WTPs in our sample, based on the size of the plant, the treatment category, and the presence of any additional processing steps. We adjusted all costs to US$2015, using the Engineering News-Record Construction Cost Index (ENR-CCI). The methodology of McGiveney and Kawamura produces preliminary design estimates, which they report vary from actual O&M and capital costs by +50% to −30% (44). Note that Table S4 contains information on the treatment technology class of each WTP.

Water-Treatment Costs and Water Quality. Treatment technology categories were compared with our estimated sediment, N, and P loads using ordinal regression, specifically a proportional odds logistic regression. See *SI Materials and Methods* for more details on the ordinal regression analysis.

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