An environmental assessment of United States drinking water watersheds

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Abstract

There is an emerging recognition that natural lands and their conservation are important elements of a sustainable drinking water infrastructure. We conducted a national, watershed-level environmental assessment of 5,265 drinking water watersheds using data on land cover, hydrography and conservation status. Approximately 78% of the conterminous United States lies within a drinking water watershed. The typical drinking water watershed had a high percentage of natural vegetation ($\tilde{x}$ = 77%) but a low percentage of it was set aside for conservation ($\tilde{x}$ = 3%). Median percentage values for urban and agriculture were 5% and 8%, respectively. Between ca. 1992 and ca. 2001, approximately 23% of the drinking water watersheds lost at least 1% of their natural vegetation, and approximately 9% of the watersheds had at least a 1% increase in the amount of urban land. Loss of natural vegetation was common in nearly all areas of the country, but also concentrated in the Ohio River and Southeast. Urbanization was concentrated in the eastern United States, primarily in the Mid-Atlantic and Southeast regions.

Keywords: Conservation; Land-cover change; Land use; Sustainability

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Introduction

There is a growing recognition of the importance of natural land and its conservation for protection of drinking water supplies. A survey of 105 of the world's larger cities revealed that nearly one-third have some form of conservation and protection for at least part of the their drinking water source areas (Dudley and Stolton 2003). In 2009, the U.S. Secretary of Agriculture emphasized the importance of forests and other rural lands for providing the nation's drinking water (Vilsack 2009). Protection of drinking water sources may also reduce the costs associated with providing clean drinking water. Ernst et al. (2004) reported a nonlinear inverse relationship between drinking water treatment costs and the percentage of forest in the source watershed. The invigoration of land conservation surrounding New York City's drinking water supply occurred because investment in land conservation was estimated to be more cost effective than investment in additional treatment facilities (NRC 2000). Seattle (WA), Boston (MA), Portland (OR), and other smaller cities have also invested in land conservation rather than additional treatment facilities because it was considered to be a more cost-effective means of providing clean drinking water (Postel and Thompson 2005).

Approximately two-thirds of the U.S. population relies on drinking water from surface sources (Levin et al. 2002; US EPA 2008). Protection of drinking water in the United States is administered through the Safe Drinking Water Act (SDWA) (P.L. 104-182), and based on a multiple barrier conceptual model (U.S. EPA 1997; Mehan 2009; Dougherty 2010). The multiple barrier concept advocates using several defenses to protect drinking water (Hrudey et al. 2006; Mehan 2009; Plummer et al. 2010). Treatment (filtration, disinfection), monitoring, infrastructure investment (US EPA 2002, 2009) and public outreach (U.S. EPA 1997; Plummer et al. 2010) are used as coordinated elements to ensure the delivery of clean drinking water.

The 1996 Amendments to the SDWA shifted the emphasis of environmental assessment from contaminant detection to source water protection (US EPA 1997; Mehan 2003). Within the framework of a multiple barrier conceptual model, the new emphasis on source water protection adds management of the land from which drinking water is drawn as another element of a coordinated defense designed to ensure delivery of clean drinking water. Source water protection is one element of a sustainable drinking water infrastructure (Dougherty 2010).

New in the 1996 Amendments was a requirement that each state develop source water assessment plans. Source water assessment plans include: 1) delineation of drinking water source areas (i.e., watersheds); 2) inventory of potential contaminants; 3) assessment of susceptibility of drinking water sources to contaminants, and; 4) public dissemination of the assessments. Under the SDWA 1996 amendments, each state submits its source water assessment plan to the U.S. Environmental Protection Agency and updates the assessment periodically**.** Section 1413 of SDWA authorizes states to assume oversight of its drinking water systems (Tiemann 2008), and to our knowledge there is no national assessment of drinking water source areas. The objective of this report is to further develop source water protection as one element of a sustainable drinking water infrastructure by conducting a national assessment of land-cover composition, land-cover change, conservation status, and hydrographic context of drinking water watersheds. Land cover is a foundation upon which many environmental assessments are based. Changes in land cover lead to changes in water quality (Wickham et al. 2005; Gilliom et al. 2006), watershed runoff (Ponce and Hawkins 1996), and climate (Marshall et al. 2004). Thus, measurement of land-cover composition and change is a necessary and needed environmental endpoint for understanding environmental condition and issues related to sustainability (Turner et al. 2007). Conducting the assessment nationally helps to integrate the individual state assessments. Within one data base, assessments can be undertaken for an individual watershed, a state, a multi-state region, and the nation. Because of the nationwide scope, the data can be used to examine regional variation in conditions, which may provide useful information about priorities for environmental management and allocation of resources.

Methods

The U.S. EPA Office of Water provided the surface drinking water intakes as point (X,Y) coordinates (groundwater sources were not evaluated). Drinking water intakes are pipes in lakes, reservoirs or streams that draw water from the source and transport it to the water treatment plant (Supplementary material Fig. S1). The mapped location of each intake was inspected prior to including it in the analyses. Inclusion was based on two criteria. First, intakes that were less than 150 meters upstream of another intake were excluded from the analysis because the upstream watersheds were deemed to be essentially the same as their downstream counterparts. Second, the National Hydrography Dataset (NHD) reach classification (Supplementary material, Table S1) was used to determine if a watershed could be delineated for each intake. Intakes that occurred on the NHD classes pipeline and canal/ditch were excluded from the analyses. The exclusion of drinking water intakes that did not meet these two criteria resulted in 5,265 drinking water intakes for which watersheds could be delineated. The watersheds delineated for these drinking water intakes were combined with land-cover, hydrographic, and protected areas data to conduct the environmental assessment. The watershed delineations and analyses were organized by U.S. Geological Survey hydrologic regions (Fig. 1) in order to track progress efficiently.

Figure 1 approximately here

Determining the total land area of the conterminous United States within a drinking water watershed required removal of the inherent nesting of watersheds. Nesting was removed by inspecting all watersheds for the occurrence of smaller, embedded watersheds. The subset of watersheds without smaller, embedded watersheds was used to estimate the amount of land area in the conterminous United States that was within a drinking water watershed.

Location adjustments were necessary for some of the intakes located in lakes and reservoirs because they were not necessarily located where the water body drained to an out-flowing stream. These intakes were moved to the water body outlet so that the delineated watershed included the entire water body. Moving intakes in lakes and reservoirs to the water body outlet had the potential to change the size of the watershed, and in turn change the total area of the conterminous United States that was within a drinking water watershed. The NHD data were used to gauge the effect of moving intakes in lakes and reservoirs on the total land area of the conterminous United States that was within a drinking water watershed. If an NHD reach did not enter the water body downstream of the original location of the intake, the intake was moved to the water body outlet, and the watershed for that intake was based on locating the intake at the water body outlet. If an NHD reach entered the water body downstream of the original point location, a complementary point was added at the water body outlet in a separate file, and the original location was used in the main dataset. The watershed sizes for the two locations were then used to determine the effect of moving the intake on the total land area of the conterminous United States that was within a drinking water watershed. Moving intakes in lakes and reservoirs to the water body outlet had a very small effect on the total area of the conterminous United States that was within a drinking water watershed (Supplementary material, Table S2).

The National Land Cover Database (NLCD) 1992-2001 land-cover change data (Fry et al. 2008) were used to estimate land-cover composition and land-cover change within the drinking water watersheds and their near-stream environments. The NLCD 1992-2001 land-cover change data provide "from" (ca. 1992) and "to" (ca. 2001) changes in land cover using an eight-class legend (Supplementary material, Table S3). Changes were computed for natural, urban, and water land-cover classes. Natural was defined as the combination of the forest, shrubland-grassland, and wetland classes. Change computations were formulated as values for 2001 minus values for 1992 so that losses were negative and gains were positive. The percentages changes that we report are based on watershed area.

For the riparian analysis, the near-stream width was set to a 120 m radius. Several high resolution (1:24,000) NHD datasets were conflated to define the near-stream environment. The conflation included NHD datasets that represented water bodies (lakes and reservoirs), large rivers, and smaller rivers and streams. By combining these datasets the near-stream environment included the shoreline of lakes and reservoirs and treated large rivers as having two banks.

We used the Protected Areas Database to estimate the amount of land set aside for conservation (DellaSala et al. 2001). The Protected Areas Database includes two primary attributes for conservation and land management. These are the International Union for Conservation of Nature (IUCN) codes and the Gap Analysis Program (GAP) (Scott et al. 1993) land stewardship codes (Supplementary material, Table S4). Our analysis included all lands with a GAP stewardship code of three or less. Lands identified with a GAP stewardship code of three or less includes all lands with IUCN codes one through six. We relied or the GAP stewardship codes rather than the IUCN codes because many lands with GAP stewardship codes of one and two did not have an associated IUCN code. Some protected lands would have been omitted if we had used IUCN codes to derive our conserved lands dataset. Our estimate of the total protected area was 209,459,669 ha, which was approximately 27% of the total area of the conterminous United States (Supplementary material, Table S5). Lands with a GAP stewardship code of three comprised approximately 75% of the 209,459,669 ha of protected area. U.S. National Forests, lands managed by the Bureau of Land Management (BLM) and U.S. military reservations were commonly assigned a GAP stewardship code of three.

Results

Approximately 78% of the conterminous United States lies within a drinking water watershed (Table 1). The proportion of land within a drinking water watershed varies regionally, from a low of 2.7% in the Great Basin region to 100% for many of the mid-continent and western regions. The typically high proportion of the land area of the conterminous United States within drinking water watersheds reflects the fact that most of the major rivers are used to supply drinking water (InsideEPA.com 2010) even though drinking water drawn from rivers is often more polluted and more expensive to treat than water drawn from lakes and reservoirs (Gray 2008). We found that approximately two-thirds of all the surface drinking water intakes in the conterminous United States are in rivers and one-third is in lakes and reservoirs.

Table 1 approximately here

The majority of drinking water watersheds are dominated by natural vegetation (Fig. 2). The median percentage natural vegetation is 77.1%, varying geographically from 17.1% in the upper Mississippi region to more than 90% for the western United States (Table 2). While drinking water watersheds are generally comprised of a high percentage of natural vegetation, the amount of land set aside for conservation is small. One-half of the drinking water watersheds have less than 3.1% of their area in set aside for conservation (i.e., protected). The much higher percentage protection in the western United States is attributable to high percentages of land in federal ownership (primarily the U.S. Forest Service and U.S. Bureau of Land Management). The high median percentage of natural vegetation in drinking water watersheds translates to relatively low median percentages for urban ($\tilde{x}$ = 5.2%) and agriculture ($\tilde{x}$ = 8.1%) (Table2). Comparing the median values for urban and agriculture with the median protected value indicates that the typical drinking water watershed has approximately 67% more urbanized land and 160% more agricultural land than land set aside in conservation. Land-cover composition and the amount of conserved land change with watershed size, approaching the national estimates for the respective statistics for the largest watersheds (Supplementary material, Table S5) (Homer et al. 2007).

Figure 2 approximately here

Table 2 approximately here

The land-cover composition and conserved land analyses were also conducted for the near-stream (riparian) environment because riparian management and restoration are activities supported by state and federal policies (Sweeney et al. 2004). In the case of drinking water, riparian areas are one example of sensitive source areas (Plummer et al. 2010), and watershed delineation based on pollutant travel time is essentially the near-stream environment. Median values for the riparian environment were very similar to the watershed median values despite a few noticeable differences in some regions (Table 2). These results are not unexpected because of the commonly strong correlation between riparian and watershed land-cover characteristics (Van Sickle 2003).

Natural vegetation in the drinking water watersheds was temporally dynamic. Approximately 23% of the watersheds (1,200 of 5,265) lost at least 1% of their natural vegetation, and approximately 5% of the watersheds had at least a 1% increase in natural vegetation between ca. 1992 and ca. 2001. The complementary statistics for the riparian area were 21% (≤ -1%) and 6% (≥ +1%). Loss of natural vegetation in drinking water watersheds was spread throughout the country but also showed some geographic concentration. At least 8% of the drinking water watersheds in 16 of the 18 hydrographic regions lost at least 1% of their natural vegetation, with only the Souris-Red-Rainy and Rio Grande hydrologic regions not reaching the 8% threshold. Overlaid on the nationwide pattern was a concentration of natural vegetation loss in the Southeast and Ohio hydrologic regions; 42% of the watersheds with at least a 1% loss of natural vegetation occurred in these two hydrologic regions (Fig. 3). Gains in natural vegetation were concentrated in four mid-continent hydrographic regions (Ohio, Missouri, Arkansas-White-Red, Texas Gulf) and the Mid-Atlantic. Gains in natural vegetation in these regions were predominantly agricultural abandonment giving way to shrublands.

Figure 3 approximately here

Much of the loss of natural vegetation was attributable to urbanization. Approximately 9% of the drinking water watersheds had at least a 1% increase in urban land between ca. 1992 and ca. 2001. Urbanization was greatest in the eastern United States. Approximately one-half of the drinking water watersheds with at least a 1% increase in urbanization were in the Mid-Atlantic and Southeast regions (Fig. 3). The highest percentage increases in urban land were not strictly confined to smaller watersheds, indicating urbanization was widespread in some larger watersheds. We also found that the amount of urban land increased in 75% of the drinking water watersheds.

Figure 4 approximately here

Discussion

A non-probabilistic risk management model, the multiple barrier defense, is used to protect U.S. drinking water resources. The multiple barrier defense is based on the assumption that the likelihood of delivering contaminated drinking water is reduced if natural vegetation is maintained and conserved, treatment of raw (e.g., river, lake) water is adequate and consistent, the delivery system is kept in a state of good repair, and there is effective communication with the public. The 1996 amendments to the Safe Drinking Water Act advanced the multiple barrier concept through its requirement that states delineate source water watersheds. Delineation of source water watersheds are used as a basis for the inventory of potential pollutants, assessment of the susceptibility of drinking water to contamination by pollutants, and public outreach (U.S. EPA 1997), establishing watersheds as the framework upon which drinking water is managed.

In a probabilistic risk assessment, land-cover composition, the amount of conserved land, and hydrographic context would be elements of exposure characterization (Suter et al. 2003). Nitrate, pesticides, industrial chemicals, pathogens, and algal toxins are all potential drinking water contaminants that are attributable to watershed land uses such as urban and agricultural land (Gray 2005). For example, it is well known the urban and agriculture land uses often contribute excess nitrate to water bodies (e.g., Frink 1991; Wickham et al. 2005). High nitrate levels in drinking water may be hazardous to young children, children with gastroenteritis, and pregnant women (Gray 2005), and may be a risk factor for some cancers (Swartz et al. 2003; Ward et. al. 2005). Removal of nitrate from drinking water supplies is costly and difficult (Gray 2005). Gilliom et al. (2006) found that pesticides occurred at detectable levels year round in streams draining from agriculture and urban areas, and that 5% to 10% of the streams in these areas had pesticide concentrations the exceeded human-health thresholds. Atrazine is the most commonly detected pesticide (Kolpin et al. 1998; Gilliom et al. 2006), and it is considered an endocrine disrupting compound that has been attributed to reproductive abnormalities in amphibians and fish (Suzawa and Ingraham 2008). Reynolds et al. (2008) estimates that there were 183 disease outbreaks due to pathogen contamination of drinking water between 1991 and 2002. Agriculture and urban land use are both significant sources of bacterial contamination of surface waters (Baxter-Potter and Gilliland 1988; Wickham et al. 2006). Toxigenic strains of *Escherichia coli*, *Giardia lamblia*, and *Cryptosporidium parvum* are three pathogens of primary concern in the U.S., and all are known to cause dysentery and have also been linked to other diseases (Reynolds et al. 2008)

Although limited, there are some studies directly linking drinking water quality to land-cover composition of the source areas. Hrudey et al. (2006) examined six cases of drinking water contamination, and land use factored into the contamination in four of the cases. Swartz et al. (2003) found a positive relationship between the amount of residential land use and drinking water nitrate concentration. Derlet et al. (2010) proposed changes to the system of cattle grazing in the Sierra Nevada Mountains as a means to further protect the drinking water drawn from the area. Mehaffey et al. (2005) showed that small decreases in urban and agricultural land use in the drinking water watersheds for New York City led to detectable improvements in water quality.

The linkage between land-cover composition and drinking water quality serves to emphasize the importance of natural vegetation for the protection of drinking water source areas (e.g., www.forest-to-faucet.org/publications.html). Our national analysis showed that most U.S. drinking water watersheds have a high proportion of natural vegetation. This pattern suggests that exposure to drinking water contaminants is likely to be greater in the relatively few watersheds where natural vegetation is not dominant. For example, approximately 20% of the watersheds (1,144 of 5,265) have less the 50% natural vegetation, and approximately 8% of the watersheds (411 of 5,265) have at least 20% urbanized land. Our analysis also showed that the overall temporal trend in land-cover composition is loss of natural vegetation and an increase in urbanized land. The number of watersheds that lost at least 1% natural vegetation (1200) was approximately five times greater than the number of watersheds that gained at least 1% natural vegetation (244), and 9% of the watersheds had a least a 1% gain in urbanized land (467). The temporal trends in land cover suggest that many drinking water source areas may be becoming more exposed to contaminants and pollutants.

Loss of natural vegetation and urbanization are motivating interest in conservation for protection of drinking water sources, but the value of conservation has only recently become of focus of drinking water protection (NRC 2000; Dudley and Stolton 2003; Ernst et al. 2004; Postel and Thompson 2005; Mehan 2009). The interest in land conservation has been mainly within the realm of biodiversity conservation (DellaSalla et al. 2001; Scott et al. 2001). The amount of protected land needed to sustain biotic populations has been studied and debated by conservation biologists (Scott et al. 2001; Shaffer et al. 2002), but similar, more broadly scoped discussions have not yet occurred with regard to source water protection. The surveys of land conservation for drinking water protection (e.g., Dudley and Stolton 2003; Postel and Thompson 2005) suggest conservation occurs on a case-by-case basis, such as was the case for New York City (NRC 2000). We found that the median percentage of conserved land in drinking water watersheds for the nation was low (~3%), and varied widely from region to region. Median percentages of conserved land were high in the western United States because of the extensive holdings of federal land and quite low in the eastern United States (often less than 1%).

Our analysis shows the value of bringing a national perspective to the assessment of drinking water resources. National assessments provide a level of integration and insight (Riitters et al. 2002; Riitters and Wickham 2003; The Heinz Center 2008; Wickham et al. 2008, 2010) that can complement state-administered management of drinking water source areas (ASDWA 2009; Tiemann 2008). Nationally over three-quarters of the conterminous United States lies within a drinking water watershed, and many of them cross state boundaries. There was strong regional variation in the amount of natural vegetation, urban and agricultural land use, and the proportion of land set aside in conservation. There was also distinct regional variation in temporal change in natural vegetation and urbanization. These regional patterns in land-cover composition and land-cover change suggest that there may also be regional patterns in exposure to drinking water contaminants. Land use pressures will also challenge U.S. drinking water systems in the next century and will require the coordinated actions of all those sharing watersheds or aquifers (sensu Levin et al. 2002). Our quantitative assessment of land-cover patterns for U.S. drinking water watersheds is consistent with the analysis of Levin et al. (2002). U.S. drinking water watersheds tend to have a high proportion of natural vegetation, but little of it is set aside for conservation, and their land-cover compositions tend to be temporally dynamic, often due to urbanization.

These patterns suggest that the status of source water protection will change as a result of ineluctable changes in natural vegetation and that the rate of urbanization will likely outpace the rate of new lands set aside in conservation (Scott et al. 2001; Raleigh News & Observer 2010).

Acknowledgments

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Figures

Fig. **1**. USGS hydrologic regions overlaid on state boundaries. Names for each region number are provided in Table 1 of the main article.

Fig. 2. Cumulative distributions of natural vegetation (A), agriculture (B), and urban (C) for 5,265 drinking water watersheds.

Fig. 3. Change in natural vegetation ca. 1992 to ca. 2001 for the entire watershed (A) and the riparian area (B). Regions 3, and 5, are symbolized as red (•), and blue (•) dots, respectively. All other regions are symbolized as a plus (+) sign. Watershed area (ha) was converted using a $\log_{10}$ base. Region names are listed in Table 1.

Fig. 4. Change in urban land ca. 1992 to ca. 2001 for the entire watershed (A) and riparian area (B) versus watershed size. Regions 2 and 3 are symbolized as blue (•) and red (•) dots, respectively. All other regions are symbolized as a plus sign (+). Watershed area (ha) was converted using a $\log_{10}$ base. Region names are listed in Table 1.

Figure 1

Figure 2

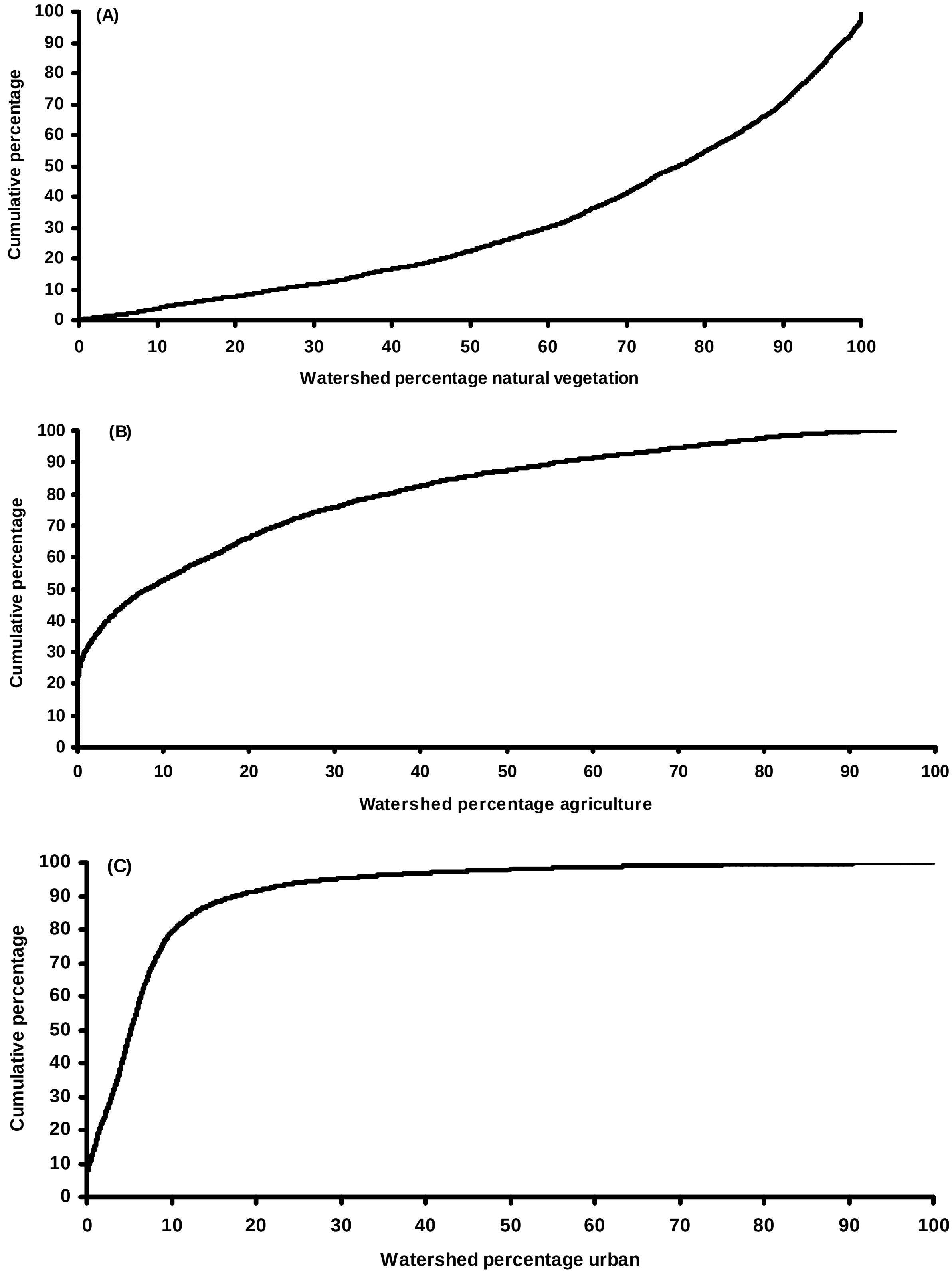
(A)
Cumulative percentage
0
10
20
30
40
50
60
70
80
90
100
Watershed percentage natural vegetation
(B)
Cumulative percentage
Watershed percentage agriculture
(C)
Cumulative percentage
Watershed percentage urban

Figure 3

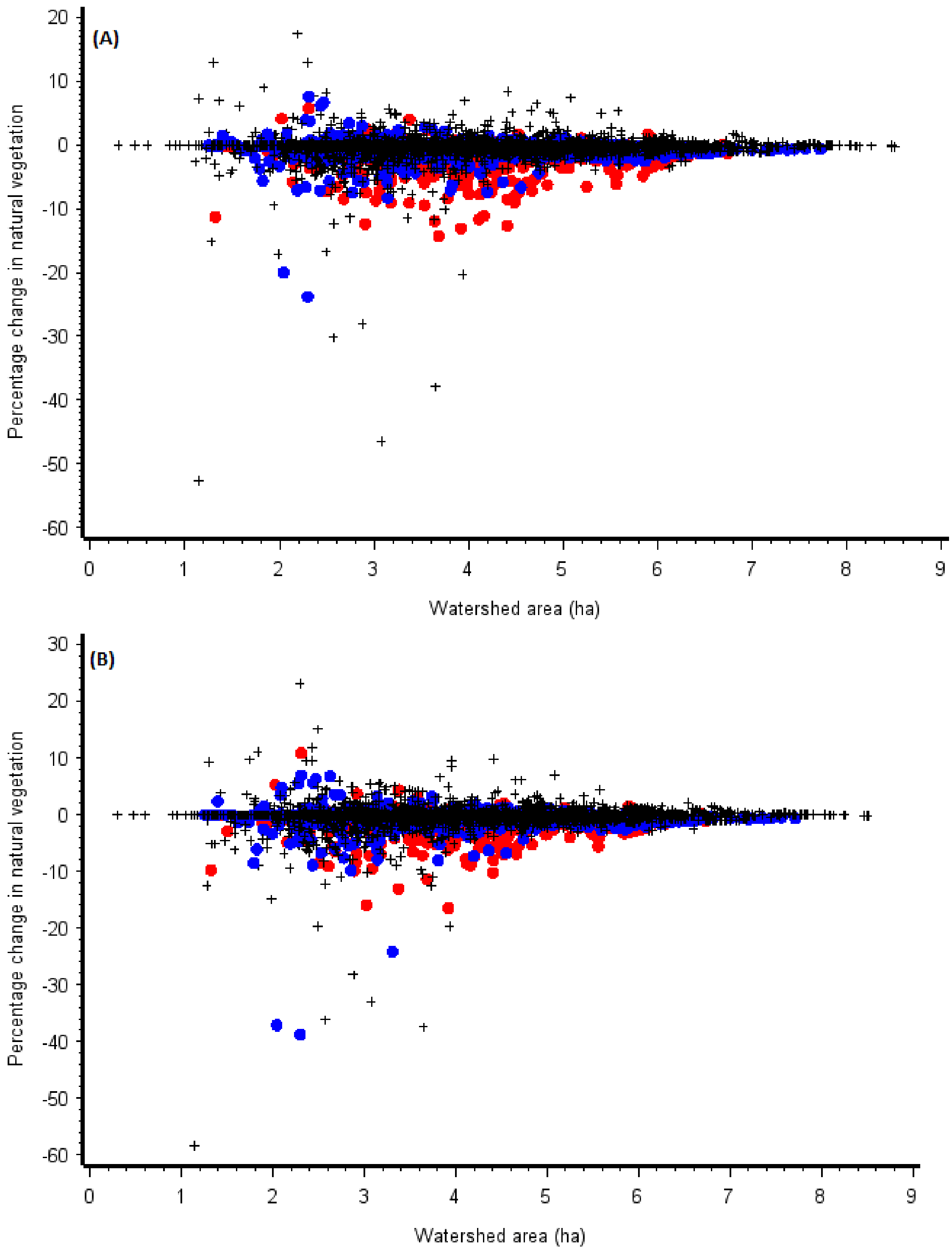
(A)
Percentage change in natural vegetation
20
10
0
-10
-20
-30
-40
-50
-60
0
1
2
3
4
5
6
7
8
9
Watershed area (ha)
(B)
Percentage change in natural vegetation
30
20
10
0
-10
-20
-30
-40
-50
-60
0
1
2
3
4
5
6
7
8
9
Watershed area (ha)

Figure 4

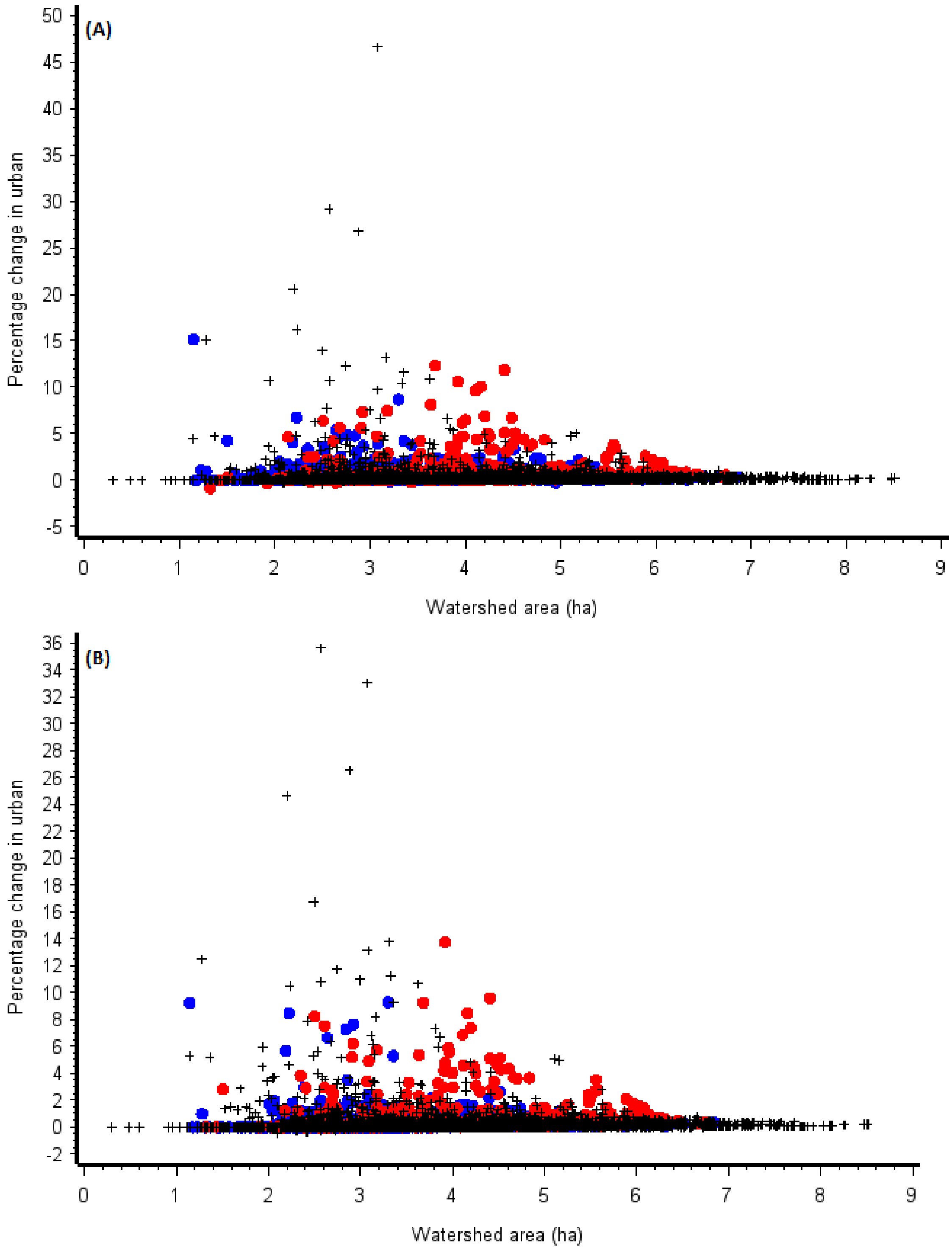
(A)
Percentage change in urban
50
45
40
35
30
25
20
15
10
5
0
-5
0
1
2
3
4
5
6
7
8
9
Watershed area (ha)
(B)
Percentage change in urban
36
34
32
30
28
26
24
22
20
18
16
14
12
10
8
6
4
2
0
-2
0
1
2
3
4
5
6
7
8
9
Watershed area (ha)

Table 1. Area of U.S. drinking water watersheds by U.S. Geological Survey hydrologic regions. Regions 5, 6, 7, 10, 11, and 14 are upstream of region 8 and 15 so the total drinking water watershed area in the upstream regions is equal to the area of the region (i.e., 100%). Area estimates for hydrologic regions were based on the USGS hydrologic region map (Fig. S1) adjusted to state boundaries, and exclusive of major water bodies (e.g., Great Lakes).

Region	Name	Drinking water watershed area (ha)	Area of Region (ha)	Percentage (%)
1	New England	5,745,791	15,544,971	37.0
2	Mid-Atlantic	22,172,165	27,171,609	81.6
3	Southeast	30,831,906	69,181,029	44.6
4	Great Lakes	7,282,712	30,280,901	24.1
5	Ohio	42,194,511	42,194,511	100.0
6	Tennessee River	10,595,378	10,595,378	100.0
7	Upper Mississippi	49,177,325	49,177,325	100.0
8	Lower Mississippi	20,811,766	25,916,411	80.3
9	Souris-Red-Rainy	10,319,496	15,704,309	65.7
10	Missouri	132,225,308	132,225,308	100.0
11	Arkansas-White-Red	64,238,408	64,238,408	100.0
12	Texas Gulf	36,355,684	46,299,359	78.5
13	Rio Grande	32,588,683	33,897,488	96.1
14	Upper Colorado	29,357,007	29,357,007	100.0
15	Lower Colorado	35,063,208	35,063,208	100.0
16	Great Basin	980,850	36,731,499	2.7
17	Pacific Northwest	63,950,968	70,846,826	90.3
18	California	13,742,548	41,452,336	33.2
All	Conterminous U.S.	607,633,714	775,877,883	78.3

Table 2: Median values of percentage conserved land, natural vegetation, urban, and agriculture for drinking water watersheds and the near-stream (riparian) environment from ca. 2001 NLCD.

Region		Conserved Land		Natural Vegetation		Urban		Agriculture	
	Number of Watersheds	Watershed (%)	Riparian (%)	Watershed (%)	Riparian (%)	Watershed (%)	Riparian (%)	Watershed (%)	Riparian (%)
1	474	2.7	1.3	78.7	74.9	6.2	6.3	3.1	2.7
2	816	4.8	2.1	77.6	73.1	4.9	5.6	8.6	6.2
3	489	0.2	0.2	65.4	70.9	9.0	6.5	17.5	14.4
4	164	0.8	0.4	35.5	43.7	6.5	7.2	39.9	35.3
5	707	1.8	2.0	69.4	69.9	6.7	7.3	20.1	17.5
6	208	7.3	6.7	70.3	68.3	6.8	7.5	18.5	19.4
7	144	0.0	0.0	17.6	30.5	7.1	6.6	68.6	53.9
8	52	11.4	13.4	58.8	64.1	5.3	4.6	22.4	28.6
9	21	3.2	3.0	22.1	30.2	4.4	4.3	68.8	56.1
10	399	14.8	17.7	67.2	72.1	3.3	2.6	23.2	12.3
11	413	0.9	1.0	70.6	73.8	4.6	4.0	18.8	15.8
12	265	0.0	0.0	80.3	86.3	4.3	3.5	13.7	6.4
13	43	33.9	36.1	95.6	97.4	1.3	1.0	1.4	0.6
14	137	80.3	79.0	91.4	92.2	0.4	0.4	0.3	0.4
15	71	85.7	79.0	96.5	96.5	1.1	1.1	0.0	0.0
16	58	61.7	65.7	92.4	93.2	1.9	2.9	0.0	0.0
17	368	44.3	49.6	93.9	94.1	2.1	2.0	0.0	0.0
18	436	17.3	28.3	93.1	93.0	3.6	3.6	0.0	0.0
US	5265	3.1	3.4	77.1	77.3	5.2	4.8	8.1	6.3

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Supplementary Material for

A national environmental assessment of U.S. drinking water watersheds

Drinking water intake

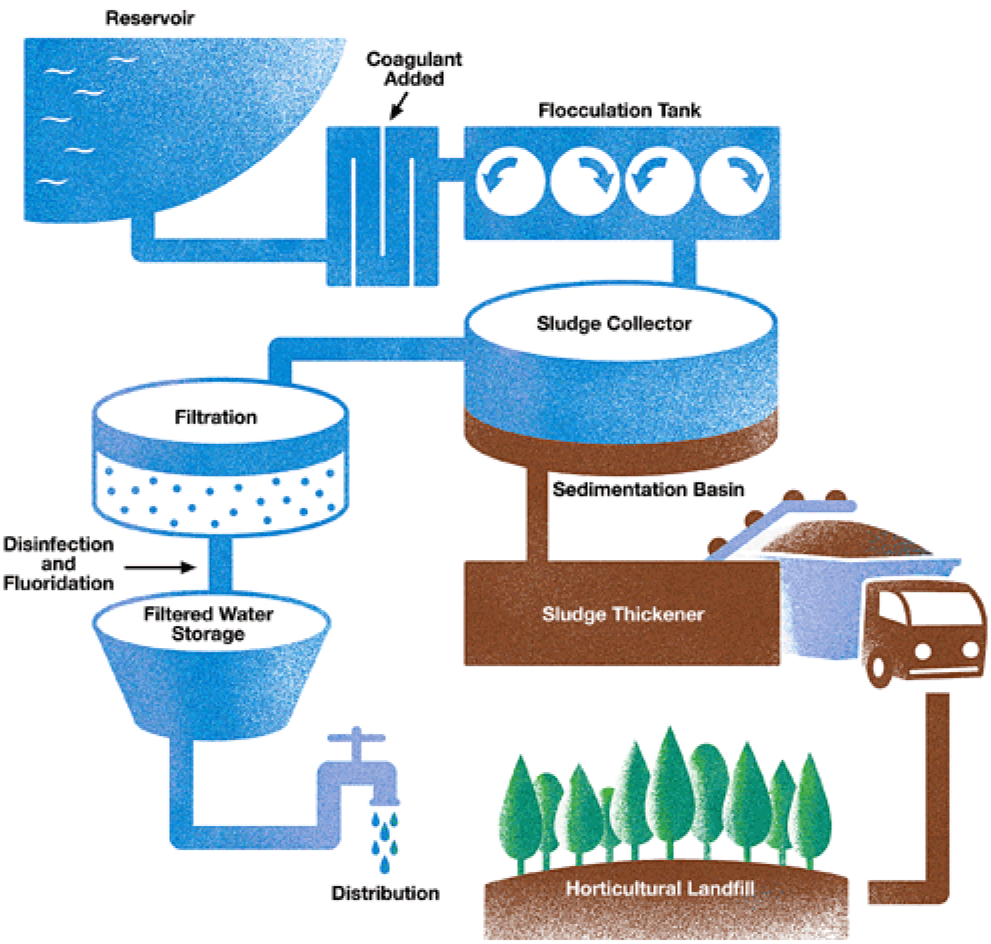

Figure S1. Schematic diagram of drinking water treatment from source to tap. source: http://www.ogwa-hydrog.ca/en/node/39

Water is drawn through a pipe from a lake, reservoir, or stream. Screens are usually placed on the pipe in the source water (e.g., reservoir) to prevent large debris from being drawn in with the water. Chemicals are then added, commonly chlorine and aluminum sulphate, to kill bacteria, improve taste and odor, and to make smaller particles in the water stick together (coagulate). The water is then passed to a flocculation tank where it is mixed to stimulate coagulation. The coagulated particles are referred to as floc. The water is then passed to a sedimentation basin to allow the floc to settle. After settling the water is passed to a filtration tank where it is passed through sand and other materials to remove any remaining particles. After filtration the water is treated again with chlorine, flouride, and perhaps other disinfectants to remove bacteria before it is moved to storage tanks for distribution. There are several variations on the steps described above (Gray 2005).

Methods

Several figures and tables supporting the delineation of U.S. drinking water watersheds are provided as supplemental information. As described in the Methods section of the main article, NHD classes were used to determine if a watershed could be delineated for a drinking water intake. Watersheds were not delineated for drinking water intakes that overlaid on NHD classes Canal/Ditch or Pipeline.

Table S1. Descriptions of linear features in the National Hydrogaphy Dataset (NHD). Descriptions taken from http://nhd.usgs.gov/FeatureDirectory.pdf (accessed November 2010).

Class	Description
Artificial Path	An abstraction to facilitate hydrologic modeling through open water bodies and along coastal and Great Lakes shorelines
Canal/Ditch	An artificial open waterway constructed to transport water, to irrigate or drain land, to connect two or more bodies of water, or to serve as a waterway for watercraft.
Connector	A known but nonspecific connection between two nonadjacent network segments.
Pipeline	A closed conduit, with pumps, valves, and control devices for conveying fluids, gases, or finely divided solids.
Stream/River	A body of flowing water.

Some drinking water intakes in lakes and reservoirs were not located where the waterbody drained to the out-flowing stream. Relocation of these drinking water intakes to the waterbody outlet increased the size of the watershed for that intake and these locational adjustments had the potential to increase the total area of the conterminous United States that was within a drinking water watershed. The effect of the locational adjustments on the total area of the conterminous United States that was within a drinking water watershed is reported in Table S2. The locational adjustments to drinking water intakes in lakes and reservoirs increased the total area of the conterminous United States with a drinking water watershed by 0.3% (compare Table S2 with Table 1 in the main article).

Table S2. Adjusted drinking water watershed areas after moving drinking water intakes (DWI) to lake or reservoir outlets. Movement of drinking water intakes to lake or reservoir outlets had no effect on the total area of drinking water watersheds in regions 5, 6, 7, 10, 11, and 14 because the watersheds in these regions are upstream of watersheds in other regions. A value of zero for DWIs moved for other regions (8, 9, 13, 15, 16) indicates that locational adjustments were not necessary. Region names are listed in Table 1 of the main article.

USGS Hydrographic Region	Drinking water watershed area (ha)	Number of DWIs moved	Area (ha) added	Adjusted watershed area (ha)	Area (ha) of region	Adjusted Percentage (%)
1	5,745,791	16	224,005	5,969,796	15,544,971	38.4
2	22,172,165	8	19,443	22,191,608	27,171,609	81.7
3	30,831,906	5	1,215,710	32,047,616	69,181,029	46.3
4	7,282,712	10	240,145	7,522,857	30,280,901	24.8
5	42,194,511	0	0	42,194,511	42,194,511	100.0
6	10,595,378	0	0	10,595,378	10,595,378	100.0
7	49,177,325	0	0	49,177,325	49,177,325	100.0
8	20,811,766	0	0	20,811,766	25,916,411	80.3
9	10,319,496	0	0	10,319,378	15,704,309	65.7
10	132,225,308	0	0	132,225,308	132,225,308	100.0
11	64,238,408	0	0	64,238,408	64,238,408	100.0
12	36,355,684	2	75,456	36,431,140	46,299,359	78.7
13	32,588,683	0	0	32,588,683	33,897,488	96.1
14	29,357,007	0	0	29,537,007	29,357,007	100.0
15	35,063,208	0	0	35,063,208	35,063,208	100.0
16	980,850	0	0	980,850	36,731,499	2.7
17	63,950,968	0	0	63,950,968	70,846,826	90.3
18	13,742,548	9	76,701	13,819,249	41,452,336	33.3
All	607,633,714	50	1,851,460	609,485,174	775,887,883	78.6

The NLCD 1992-2001 land-cover change data (Fry et al. 2008) were used to derive land-cover and land-cover change percentages. The land-cover class descriptions are provided in Table S3.

Table S3. Legend for the NLCD 1992-2001 land-cover change data. Descriptions adapted from http://www.mrlc.gov/nlcd_definitions.php. The perennial ice & snow class was combined with open water in our analysis.

Class	Description
(1) Open Water	All areas of open water, generally with < 25% cover of vegetation or soil
(2) Urban	Includes all urbanized areas from low-density residential to commercial areas where constructed materials cover 100% of the surface. The class also includes roads and open areas associated with urban areas (e.g., parks, lawns, golf courses).
(3) Barren	Vegetation accounts for less than 15% of cover, and includes exposed areas of bedrock, desert pavement, scarps, talus, mining activity, gravel pits, and unconsolidated shore.
(4) Forest	Areas dominated by tree generally greater than 5 meters tall, and greater the 20% of total vegetation cover.
(5) Shrubland-grassland	Areas dominated by shrubs generally less than 5 meters tall with a shrub canopy typically greater than 20%, or areas dominated by grammanoid or herbaceous vegetation (cover generally greater than 80%). The shrub component of the class can include true shrubs, young tree in an early succession stage, or trees that are stunted from environmental conditions.
(6) Agriculture	Areas use for the production of crops (e.g., corn, soybeans, vegetables, orchards) and areas of grass devoted to livestock grazing or the production of hay crops.
(7) Wetland	Areas of woody or herbaceous cover on soil that is periodically saturated or covered with water. Vegetation cover is greater than 20%.
(8) Perennial Ice & snow	All areas characterized by a perennial cover of ice or snow; ice or snow cover is generally greater than 25%.

We used the protected areas database (DellaSalla et al. 2001) to estimate percentages of conserved land. The protected areas database includes two different attributes to define conserved land (Table S4) – the International Union of Conservation of Nature (IUCN) codes and the Gap Analysis Program (GAP) land stewardship codes (Scott et al. 1993). We used GAP land stewardship codes of three or less to define conserved lands.

Table S4. Descriptions of IUCN conservation GAP stewardship codes.

IUCN codes	Description
Ia	Strict nature reserve - protected and managed for science
Ib	Wilderness area - protected and managed for wilderness protection
II	National Park - protected and managed for ecosystem protection & recreation
III	Natural Monument - protected area managed for conservation of natural features
IV	Habitat or species management area - managed for conservation
V	Protect landscape or seascape - managed for conservation or recreation
VI	Managed resource protected area - manage for sustainable use

GAP codes	Description
1	Area with active management plan to maintain natural state
2	Area managed for natural values but some uses may degrade natural communities
3	Legal mandates prevent permanent conversion of natural habitat
4	Private or public lands without irrevocable management agreement

Additional Results

Most U.S. drinking water watersheds are small (Fig. S2). Approximately one-half of all U.S. drinking water watersheds are less than 50 km^2. Drinking water distribution systems are classified as community water systems (CWS), Non-Transient Non-Community Water System (NTNCWS), and transient non-community water system (TNCWS) (US EPA 2008). CWS systems supply drinking water to the same community throughout the year. A NTNCWS supplies drinking water to factories, schools, and similar facilities, and a TNCWS supplies drinking water to entities such as gas stations and campgrounds.

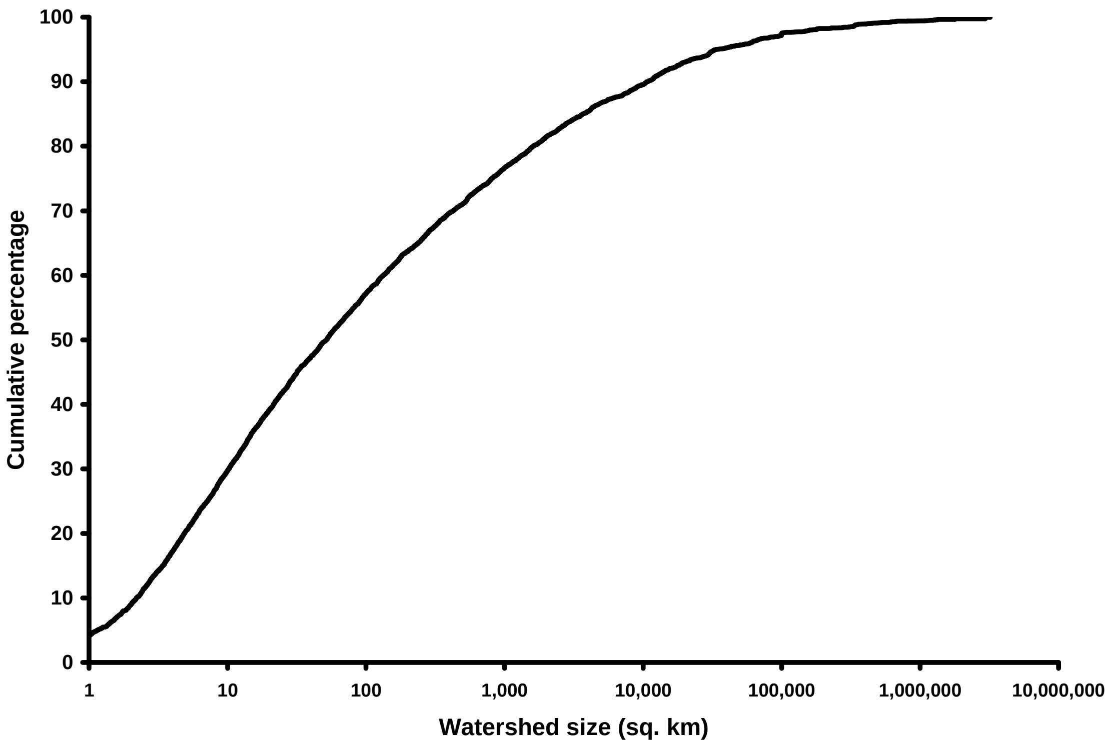

Fig. S2. Cumulative distribution of 5,265 drinking water watersheds as a function of watershed size. Watersheds less than 1 km^2 (~ 4% of the watersheds) are not shown.

Many drinking water watersheds are small because the CWS systems for smaller urbanized areas are naturally small, as are the watersheds for NTNCWS and TNCWS distribution systems. The majority of the U.S. population is served by a few large CWS systems associated with the major urban areas (US EPA 2008).

The amount of conserved land, natural vegetation and agriculture changed as a function of watershed size (Table S5). The smallest drinking water watersheds were almost exclusively comprised of natural vegetation but it was essentially unprotected, whereas the land-cover composition for the largest watersheds was similar to the national statistics for land cover (Homer et al. 2007) but not for conserved land. As a set, the land-cover composition for the largest watersheds would be expected to be similar to their national counterparts because these watersheds comprise a high proportion of the conterminous United States. The amount of conserved land for the largest watersheds was not similar to its national estimate because the majority of conserved land was in the western United States but the majority of surface water watersheds were in the eastern United States.

Table S5. Median percentages of conserved land, natural vegetation, urban and agriculture by watershed size class for drinking water watersheds. Land-cover composition percentages for the conterminous U.S. are from (Homer et al. 2007), and the conserved land percentage is reported in the methods section of the main article.

Drinking water watershed size class (hectares)	Number of observations	Conserved land (%)	Natural vegetation (%)	Urban (%)	Agriculture (%)
< 1,000	1544	0.0	84.8	4.3	0.9
1,000 - 100,000	2481	2.3	76.4	5.4	8.5
100,000 - 1,000,000	683	6.6	71.6	5.7	16.7
≥ 1,000,000	557	12.1	71.2	5.3	18.8
Conterminous United States		27.0	66.0	5.1	22.5

Percentage impervious surface, derived from NLCD 2001 (Homer et al. 2007), was quite low in U.S. drinking water watersheds (Fig. S3). The median percentage impervious surface in U.S. drinking water watersheds was less than one percent ($\tilde{x}$ = 0.62%), and only 5% of the drinking water watersheds had percentage impervious surface estimates that were $\geq$ 10%, which is considered a nominal threshold indicating water quality impairment (Arnold and Gibbons 1996, Brabec et al. 2002).

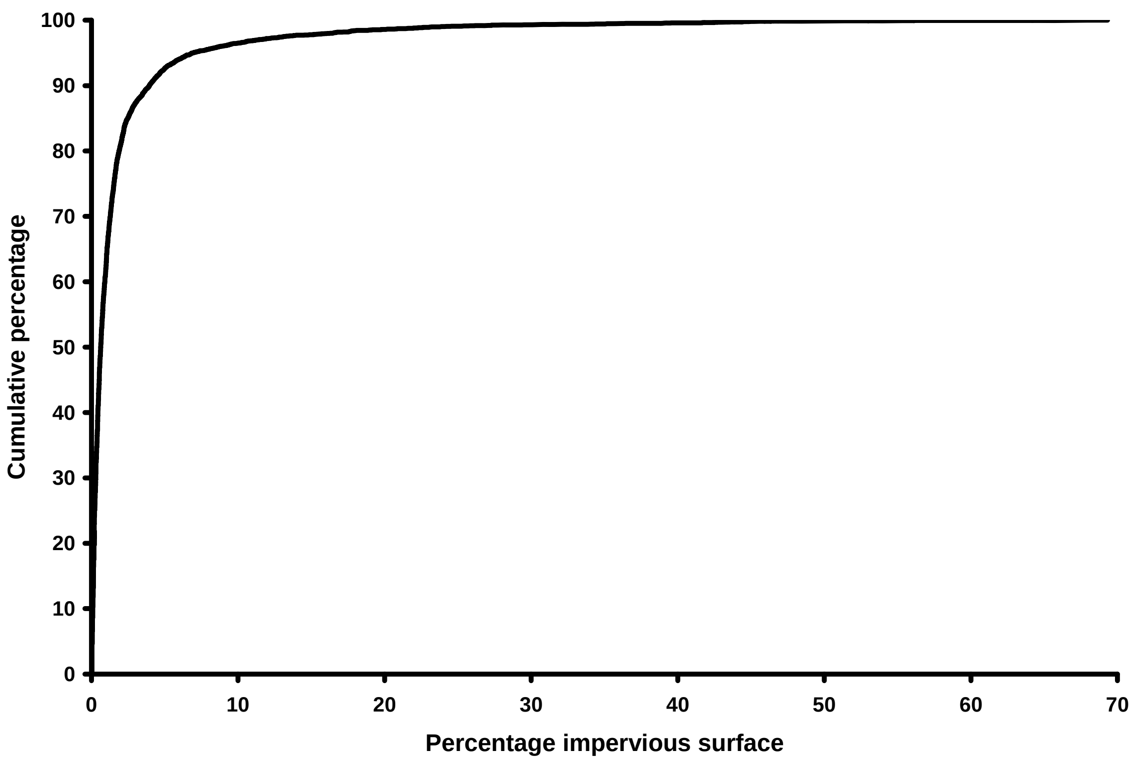

Fig. S3. Cumulative distribution of 5,265 drinking water watersheds as a function of percentage impervious surface.

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