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Potential Effects of Landscape Change on Water Supplies in the Presence of Reservoir Storage

Andrew John Guswa
Smith College, aguswa@smith.edu

Perrine Hamel
Stanford University

P. James Dennedy-Frank
Stanford University

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Key Points:

- Records of streamflow, rainfall, and snowmelt can be used to bound the effects of landscape change on water supply
- Across 593 U.S. watersheds, flow regulation diminishes in value relative to the costs of water losses as reservoir storage increases
- Water supplies are buffered from effects of landscape change when reservoir storage is 0.1–10% of mean-annual-streamflow

Correspondence to:
A. J. Guswa,
aguswa@smith.edu

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Potential effects of landscape change on water supplies in the presence of reservoir storage

Andrew J. Guswa[1], Perrine Hamel[2], and P. James Dennedy-Frank[3]

[1]Picker Engineering Program, Smith College, Northampton, Massachusetts, USA, [2]Natural Capital Project, Stanford University, Stanford, California, USA, [3]Department of Earth System Science, Stanford University, Stanford, California, USA

Abstract This work presents a set of methods to evaluate the potential effects of landscape changes on water supplies. Potential impacts are a function of the seasonality of precipitation, losses of water to evapotranspiration and deep recharge, the flow-regulating ability of watersheds, and the availability of reservoir storage. For a given reservoir capacity, simple reservoir simulations with daily precipitation and streamflow enable the determination of the maximum steady supply of water for both the existing watershed and a hypothetical counter-factual that has neither flow-regulating benefits nor any losses. These two supply values, representing land use end-members, create an envelope that defines the water-supply service and bounds the effect of landscape change on water supply. These bounds can be used to discriminate between water supplies that may be vulnerable to landscape change and those that are unlikely to be affected. Two indices of the water-supply service exhibit substantial variability across 593 watersheds in the continental United States. R_{cross}, the reservoir capacity at which landscape change is unlikely to have any detrimental effect on water supply has an interquartile range of 0.14–4% of mean-annual-streamflow. Steep, forested watersheds with seasonal climates tend to have greater service values, and the indices of water-supply service are positively correlated with runoff ratios during the months with lowest flows.

1. Introduction

The concept of ecosystem services recognizes the value to people of what are considered to be natural ecosystem and landscape processes [e.g., *National Research Council*, 2004; *Daily*, 1997]. Water-related services include filtration, erosion prevention, flood mitigation, and the storage and release of water to sustain streamflows [*Martin-Ortega et al.*, 2015; *Guswa et al.*, 2014; *Gartner et al.*, 2013; *Brauman et al.*, 2007]. In the United States and around the world, ecosystem services are being incorporated in planning and decision-making. Multiple water funds have been established in Latin America to facilitate payments for water-related ecosystem services [e.g., *Bremer et al.*, 2016; *Martin-Ortega et al.*, 2013; *Anderson*, 2007]. In China, over $50 billion have been spent on the Natural Forest Conservation Program and the Sloping Land Conversion Program to restore forests and grasslands and provide ecosystem-service benefits [e.g., *Ouyang et al.*, 2016; *Yin et al.*, 2014; *Ma et al.*, 2009; *Liu et al.*, 2008]. All federal projects in the United States are now required to assess the impacts to ecosystem services [*Office of Management and Budget*, 2015].

Within this ecosystem-services context, decision makers would like to know how landscape changes will affect water supplies. Water availability is largely a function of climate, but that climate signal is modulated by the landscape. Watersheds provide a benefit to local supplies by concentrating precipitation inputs in space and distributing them in time. Watersheds also remove water via evapotranspiration and deep recharge. While this redistribution and recycling of water is essential for the maintenance of downgradient and inland ecosystems at regional to global scales [*Ellison et al.*, 2012; *Brubaker et al.*, 1993; *Salati et al.*, 1979], it represents a cost to the local water supply. Because landscape changes have the potential to affect both costs and benefits, predicting their effects on water supplies is challenging. Additionally, proper assessment of the impact to water supplies requires the consideration of built infrastructure. With little or no reservoir storage, the flow-regulating benefits of natural watersheds are necessary to ensure reliable water supplies between periods of rain. A storage reservoir, however, may diminish the value of the flow regulation service of a natural watershed and amplify the cost of water lost to evapotranspiration or deep drainage [*Smakhtin*, 2001].

Many ecosystem-service decisions contexts are resource constrained, whether in time, money, or data. These constraints increase the already challenging task of predicting the consequences of land-management changes, which result from complex interactions among climate, watershed processes, and built infrastructure. Being able to discriminate among situations for which the potential effects of land use changes on water supplies are large from those for which the effects are likely to be small or irrelevant would enable resources to be allocated appropriately to support effective decisions.

This work does not attempt to predict the specific effects of a particular landscape change on water supply. Rather it provides a set of methods to assess the current value of natural watershed processes to water supplies and to identify when land use changes might put those supplies at risk. In essence, this work leapfrogs the hydrologic-science question of "what are the effects of landscape changes on streamflow?" to answer the water-resources question of "will landscape changes matter to water supply?" The intellectual novelty and innovation of this work is the integration of natural watershed processes with built infrastructure to quantify the water-supply service of watersheds and the assessment of variability of that service across 593 U.S. watersheds. Pragmatically, this work provides a set of methods, with a range of data requirements, for bounding the effects of landscape changes on water supplies.

While water supply is the focus of this work, we recognize that it is neither the only nor perhaps even the most important water-related ecosystem service [e.g., *Gartner et al*., 2013; *Keeler et al*., 2012; *Brauman et al*., 2007]. Thus, interpretations and conclusions presented in this paper should not be construed as recommendations for specific actions. The intention is that the analyses and results from this work can inform holistic and integrative decisions.

2. Background: Effect of Land-Management on Water Supply

Ecosystem-service decisions are often decisions regarding land-management. Common decision contexts range from scenario analysis to payments for ecosystem services to spatial planning [*Guswa et al*., 2014]. All require an ability to estimate the effects of landscape changes on the services of interest, which may range from pollination to carbon storage to recreation to water supply. These decision contexts are challenging due to the desire to consider the response of multiple services to land use changes coupled with often-limited resources. Consequently, ecosystem-service assessments benefit from a tiered approach [e.g., *Kareiva et al*., 2011] that allows for rapid screening, followed by more detailed investigations when and where needed. Decisions that potentially impact water supplies will be most effective when hydrologic understanding is used to select the most appropriate approaches given the available data and information [*Fatichi et al*., 2016; *Mulligan et al*., 2015; *Guswa et al*., 2014; *Tallis and Polasky*, 2011; *Daily et al*., 2009].

Reviews of paired-catchment experiments show that deforestation leads to an increase in overall water yield, the long-term ratio of streamflow to precipitation [e.g., *Brown et al*., 2013, 2005; *Andréassin*, 2004; *Bruijnzeel*, 2004; *Bosch and Hewlett*, 1982]. Some simple models incorporate this knowledge into water balances that depend on annual precipitation and potential evapotranspiration [e.g., *Boithias et al*., 2016; *Duku et al*., 2015; *Hamel and Guswa*, 2015; *Terrado et al*., 2013]. However, unless in the presence of a very large reservoir, the provision of a water supply depends not only on the annual water yield, but also the timing and variability of streamflow, and the magnitude and steadiness of low flows. In particular, domestic, industrial, and commercial uses of water require a relatively steady supply, and limits to these water uses are often dominated by low-flow periods. A variety of low-flow indices, such as flow quantiles and the lowest-flow of *d* consecutive days with a specified return period, have been used to characterize low flows [e.g., *Laaha et al*., 2013], and organizations, such as the U.S. Geological Survey and World Meteorological Organization, have developed tools for estimating low flows and sustainable waters supplies [*Archfield et al*., 2009; *World Meteorological Organization* (*WMO*), 2008]. However, these efforts tend to focus on existing watershed conditions rather than the effects of land use changes, and, therefore, have less applicability to ecosystem-service decisions. Effective assessments of water-related ecosystem services require an understanding of how landscape changes affect supplies during critical low-flow periods. For example, in a survey of sixteen water funds in Latin America, *Bremer et al*. [2016] found that more than half had the maintenance of dry-season flows as an important goal for investments in land-management activities.

The hydrologic literature is less clear about the effects of landscape change on low flows due to the competing processes of flow regulation and evapotranspiration, which depend on site-specific soils, geology, geomorphology, and land cover [*Laaha et al*., 2013; *Jencso and McGlynn*, 2011; *Price*, 2011; *Devito et al*., 2005; *Smakhtin*, 2001]. Previous work has controlled for climate and geology by comparing the hydrologic behavior of catchments from the same physiogeographic setting to understand how land cover and other watershed features affect low flows. *Price et al*. [2011] examined the 99% exceedance flow, minimum day flow, and minimum 7 day mean flow for 35 streams in the Blue Ridge Mountains of Georgia and North Carolina. They found that low flows were positively correlated with topographic complexity and low drainage densities, and consistently higher low flows were observed in forested watersheds among geomorphically similar watersheds [*Price et al*., 2011]. Similarly, a forested headwater catchment in the Panama Canal Watershed had higher low flows in comparison with the low flows from a neighboring watershed with mixed land covers [*Ogden et al*., 2013]. These findings contradict results from 16 paired-catchment studies in the southern hemisphere for which afforestation led to lower streamflows across all parts of the flow-duration curves [*Brown et al*., 2013]. Similarly, *Scott and Lesch* [1997] reported that afforestation with eucalyptus and pine in South Africa led to reductions in dry-season (April–September) flows and that those flows recovered upon deforestation. *Bruijnzeel* [2004] offers an explanation for this contradictory behavior, asserting that when forest clearing does not disturb the soils it results in increased total and low flows; if clearing reduces infiltration, then low flows may decrease. However, recent results add to the confusion; *Biederman et al*. [2015] found no evidence of increased streamflow following forest mortality induced by bark beetle infestation in eight headwater catchments of the Colorado River.

The ambiguity associated with the effects of landscape change on hydrology and low flows presents an important challenge for decision-making involving water supplies. Compounding this issue is the need to account for the effects of reservoir storage when translating effects on low flows to impacts on water supplies. Simple models and tools are limited in their ability to adequately represent effects of landscape change on low flows and water supplies, and more sophisticated models are resource intensive [*Dennedy-Frank et al*., 2016; *Fatichi et al*., 2016; *Mulligan et al*., 2015; *Sharp et al*., 2015; *Villa et al*., 2014; *Bagstad et al*., 2013; *Vigerstol and Aukema*, 2011]. What is needed is a method to determine whether landscape changes are likely to impact water supplies so that resources can be used efficiently to support effective decisions.

3. Methods

In this work, we assess the water-supply service of natural watersheds. We compare the reliable, steady water supply from a reservoir of a given size at the base of an existing watershed to the supply that could be provided from that same reservoir if the watershed had neither flow regulation benefits nor evapotranspiration losses. This hypothetical counter-factual, what we call a "paved watershed," represents an extreme case—flow regulation could not be any worse, and local water yield could not be any better. These two cases—natural and paved—provide end-members with respect to land use and watershed function. Comparison of the steady water supply from these two limiting cases defines the water-supply service of a watershed for a given reservoir size. We develop two indicators of this water-supply service and assess their variability for 593 watersheds across the United States.

3.1. Water-Supply Service of a Natural Watershed

For this paper, we consider the water-supply service of a natural watershed to be related to the magnitude of the steady supply that could be reliably delivered from a reservoir of a given size. By reliable, steady supply, we mean a constant rate of outflow from a reservoir that can be met or exceeded for an entire period of record. Supply is not meant to imply any particular end-use of the water, such as domestic use, irrigation, or maintenance of environmental flows. Rather, it simply indicates a discharge that can be consistently maintained in the presence of a given amount of reservoir storage. This steady supply is determined by the critical period when inputs to the reservoir are particularly low. While this low-flow period may not formally be considered a drought [e.g., *Dracup et al*., 1980], pragmatically we are considering the steady supply of water that can be maintained under drier conditions.

For a particular watershed, one can create a relationship between reservoir size and the steady supply of water delivered. Reservoir capacity, R_f, is quantified by the fraction, f, of the mean-annual-flow (MAF) that it can store [*McMahon et al*., 2007; *Vogel et al*., 1999]. This capacity can also be interpreted as a timescale of storage; e.g., a reservoir equal to 1% of the mean-annual-flow can store approximately 3.6 days of the mean streamflow. Quantifying reservoir capacity in this way directly addresses flow regulation. The maximum rate at which water can be reliably delivered from the reservoir, Q_f, is a function of that capacity. We determine the relationship between R_f and Q_f through a reservoir simulation of daily inflows and outflows, akin to the sequent-peak algorithm [*Thomas and Burden*, 1963]:

$$S_{t+1}=\min\left(S_{\max},\ \ S_t+In_t-Q_f^*\right) \tag{1}$$

$$S_{\max}=R_f\cdot \text{mean annual flow} \tag{2}$$

$$Spill=In_t-Q_f^*-(S_{t+1}-S_t) \tag{3}$$

where S is the water stored in the reservoir (mm), S_{max} is the reservoir capacity (mm), In is the time-varying daily inflow to the reservoir (mm), Q_f^* is the steady daily supply (mm) provided from the reservoir, and $Spill$ is the water released from the reservoir in excess of the steady supply when the reservoir is full. Q_f is the maximum value of Q_f^* that satisfies equations (1)–(3), subject to the constraint that S is never less than zero.

The steady supply of water, Q_f, depends on both the timing and amount of inflow and the capacity of the reservoir. As the capacity of the reservoir increases, so will the amount of water that can be supplied (up to the mean rate of input). For a reservoir of a given size, both larger and steadier inflows will mean that a larger supply can be delivered. Across watersheds, the inflows depend on both the climate and the flow regulation capability of the catchment. Watersheds that appreciably dampen an intermittent or seasonal precipitation signal may provide larger steady supplies than flashy catchments. On the other hand, if precipitation is frequent, the steady water supply may be far less dependent on the flow-regulating ability of the watershed.

To understand the impact of watershed processes on water supplies, we compare two cases that share the same climate and the same reservoir capacity. We compare the water that could be supplied from a natural watershed to what could be delivered from a hypothetical "paved" watershed for a given climate and amount of reservoir storage. That is, we compare two different sets of reservoir simulations (Figure 1). In the first set, we determine the reliable steady supply, Q_f, if historical streamflow were the input to the reservoir (equations (1)–(3)); in the second, we determine the steady supply, Q_f^p, that could be delivered if historical rainfall and snowmelt were the input. The second case represents an extreme end-member in which the watershed provides no benefit with respect to timing—water travels instantly through the watershed to the reservoir—and also exacts no costs in evapotranspiration or deep drainage.

We use rainfall and snowmelt (rather than precipitation) to isolate the watershed processes and separate the effect of storage as snow. While land cover can affect the accumulation, sublimation, and melting of snow [e.g., *Biederman et al*., 2015; *Saksa*, 2015; *Szczypta et al*., 2015], we attribute snow effects primarily to climate and consider them to be distinct from the water-supply service of a watershed. For each day, the input of rainfall and snowmelt (In) is computed as the precipitation (P) minus the change in snow-water-equivalent (swe):

$$In_t=P_t-(swe_t-swe_{t-1}) \tag{4}$$

The water-supply service of a watershed can be quantified as the ratio (or difference) of the flow that can be supplied from the natural watershed, Q_f, to the flow that can be supplied from the hypothetical paved watershed, Q_f^p, for a reservoir of size, R_f.

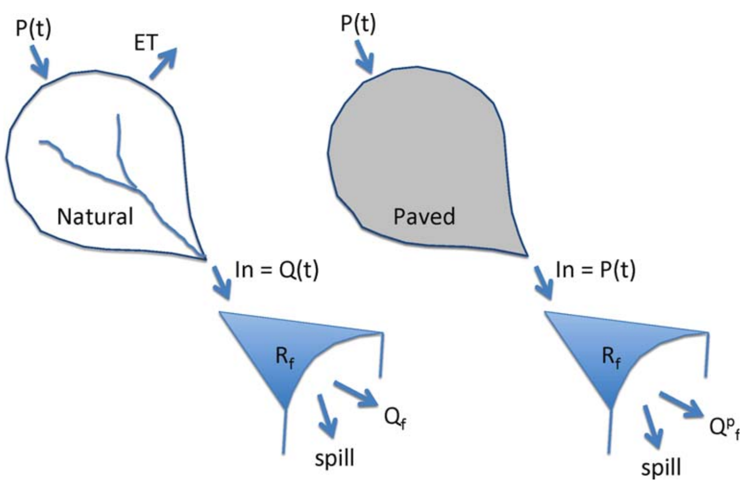

Figure 1. Conceptual representation of the reservoir simulations (equations (1)–(3)) for natural and paved watersheds. Historical streamflows are the inputs for the natural simulations; historical rainfall and snowmelt are the inputs for the paved simulations. Q_f and Q_f^p are the steady supplies that can be provided by the natural watershed and paved watershed, respectively, in the presence of a reservoir of size, R_f.

3.2. Application to Multiple U.S. Watersheds

We employ a data set of daily meteorology and streamflow for 671 minimally disturbed watersheds across the United States [*Newman et al*., 2015, 2014] to examine the variability in the water-supply service of watersheds. These watersheds have less than 5% impervious cover, and we use these minimally disturbed watersheds as a proxy for truly natural watersheds. The watersheds range in size from 1 to 25,000 km^2, with a median size of 335 km^2; two-thirds of the basins range from 100 to 1000 km^2 [*Newman et al*., 2015]. Streamflow data are from the U.S. Geological Survey, and the Daymet data set is used for basin-averaged meteorological forcing with potential evapotranspiration calculated via the Priestly-Taylor equation [*Newman et al*., 2015]. We eliminated or shortened the records for some of the watersheds after quality assurance checks; details are provided in the supporting information. After this quality check, we retained 593 watersheds for analysis. Five hundred and three have daily records of precipitation and streamflow for 31 years from 1 January 1980 to 31 December 2010. Of the remaining 90 watersheds, all have at least 18 years of daily data, 88 have more than 20 years, and 55 have at least 25 years. Average discharge per area for the 593 watersheds ranges from 0.006 to 7.9 mm/d, with a median of 1.1 mm/d. This corresponds to a range of volumetric discharges of 0.4–240 m^3/s with a median of 3.9 m^3/s for the U.S. watersheds.

The steady water supply under natural and paved conditions is determined for each of the 593 watersheds via equations (1)–(4) for a range of reservoir capacities. From those daily reservoir simulations, we compute two indices of water-supply service for each watershed and examine their variation across the U.S. watersheds. These indices are detailed in the Results.

We examined correlations between climate, topography, soil, and landscape characteristics and our indices of water-supply service. Specific characteristics examined include climate seasonality, watershed area and slope, soil porosity, and fraction of forest cover (see Table 2). Sources for geomorphologic and landscape characteristics are described in *Newman et al*. [2015], and soil data are from the SSURGO database [*Soil Survey Staff, USDA*, 2016]. We log-transformed the following variables, which showed skewed distributions, to ensure homoscedasticity: aridity, watershed area, slope, elevation, and saturated hydraulic conductivity.

We also included two hydrologic response variables in our regression analysis: long-term watershed yield (Q/P) and the median runoff ratio for the month of each year with the lowest streamflow (low-flow runoff ratio, hereafter). Watershed yield is a fundamental hydrologic response variable that can be estimated as a function of climate [*Budyko*, 1974] or climate and watershed properties [e.g., *Porporato et al*., 2004; *Zhang et al*., 2001]. We included the runoff ratio during low-flow months because of the importance of low flows to steady water supplies. When examining the low-flow runoff ratio, we eliminated watersheds for which the ratio was zero (no flow) or infinity (no precipitation), leaving 545 of the 593 watersheds. In all correlation analyses, we calculated hydrologic and response variables over the entire period of record, we did not perform any spatial declustering, and explanatory variables were considered as fixed effects.

4. Results

4.1. Water-Supply Service for Single Watershed

Figure 2 presents the relationship between reservoir size and the steady water supply that could be delivered reliably for a watershed of the Green River, defined by USGS gauge 01170100 near Colrain, Massachusetts, USA. The solid line represents the relationship between supply and reservoir size for a natural watershed; average streamflow is 2.0 mm/d, and the steady supply increases from 0.09 mm/d with no reservoir storage to 0.59 mm/d with a reservoir that can store 6% of the mean-annual-flow. The dashed line represents the relationship for a hypothetical paved watershed (i.e., instant translation and no loss of water).

The natural watershed can provide a larger steady supply than the paved watershed—the vertical difference between the solid and dashed lines—when reservoir capacity is smaller. Or, put another way, when the desired steady supply of water is smaller, the natural watershed requires less built infrastructure than a paved watershed to deliver that supply—the horizontal distance between the lines. However, if reservoir storage were to exceed 4% of the mean-annual-flow of the Green River (equivalent to 3.2×10^6 m^3 or 2600 acre-feet), the steady supply from the paved watershed would overtake what could be provided from the natural watershed. The crossing of the curves in Figure 2 can be thought of as the point at which the flow-regulating benefit of the natural watershed is overcome by the cost of the water losses.

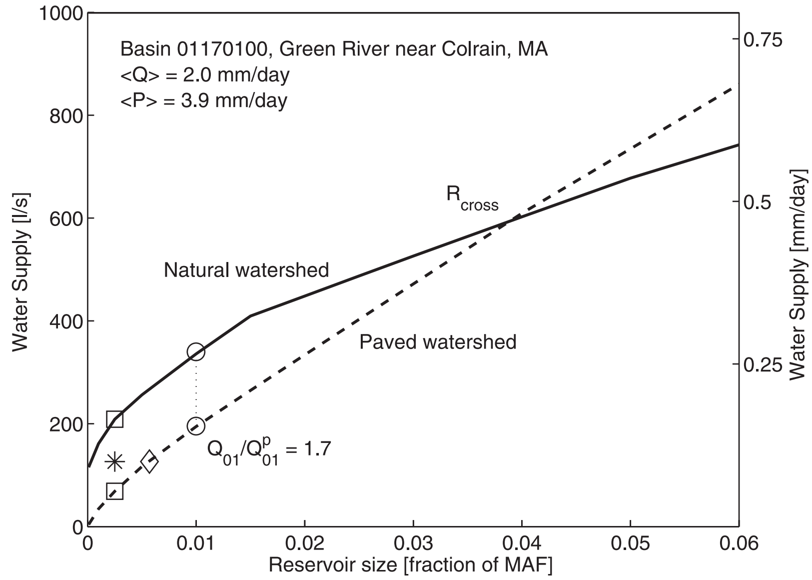

Figure 2. Illustrative example of the relationship between steady water-supply and reservoir size for the watershed upstream of USGS gauge 01170100 near Colrain, MA. The solid line represents the supply provided by the existing watershed, and the dashed line represents the hypothetical supply from a paved watershed. The star represents the supply—0.1 mm/d—required for a population density of 250 people/km^2 (at 200 L/person/d) plus an environmental flow of 0.05 mm/d. For a reservoir that can hold about 1 day of the mean flow (0.25% of the mean-annual-flow), the supply from the natural watershed (0.17 mm/d) can meet that demand, whereas the supply from the paved watershed cannot (square symbols). The diamond represents the minimum level of reservoir storage required for the supply from the paved watershed to meet the demand of 0.1 mm/d. R_{cross} represents the reservoir size at which the supply from the paved watershed overtakes the supply from the natural watershed. The circles represent the water supply from the natural and paved watersheds when reservoir capacity equals 1% of the mean-annual-flow.

The two curves, representing end-members of land use, provide an indication of the potential impact of land use change on water supply. For the Green River, consider a reservoir that can store approximately one day of mean streamflow (0.25% of the mean-annual-flow or 165 acre-feet). With this level of built infrastructure, the natural watershed can reliably supply 0.17 mm/d, whereas the paved watershed can supply only 0.054 mm/d (marked by squares in Figure 2). Whether or not this difference matters depends on the desired level of supply. As an illustration, a hypothetical population density of 250 people/km^2 with a demand of 200 L/person/d, plus an environmental-flow requirement of 0.05 mm/d, results in a total demand of 0.1 mm/d. Since that demand (the star in Figure 2) is bracketed by the supply from the natural and paved watersheds, a more detailed study to predict the effects of land use change on water supply may be warranted in that scenario. Had the gray infrastructure been 1% of the mean-annual-flow (circles in Figure 2), the demand of 0.1 mm/d would lie outside the envelope of both curves. In such a case, a detailed study may not be warranted, as any landscape change is unlikely to have a substantial effect on that water supply. The diamond (Figure 2) indicates the minimum level of reservoir storage for which the desired steady supply lies outside the envelope of the natural and paved curves, i.e., the reservoir storage above which that water supply (0.1 mm/d, in this case) is likely to be insensitive to landscape change.

Table 1. Indices of Water-Supply Service

Index	Description
Q_f-service	Ratio of steady supply of water from natural watershed to paved watershed for a reservoir with capacity equal to 100·0.*f* percent of the mean-annual-flow
R_{cross}	Capacity of reservoir, expressed as a fraction of the mean-annual-flow, for which the steady supply from the natural watershed is equal in magnitude to that from the paved watershed

4.2. Indices of Water-Supply Service and Variability Across U.S. Watersheds

To consider the variability of water-supply service across multiple watersheds, we characterize the two curves, illustrated in Figure 2, by two indices (Table 1). The first, R_{cross}, is the size of the reservoir at which point the two curves cross (Figure 2). Figure 3 presents the cumulative distribution function for R_{cross}, which spans more than three orders of magnitude for 593 watersheds across the United States. R_{cross} is greater than 1% of the mean-annual-flow for just over half of the watersheds. For context, a

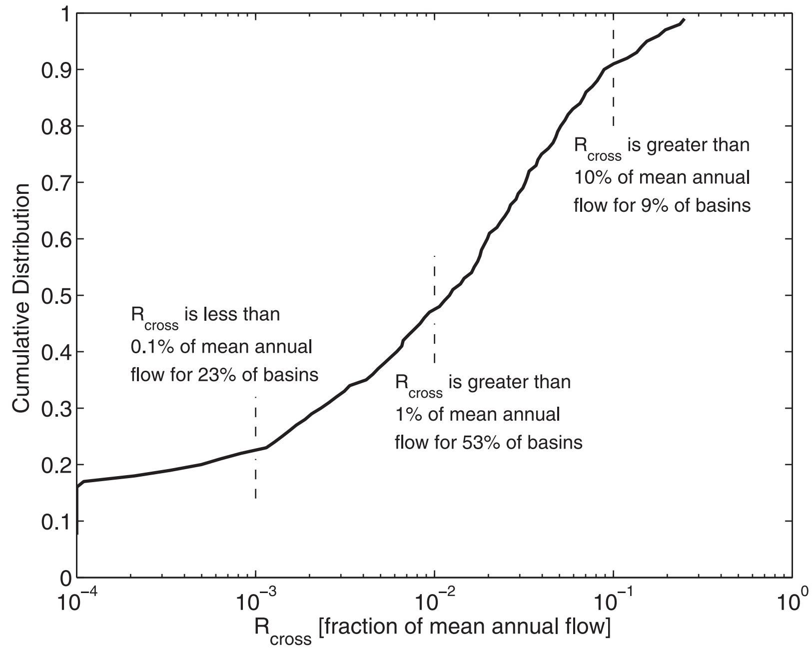

Figure 3. Cumulative distribution function of reservoir size for which the steady supply is equivalent for natural and paved watersheds for 593 watersheds across the United States.

reservoir that is 1% of the mean-annual-flow on a stream with a mean discharge of 4 m^3/s (140 cfs) would have a capacity of 1,300,000 cubic meters, equivalent to 1000 acre-feet or 330 million gallons. For 9% of the catchments, R_{cross} is greater than 10% of the mean-annual-flow, indicating a storage timescale of months. R_{cross} is less than 0.1% of the mean-annual-flow (i.e., less than 9 h of mean streamflow) for 23% of the watersheds. R_{cross} has an interquartile range of 0.14–4% of mean-annual streamflow, corresponding to storage times of 12 h to 2 weeks.

The second metric of water-supply service, Q_f-service, is the ratio of the steady supply from the natural watershed to the supply from the paved watershed in the presence of a reservoir with capacity equal to 100·0.*f* percent of the mean-annual-flow. For the Green River, the Q_{01}-service is 1.7 (Figure 2), indicating that the steady supply from the natural watershed is almost double that from the paved watershed in the presence of a reservoir equal to 1% of the mean-annual-flow (equivalent to 650 acre-feet or 210 million gallons, in this case). The Q_{001}-service for the Green river is 4.7; the Q_{05}-service is 0.92. To examine variability across multiple watersheds, we choose to show the Q_{01}-service, since the median value of R_{cross} is approximately 1% (Figure 3). The variability of water-supply service across the United States is not dependent on this particular choice. Values of Q_f-service with different levels of reservoir storage are highly correlated with each other (e.g., Pearson's $r = 0.95$ for correlation of log(Q_{01}-service) and log(Q_{001}-service)), as are log(Q_{01}-service) and log(R_{cross}) (Pearson's $r = 0.94$, $p < 0.001$).

Figure 4 presents a map of Q_{01}-service, which ranges from 0.04 to 12, with a median value of 1.1. Approximately half of the watersheds provide a water-supply benefit when reservoir capacity is 1% of mean-annual-flow, indicated by a value of Q_{01}-service greater than one. For the other half, the loss of water to evapotranspiration or deep recharge outweighs the benefit of flow regulation and results in a disservice, i.e., the steady supply would be greater from a paved version of the catchment than from the natural watershed. Regions of high service coincide with the West Coast, northern Midwest, and mountainous regions. The identification of large values of Q_{01}-service with mountainous areas is also illustrated by its correlation with slope (Table 2).

4.3. Relationships of Water-Supply Service With Other Watershed Characteristics

Table 2 presents the explanatory power of watershed characteristics with respect to the variability in the log of Q_{01}-service. Q_{01}-service exhibits stronger correlations (Pearson's $r > 0.30$, $p < 0.001$) with slope, elevation, porosity, plant-available water, and fraction of forest cover, and weaker correlations (Pearson's $r < 0.30$,

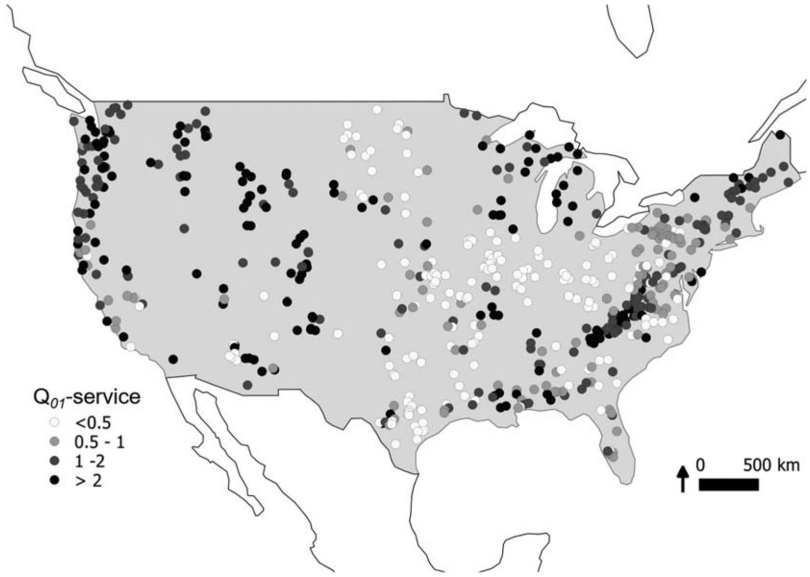

Figure 4. Q_{01}-service (ratio of the steady supply from a natural watershed to the supply from a paved version of the watershed, both in the presence of a reservoir with capacity equal to 1% of the mean-annual-flow) for 593 watersheds across the United States.

$p < 0.001$) with aridity, seasonality, and topsoil hydraulic conductivity. A number of these characteristics are themselves correlated; for example, slope is correlated with elevation (Pearson's $r = 0.78$, $p < 0.001$), and the fraction of forest cover is correlated with log(aridity), log(slope), and plant-available water (Pearson's $r = 0.62$, 0.50, and 0.53, respectively, $p < 0.001$).

With respect to hydrologic variables, Figure 5 demonstrates that the Q_{01}-service is only modestly correlated with overall water yield (Pearson's $r = 0.41$, $p < 0.001$). The horizontal dashed line indicates the condition that the steady supply from the natural watershed is equal to the steady supply from the paved watershed, with catchments above the line providing a steady supply greater than the hypothetical paved watershed. High-yielding watersheds, i.e., those for which streamflow is greater than 75% of precipitation, have large service values. Watersheds with moderate to low yields exhibit both high and low values of water-supply service.

Table 2. Significant ($p < 0.001$) Correlations Between Watershed Characteristics and Log(Q_{01}-Service)[a]

Category	Characteristic	Direction	Pearson's r
Climate	Log(Aridity (P/PET))	Pos	0.17
	Seasonality of precipitation [*Markham*, 1970 in *Dingman*, 2015]	Pos	0.21
	Mean event depth (mm)		Not significant
Geomorphology	Log(Watershed Area (km^2))		Not significant
	Log(Watershed-Average Slope (m/km))	Pos	0.48
	Log(Watershed Elevation (m))	Pos	0.33
Soil	Log(K_{sat} (topsoil, m/s))	Pos	0.21
	Porosity	Pos	0.44
	Plant-available water, PAW (mm); the product of root depth and the difference in water content between field capacity and the wilting point	Pos	0.38
Landscape	% Forest	Pos	0.45
Hydrologic response	Yield (Q/P)	Pos	0.41
	Log(Median runoff ratio for the month of each year with the lowest streamflow)	Pos	0.81

[a]Streamflow data and watershed characteristics are from the USGS and the climate characteristics are from the Daymet data set as described in *Newman et al.* [2015]. Aridity and yield are long-term averages over the period of record. Direction indicates whether the variable is positively or negatively correlated with log(Q_{01}-service).

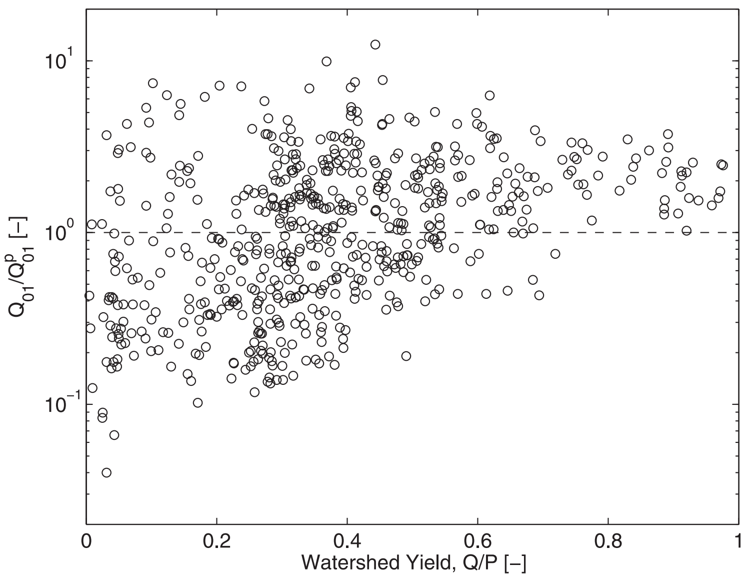

Figure 5. Q_{01}-service (ratio of the steady supply from a natural watershed to the supply from a paved version of the watershed, both in the presence of a reservoir with capacity equal to 1% of the mean-annual-flow) versus watershed yield.

Q_{01}-service exhibits a far stronger relationship (Pearson's $r = 0.81$, $p < 0.001$) with the median runoff ratio for the month of each year with the lowest streamflow (Figure 6 and Table 2). When the low-flow runoff ratio is greater than one—meaning a significant amount of water is draining from storage—the Q_{01}-service is greater than one. When the ratio is greater than 0.1, as it is for just over half of the 545 watersheds, the Q_{01}-service is greater than one for 90% of those watersheds. For the 468 watersheds with values of the low-flow runoff ratio between 0.01 and 1, there appears to be a power law dependence of the Q_{01}-service on the low-flow runoff ratio, and a regression model fit to those data (dashed line in Figure 6) explains over 60% of the variability.

5. Discussion

5.1. Variability of Water-Supply Service

With respect to local water supply, natural watersheds provide ecosystem-service benefits via flow regulation and costs in the form of losses to evapotranspiration and deep recharge. The Q_{01}-service and R_{cross} are

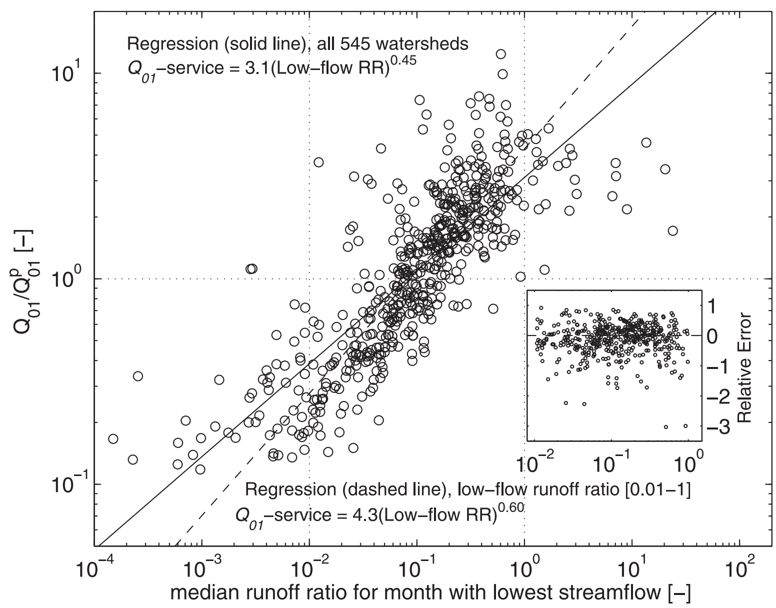

Figure 6. Relationship between Q_{01}-service (ratio of the steady supply from a natural watershed to the supply from a paved version of the watershed, both in the presence of a reservoir with capacity equal to 1% of the mean-annual-flow) and median runoff ratio for the month of each year with lowest streamflow. The inset figure shows the relative error, (obs-pred)/obs, as a function of low-flow runoff ratio for the prediction of Q_{01}-service for watersheds with low-flow runoff ratios ranging from 0.01 to 1.

both indicators of the relative importance of those benefits and costs, i.e., indices of the water-supply service of natural watersheds. As reservoir storage increases, the importance of natural flow regulation decreases, and R_{cross} represents the reservoir capacity for which the steady supply from a natural watershed is equivalent to that from a paved watershed with no flow regulation benefits and no water losses. For over half of the 593 U.S. watersheds, R_{cross} is greater than 1% of the mean-annual-flow, indicating that even when reservoir storage is on the order of days to weeks of mean streamflow, the flow-regulating benefits of a watershed can outweigh evapotranspiration losses. Conversely, flow regulation becomes inconsequential for all watersheds when reservoir capacity exceeds twenty to twenty-five percent of the mean-annual-flow (Figure 3), as it does for the larger reservoirs in the United States [*Vogel et al*., 1999]. At the other end of the distribution, R_{cross} is less than 0.1% of mean-annual-flow for 23% of the watersheds. In those catchments, the flow-regulating benefit of the natural watershed is small relative to the losses due to evapotranspiration, and very little storage is required to create a condition in which the supply from the paved watershed is greater than that from the natural watershed. Among U.S. watersheds, R_{cross} spans more than three orders of magnitude and ranges between 0.1% and 10% of the mean-annual-flow for over two-thirds of the watersheds. This is a scale that is relevant to water-resources decisions and is neither trivially small nor exceptionally large [*Vogel et al*., 1999].

Water-supply service can also be quantified by the Q_{01}-service. Values greater than one indicate watersheds for which the benefits of flow regulation exceed the cost of losses, in the presence of a reservoir with capacity equal to 1% of the mean-annual-flow. The map of Figure 4 indicates the spatial variability of this index of water-supply service, with larger values appearing in mountainous regions, along the West Coast, and in the northern Midwest. Regions west of the Appalachian Mountains through the Central Great Plains tend to have low values of water-supply service.

On the West Coast, the seasonality of the Mediterranean climate sets the stage for watersheds to provide an important water-supply service. Without the flow regulation of natural watersheds, large reservoirs would be necessary to sustain steady water supplies throughout the rainless summer months. Similarly, the cold climate of the northern Midwest leads to extended periods in the winter during which there is little or no addition of liquid water. The flow regulation of natural watersheds or built reservoirs is needed to sustain water supplies during those winter months.

The high degree of water-supply service in mountainous regions (Figure 4 and Table 2) may seem counterintuitive. However, *Price et al*. [2011] found higher topographic complexity—a characteristic of mountain watersheds—to be positively correlated with the magnitude of low flows. Similarly, *Rumsey et al*. [2015] found that the base flow index (ratio of base flow to streamflow) is positively correlated with slope for watersheds in the Upper Colorado River Basin. Also, in a study of 254 global watersheds, *Jasechko et al*. [2016] found that the fraction of "young" streamflow is less in steeper landscapes, indicating longer, slower flow paths and greater flow regulation in mountainous areas. The large values of water-supply service for mountain watersheds may also be related to a correlation between watershed slope and basin yield. All watersheds with yields greater than 0.75 have large values of water-supply service (Figure 5), and they also all have slopes greater than 29 m/km with a median slope of 117 m/km (relative to a median slope of 24 m/km for all US basins).

We found only weak relationships between Q_{01}-service and a number of watershed and climate characteristics. While it would be valuable to be able to predict the water-supply service from simple characteristics, it is not surprising that our analyses found only limited relationships given the complexity of the interactions among climate, soil, topography, and land use and the dependence of low flows on subsurface geology. The signs of the correlations, however, align with expectations. Q_{01}-service shows positive correlations with elevation and slope, consistent with large values in mountainous regions (see above). Q_{01}-service also increases with increasing plant-available water content, porosity, saturated hydraulic conductivity, and forest cover, all of which are associated with greater recharge and water storage in the soil. Additionally, the lack of correlation of water-supply service with watershed area, while perhaps surprising, is consistent with previous findings that mean residence time of base flow is also uncorrelated with watershed area [*McGuire et al*., 2005; *McGlynn et al*., 2003]. Lastly, we note that we considered only catchment-averaged quantities for both precipitation forcing and catchment characteristics. Thus, we are unable to address the effects of topology and within-watershed heterogeneity, both of which can be important [e.g., *Ogden et al*., 2013; *Jencso and McGlynn*, 2011].

When hydrologic responses are included, the Q_{01}-service shows a strong correlation with the low-flow runoff ratio (Figure 6). Not surprisingly, watersheds that are able to sustain streamflows during periods of little or no rainfall are also those that provide an important service with respect to water supplies. Correlation of water-supply service with overall watershed yield is modest and positive (Table 2 and Figure 5) with higher yields indicating a lower cost (water loss) of the water-supply service.

5.2. Relationship to Land Use Change

Indices of water-supply service can be used as general indicators of the vulnerability of water-supplies to landscape changes. While both R_{cross} and the Q_{01}-service have specific definitions, they also indicate the relative importance of flow regulation to losses of water by comparison of an existing watershed to a hypothetical catchment with no flow regulation and no losses. Watersheds with larger values of Q_{01}-service are those for which the benefits of flow regulation outweigh the costs of evapotranspiration. If landscape changes reduce the capacity for flow regulation, even with a concomitant increase in overall yield, there is the potential for water supplies to be adversely affected. Conversely, watersheds with smaller values of the Q_{01}-service are those for which the flow regulation benefits are not as important relative to the costs of water losses. In those situations, landscape changes that result in an increase in overall yield, even if accompanied by a reduction in flow regulation, may have little detrimental effect on water supplies, or, perhaps, may even enhance them.

We illustrate this through Figure 5, which can be interpreted as presenting the starting and ending points for trajectories of land use change. The location of a watershed on this plot represents the starting point for that natural watershed in terms of overall yield and Q_{01}-service before land use change. If, in fact, the entire watershed were to be paved, with no additional storage, the resulting watershed would plot at the point (1,1) on the right-hand side of the figure. Thus, land use changes that result in urbanization, removal of vegetation, and compaction, can be thought of as moving from the initial starting point toward the (1,1) point on the right-hand side.

A completely impervious watershed is an extreme example, however, and how a catchment would move through the space of Figure 5 under different land use changes is unclear. There is no reason to expect a trajectory to be linear or even monotonic. For example, landscape changes that reduce potential evapotranspiration but largely leave the soils and understory unaffected (e.g., tree die-off due to disease) may increase both overall yield and also water-supply service, recent results from *Biederman et al*. [2015] notwithstanding. In other cases, overall yield may be increased, but compaction of the land-surface may reduce infiltration and low flows. For example, *Ogden et al*. [2013] showed that low flows (0.2–0.8 mm/d, 80% exceedance) from a forested watershed in Panama are greater than those from a neighboring watershed that contains a mix of land uses, including pasture; total yield (total Q/total P), however, is much greater for the modified landscape (70% versus 40%, for mosaic and forest, respectively). Of course, the impact of those streamflow differences on water supply would also be a function of the presence and amount of reservoir storage.

In their study of streams in the Blue Ridge Mountains of northern Georgia and south-western North Carolina, *Price et al*. [2011] found that low flows were higher in forested watersheds than in catchments for which the natural land cover had been converted to pasture or low-density development. That result is consistent with our finding of high levels of water-supply service for natural watersheds in that geographic region (Figure 3). In contrast, *Homa et al*. [2013] found that impervious cover increased low flows for watersheds throughout New England. The authors indicate that the result could be due to reductions in evapotranspiration that outweigh the losses of flow regulation, consistent with our finding of low to medium values of water-supply service for New England watersheds.

Ongoing and future hydrologic research—both modeling studies and manipulative experiments—can further elucidate the trajectories of land use changes in Figure 5. Even when the path is unclear, however, the starting point for natural watersheds provides a measure of the potential impact of land use change on water supply.

5.3. Implications for Land-Management Decisions

Our work provides a set of methods to discriminate between water supplies that are likely to be impacted by land use changes and those that are not. Such knowledge can help decision makers deploy resources effectively to improve ecosystem-service decisions. If daily streamflow and precipitation data are available, they can be used, as we have used them in this work, to simulate the performance of an existing or planned reservoir for both current land use and a hypothetical paved watershed. The resulting envelope for the reliable steady supply can be compared to existing or future demand to determine if the water supply is vulnerable to landscape change (Figure 2). Additionally, such simulations can also identify the minimum level of reservoir storage that would protect a given water supply against the effects of landscape change (e.g., diamond in Figure 2). With reservoir capacity at or above R_{cross}, landscape change is unlikely to have a detrimental effect on water supplies of any magnitude.

This analysis applies only to land use changes from a current state to one that is more compacted or urbanized, i.e., in the direction of a paved watershed. It cannot be used to estimate the potential effects of restoration or other activities that would move a landscape toward a more natural state. Additionally, conclusions drawn from results based on historical data may need to be reinterpreted in light of climate change. Specifically, as precipitation becomes more intermittent, flow regulation will become more important, and the water-supply service of natural watersheds is likely to increase. This work also focused on the provision of a steady supply of water; with more knowledge and understanding of the intended uses of water, a time-varying demand function could be used in the reservoir simulation. This would better quantify the water-supply service for a particular community and its potential vulnerability to landscape changes.

If records of daily streamflow and precipitation are not available, the strong correlation of the Q_{01}-service with the low-flow runoff ratio (Figure 6) implies that short-term monitoring efforts during low-flow periods could be used to estimate the water-supply service. Higher values of the low-flow runoff ratio indicate higher values of the Q_{01}-service and the greater likelihood of water supplies being affected by land use changes. Without any hydrologic data, the water-supply service can be estimated only approximately from simple characteristics. Steep, forested watersheds with seasonal climates are likely to provide higher levels of water-supply service.

Within this context of land-management decisions, it bears repeating that water supply is but one ecosystem-service that may be impacted by changes to the landscape. Additionally, conservation of natural lands and construction of reservoirs have their own costs, both monetary and external [e.g., *Deemer et al*., 2016; *Poff et al*., 1997]. The methods and results presented here are intended to be one piece of larger and more holistic assessments of land-management options. Being able to quickly and easily differentiate between water supplies that rely heavily on natural infrastructure from those that are unlikely to be impacted by landscape change will enable resources to be allocated effectively to such assessments.

6. Conclusions

This work examines the local water-supply service of natural watersheds in the presence of reservoir storage. We compare each natural watershed to a counterfactual paved watershed—an extreme in which rainfall and snowmelt are instantly conveyed to the outlet and no water is lost (Figure 1). This comparison requires no hydrologic model, only observations of streamflow and rainfall. Even so, it provides bounds on the potential effects of landscape changes to water supplies.

Indices of water-supply service, Q_{01}-service and R_{cross}, quantify the relative importance of the benefits of flow regulation to the costs of water losses. These indices exhibit substantial variability across 593 U.S. watersheds. R_{cross} spans a decision-relevant range from less than 0.1% to greater than 10% of mean-annual-flow. This variability in water-supply service is not easily estimated from simple catchment and climate characteristics, though it is well correlated with the low-flow runoff ratio. These results and methods can be used to distinguish situations when landscape changes may be important for water supply from those when resources may be better directed to other ecosystem services.

Acknowledgments
Data for 671 United States watersheds, including catchment characteristics and daily streamflow and precipitation, are available through the University Corporation for Atmospheric Research at http://ral.ucar.edu/projects/hap/flowpredict/hydromet_data/. Modifications to this data set for the analyses in this paper are reported in the supporting information. Funding for Andrew Guswa was provided by Smith College and The Natural Capital Project.

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