SPECIAL FEATURE: PERSPECTIVE

Reclaiming freshwater sustainability in the Cadillac Desert

John L. Sabo[a,1], Tushar Sinha[a,2], Laura C. Bowling[b], Gerrit H. W. Schoups[c], Wesley W. Wallender[d,e], Michael E. Campana[f], Keith A. Cherkauer[g], Pam L. Fuller[h], William L. Graf[i], Jan W. Hopmans[d], John S. Kominoski[j,3], Carissa Taylor[k], Stanley W. Trimble[l], Robert H. Webb[m], and Ellen E. Wohl[n]

[a]*Faculty of Ecology, Evolution and Environmental Sciences, School of Life Sciences, Arizona State University, PO Box 874501, Tempe, Arizona, 85287-4501;* [b]*Department of Agronomy, Purdue University, West Lafayette, IN 47907-2054;* [c]*Department of Water Resources Management, Delft University of Technology, 2600 GA, Delft, The Netherlands;* [d]*Department of Land, Air and Water Resources, University of California, Davis, CA 95616-8628;* [e]*Department of Biological and Agricultural Engineering, University of California, Davis, CA 95616-8628;* [f]*Department of Geosciences, Oregon State University, Corvallis, OR 97331-5506;* [g]*Department of Agricultural and Biological Engineering, Purdue University, West Lafayette, IN 47907-2093;* [h]*US Geological Survey, Southeast Ecological Science Center, Gainesville, FL 32653;* [i]*Department of Geography, University of South Carolina, Columbia, SC 29208;* [j]*Department of Forest Sciences, University of British Columbia, Vancouver, BC, Canada V6T 1Z4;* [k]*School of Sustainability, Arizona State University, Tempe, AZ 85287-5502;* [l]*Department of Geography, University of California, Los Angeles, CA 90095;* [m]*US Geological Survey, Tucson, AZ 85719; and* [n]*Department of Geosciences, Warner College of Natural Resources, Fort Collins, CO 80523-1482*

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Increasing human appropriation of freshwater resources presents a tangible limit to the sustainability of cities, agriculture, and ecosystems in the western United States. Marc Reisner tackles this theme in his 1986 classic *Cadillac Desert: The American West and Its Disappearing Water*. Reisner's analysis paints a portrait of region-wide hydrologic dysfunction in the western United States, suggesting that the storage capacity of reservoirs will be impaired by sediment infilling, croplands will be rendered infertile by salt, and water scarcity will pit growing desert cities against agribusiness in the face of dwindling water resources. Here we evaluate these claims using the best available data and scientific tools. Our analysis provides strong scientific support for many of Reisner's claims, except the notion that reservoir storage is imminently threatened by sediment. More broadly, we estimate that the equivalent of nearly 76% of streamflow in the Cadillac Desert region is currently appropriated by humans, and this figure could rise to nearly 86% under a doubling of the region's population. Thus, Reisner's incisive journalism led him to the same conclusions as those rendered by copious data, modern scientific tools, and the application of a more genuine scientific method. We close with a prospectus for reclaiming freshwater sustainability in the Cadillac Desert, including a suite of recommendations for reducing region-wide human appropriation of streamflow to a target level of 60%.

Manifest Destiny and the westward expansion of European civilization in the United States during the 19th century were predicated on an adequate freshwater supply. The assumption of adequate freshwater in the western United States was justified by the prevailing view of hydroclimate, which included a theory that agriculture would stimulate rainfall, or "rain would follow the plow." Early stewards of freshwater resources—like John Wesley Powell—warned that the American West was a desert, only a small fraction of which could be sustainably reclaimed (1).* Notably, Powell remarked that irrigation would be required in the arid region west of the 100th meridian, to make the parcels provided by the Homesteading Act livable (3). Indeed, irrigation was necessary to create a sustainable society in the western United States. Today dams, irrigated agriculture, and large cities are the hallmark of western US landscapes. There are more than 75,000 dams in the United States, and the largest five reservoirs by storage capacity lie west of the 100th meridian. The storage capacity of US reservoirs increased steadily between 1950 and 1980—from 246 to 987 km^3 (4)—and the beginning of these "go-go years" of dam building (5) coincides with the US "baby boom" (roughly 1943–1964). Since that time, there has been an exodus from east to west: population of the 15 largest eastern US cities has declined by an average of 51% but increased by 32% in western cities (6, 7). Similarly, although 74% of the cropland in the coterminous United States lies in the eastern United States, 68–75% of the revenue from vegetables, fruits, and nuts derives from western farms (8). Water—not rain—has followed the plow, exceeding the expectations of even the most zealous proponents of Manifest Destiny 150 y ago.

Reisner and the Cadillac Desert

Numerous critiques of the sustainability of freshwater infrastructure in the western United States have appeared (5, 9–12). Most poignant of these is Marc Reisner's book *Cadillac Desert: The American West and Its Disappearing Water*. Reisner sketches a portrait of the political folly of western water projects; his principal argument is that impaired function of dams, reservoirs, and crop lands, coupled with rapidly growing western cities, would eventually pit municipal water users against farms and catalyze an apocalyptic collapse of western US

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[1] To whom correspondence should be addressed. E-mail: john.l.sabo@asu.edu.

[2] Present address: Department of Civil, Construction, and Environmental Engineering, North Carolina State University, Raleigh, NC 27695-7908.

[3] Present address: Odum School of Ecology, University of Georgia, Athens, GA 30602.

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*Powell writes: "A rough estimate may be made that [404, 686 square kilometers] can be redeemed at the rate of [$2,470 per square kilometer] that is for US $1 billion [in 1890]. In this work vast engineering enterprises must be undertaken. To take water from streams and pour them upon the lands, diverting dams must be constructed and canals dug." The area of irrigated croplands as of 2000 is 173,858 square kilometers, as referenced in: de Buys (2).

society.[†] In this article we explore some of the trends described by Reisner more than 2 decades ago using a more up to date and scientific approach. Specifically, we compare hypothetical calamity in the West with a control by means of direct comparison with watersheds east of the 100th meridian. The 100th meridian has some historical importance because it was the line implicated by Powell—and advocated by Reisner—as a dividing line between climates capable of supporting rainfed agriculture and regions where irrigation was necessary for dependable harvest. For the remainder of this article we use the 100th meridian as the dividing line between east and west regions in the coterminous United States. Thus, we explore whether the problems Reisner envisioned in *Cadillac Desert* exist and are unique to western watersheds. More importantly, we present a suite of metrics and indicators that summarize freshwater sustainability (or departures from sustainability) in the Cadillac Desert region.

We first synthesize a comprehensive geographic dataset that allows us to quantify and compare regional patterns of freshwater sustainability east and west of the 100th meridian. In doing this we combine data from humid western basins (i.e., Columbia) with those in more arid western regions (i.e., Colorado) for much of our analysis, noting important exceptions where necessary. Inclusion of the Columbia River basin was necessary for two reasons. First, the Columbia basin is a prime example of the grand scale of water projects that characterize development of the western United States. Second, the Columbia River originates in part in the Snake River headwaters on the Columbia Plateau, a semiarid region that illustrates many of the same impacts associated with large-scale water projects as outlined in *Cadillac Desert*. We define freshwater sustainability as renewable surface water—hereafter "streamflow"—and its allocation to people, farms, and ecosystems. We exclude groundwater as a source of freshwater in our analysis because it is not as immediately renewable as surface water, and it is less relevant to our objective because Reisner's focus was on harnessing surface water. Below we quantify patterns of mean annual streamflow in the coterminous United States. We then quantify freshwater sustainability in terms of (*i*) human water stress, (*ii*) the efficacy and lifespan of reservoir storage, (*iii*) the impact of salt loads in croplands on agricultural revenue, and (*iv*) biodiversity and invasion of native fish faunas. After analyzing broad patterns of sustainability and comparing sustainability indices east and west of the 100th meridian, we narrow our focus to the arid lands west of this divide and estimate water stress to assess the future for sustainable urban growth in the region.

Results

Climate and Surface Water Supply Set the Stage. One of Powell's key observations was that rainfall was insufficient to provide adequate vadose zone water storage during the growing season for nonirrigated agriculture in much of the western United States. The upshot of this observation was that streamflow would need to be harnessed to provide irrigation and sustain agriculture. Estimated streamflow normalized by area (runoff) is low (<10 cm) for most of the west and much higher (≥40–100 cm) for much of the eastern United States (Fig. 1*A*), with two notable exceptions. First, the Pacific Northwest and the northern mountains of California have the highest runoff in the coterminous United States. Second, the longitude of the east–west transition between high and low runoff in the Great Plains varies by nearly 10°—from the 95th meridian in the northern plains to the 105th meridian near the Gulf of Mexico. However, there are clear differences in the distribution of runoff, cities, and farms in eastern and western US watersheds. Below we define US watersheds using boundaries of the US Geological Survey (USGS) four-digit hydrologic unit code regions or hydrologic subregions (13). Cities and farms are more likely found in hydrologic subregions with abundant surface water (runoff >40 cm) in the East (nearly 94% of the population and 65% of the cropland in the East is in a hydrologic subregion with streamflow exceeding 40 cm, compared with 55% of the population and 41% of the croplands in the West). More relevant to the thesis of *Cadillac Desert*, 23% of the population and 28% of the cropland in the West falls within a hydrologic subregion where runoff is <10 cm [compared with 1% and 13% of the population and cropland, respectively, found in a hydrologic subregion with similarly low (10 cm) mean annual streamflow east of the 100th meridian].

State of Current Infrastructure. The impacts of dams and reservoirs include increases in hydrologic storage and fragmentation of river networks. Relative storage capacity gives a measure of the number of years of average streamflow stored in the reservoir system, and dam density provides a proxy for fragmentation of river networks by impoundments. Total storage capacity of reservoirs does not differ east and west of the 100th meridian (Fig. S1). Storage in more numerous but smaller reservoirs in the East is nearly equivalent to that in the generally fewer, larger reservoirs in the West. As a result, dam density is higher in the eastern United States (Figs. 1*B* and 2*A*). However, more than 73% of watersheds with relative storage capacity values >1 are located in the West, and another 19% straddle the 100th meridian between −90° to −100° W. Overall, relative storage

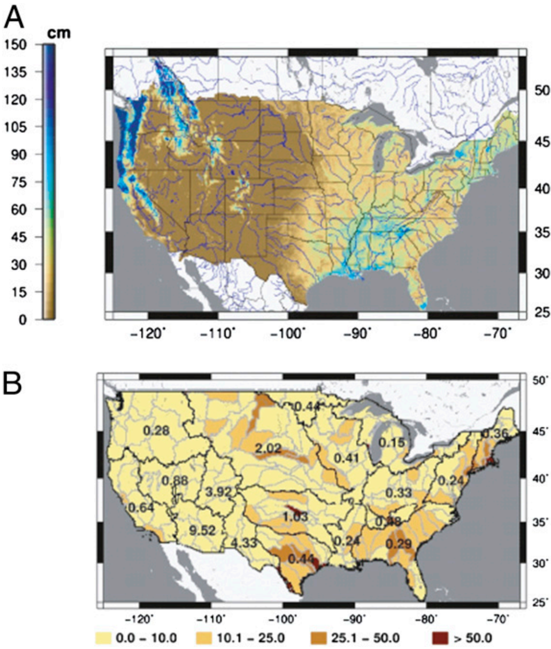

Fig. 1. Patterns of hydroclimate and freshwater infrastructure in the coterminous United States. (*A*) Mean annual streamflow (cm) estimated using the VIC macroscale hydrologic model (*SI Appendix*). (*B*) Average number of dams per 100 km of river length (color coded, see legend) in each USGS hydrologic subregion in the coterminous United States and total storage capacity per unit streamflow, or *relative* storage capacity (text) for each USGS hydrologic region.

[†] The apocalypses sketched by Reisner in *Cadillac Desert* are (*i*) that western reservoirs will fill with sediment soon, and reduced storage capacity will present unprecedented water scarcity issues; (*ii*) crop lands will be increasingly retired due to salinity issues, to the extent that water projects will ultimately poison the farmlands that western societies depend on for food; and (*iii*) growing urban populations will draw increasing water away from agricultural areas, further reducing the capacity for the West to feed its people.

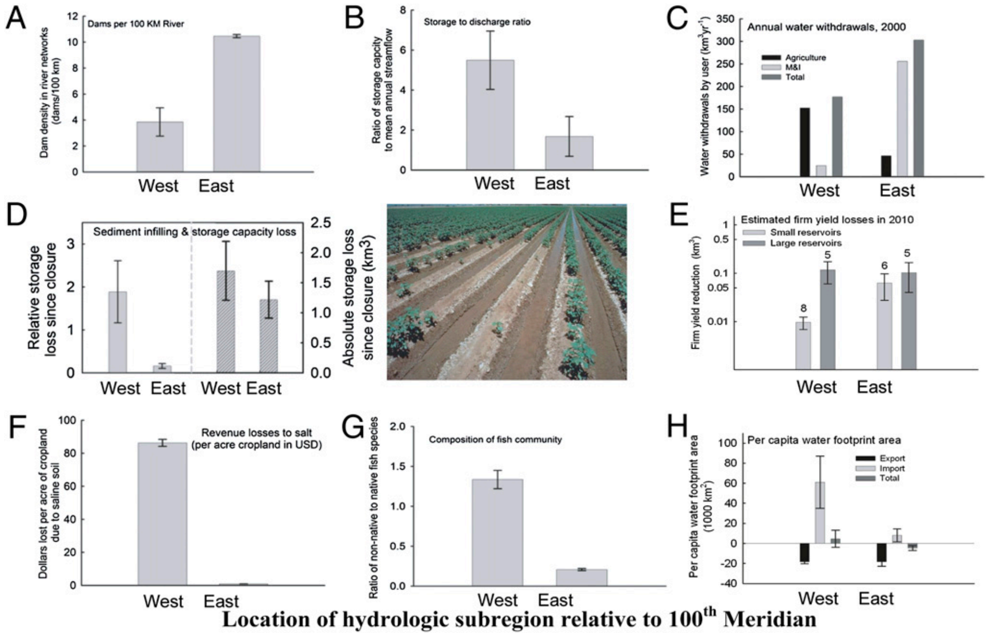

Fig. 2. Comparison of infrastructure and impacts of infrastructure east and west of the 100th meridian. (*A*) Average number of dams per 100 km of river length. (*B*) Relative storage capacity (total reservoir storage/mean annual streamflow). (*C*) Sum of water withdrawals by category—municipal, industrial, agricultural, and total. (*D*) Average storage capacity losses in reservoirs as a result of sediment infilling expressed relative to mean annual streamflow (*Left*) and in absolute terms (km^3, *Right*). (*E*) Estimated average reductions in firm yield (km^3) for large (>1.23 km^3) and small (<1.23 km^3) reservoirs. Numbers above error bars (±1 SE) are sample sizes in each category. (*F*) Estimated average revenue losses (millions USD) as a result of salt accumulation in croplands. (*G*) Average ratio of nonnative to native fishes (color) and number of nonnative species (text). (*H*) Average per capita virtual water footprints (VWF) for all metropolitan statistical areas >100,000 in size. Footprints are negative if virtual water is exported in crops from the watershed hosting the city, or positive if the city requires imports of virtual water (in crops) to feed the population. Error bars are SEs using hydrologic subregions as the unit of replication (127 and 77 east and west of the 100th meridian, respectively), unless otherwise indicated.

is 3.3 times higher in the West (Figs. 1*B* and 2*B*). Dams fragment riverscapes more in the East, but large reservoirs alter hydrologic dynamics more in the West—holding more water relative to streamflow.

Focus Area 1: Human Water Stress. Total annual water withdrawals are 1.7-fold higher in the East, but the withdrawals for agriculture are 3.2-fold higher in the West (Fig. 2*C*). To assess the sustainability of surface water withdrawals in the United States, we estimated the water scarcity index (WSI) (14, 15) for each hydrologic subregion. WSI is the ratio of total withdrawals of freshwater for human use (W) (16) to renewable supply (mean annual streamflow, MAF). We defined supply as the sum of local and unused upstream annual average streamflow estimated by the variable infiltration capacity (VIC) model (*SI Appendix*). Our application of WSI provides a measure of freshwater sustainability defined as the capacity for locally generated and unused upstream streamflow to meet local demand. Subregions with WSI ≈0 appropriate little of their streamflow. Higher WSI indicates greater appropriation of local renewable freshwater resources. WSI values >1 are possible where streamflow is low and withdrawals include a substantial groundwater component. Water stress is commonly defined as WSI 0.4 (14), indicating 40% appropriation of renewable fresh water resources. This threshold is set at less than half of available streamflow to buffer against high spatial and temporal variability in streamflow and to set aside water for ecosystems, navigation, and recreation. Water stress occurs in 58% of subregions in the West, compared with 10% in the East (Fig. 3*A*), and withdrawals exceed local streamflow by 2-fold (WSI >2) in 10 western watersheds. Nine of the top 10 WSI values are in the West (Fig. 3*A*; average ± SE WSI: 0.85 ± 0.1 West and 0.22 ± 0.03 East). In a few eastern subregions WSI is high because withdrawals from large freshwater lakes (e.g., the Laurentian Great Lakes) in neighboring subregions exceed local streamflow. Finally, consumptive use values were not estimated in 2000, such that our estimates of WSI include consumptive and nonconsumptive withdrawals of freshwater (*SI Appendix*).

Focus Area 2: Efficacy and Lifespan of Reservoir Storage. One of Reisner's key criticisms of western reliance on reservoir storage was inevitable sediment infilling and subsequent storage deficits for growing cities and agriculture (17).[‡] The question we ask here is not whether, but how fast will the nation's reservoirs fill with sediment? Assuming observed infilling rates over the last century are representative and constant, we estimate that 276 of the reservoirs (22%) in the Reservoir Sedimentation Survey Information System (RESIS-II) are already completely filled with sediment or have been dredged to maintain function. However, only 1 of these reservoirs is >0.123 km^3 (moderately sized), and only 11 are even within an order of magnitude of this size (2 in the West and 9 in the East >0.0123 km^3; Fig. S2). Predicted minimum lifespans for the remaining (unfilled) reservoirs are lowest in the central United States and Desert Southwest (Fig. S2); however, estimated minimum lifespans are all ≥1.5–2 centuries. Thus, although Reisner was correct that reservoirs fill with sediment, observed infilling and complete loss of storage function is by no means exclusively a western phenomenon and will not likely occur for most large reservoirs in the foreseeable future. Given the long time horizon for complete infilling, we extrapolated estimated capacity losses from single structures to entire hydrologic subregions to construct a metric of storage loss more comparable to available water supply. We normalized this estimate of regional storage loss by MAF because this metric better quantifies the change in the region's ability to withstand prolonged drought or flooding (15). Relative capacity losses for the 95 (of 204) subregions with adequate data from RESIS-II range from 8×10^{-4} to >11 (units = mean annual streamflow equivalents) and are higher by a factor of ≈11.7 in the West (Figs. 2*D* and 3*B*).

Storage loss in a water supply reservoir directly impacts the firm yield, or the largest withdrawal rate that the reservoir can reliably provide. The relationship between firm yield and active storage is generally nonlinear, with an initially

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[‡] In the second printing of *Cadillac Desert*, Reisner writes (p 473), "As a result of [intensive machine based agriculture and loopholes allowing for agriculture on Class VI land]—and because it was inevitable anyway—the dams are silting up." He then lists infilling statistics for 12 reservoirs in the United States, including Lake Mead, writing (p 474), "In thirty five years, Lake Mead was filled with more acre feet of silt than 98% of the reservoirs in the United States are filling with acre feet of water. The rate has slowed considerably since 1963, because the silt is now building up behind Flaming Gorge, Blue Mesa and Glen Canyon dams."

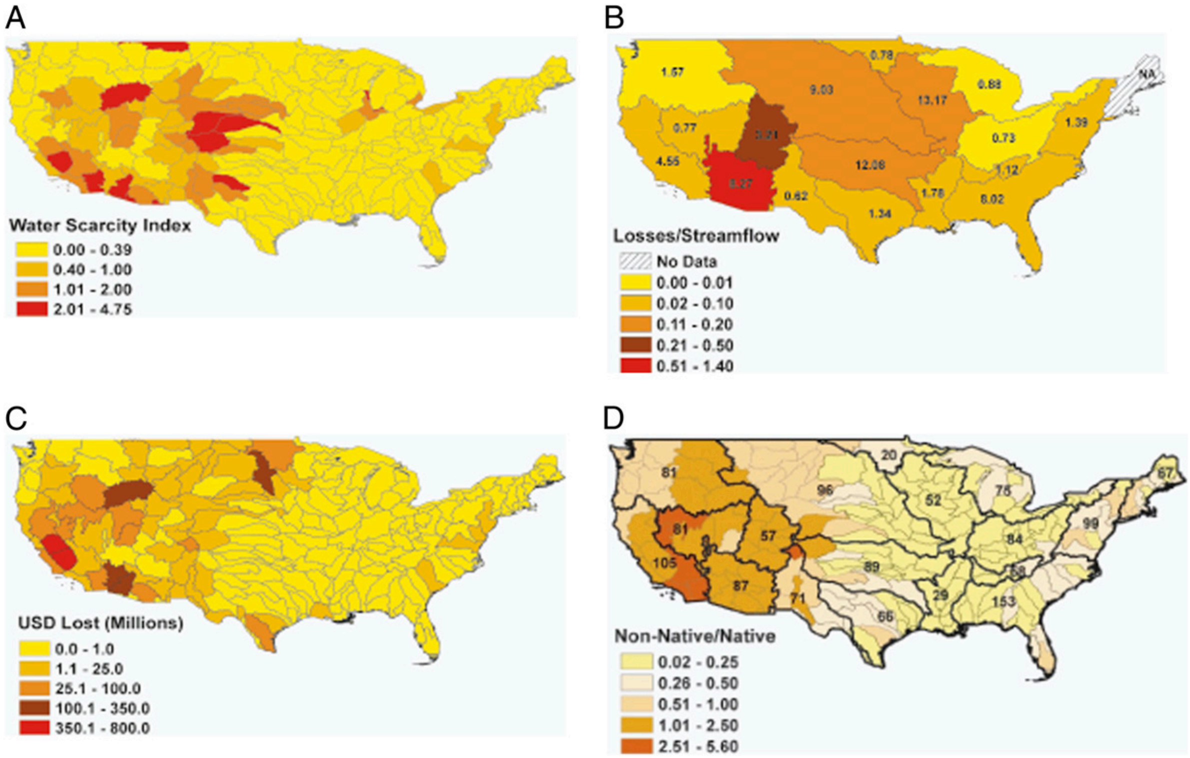

Fig. 3. Assessment of current freshwater sustainability. (*A*) WSI for 204 coterminous hydrologic subregions. Here, WSI = W/MAF, where W is total withdrawals based on USGS estimates from 2000, and MAF is total mean annual streamflow, including locally generated streamflow and flow unused by upstream hydrologic regions. (*B*) Estimated relative (storage loss/streamflow, color coded) and total losses (km^3, text) of storage capacity in each USGS hydrologic region due to infilling by sediment. NA in Hydrologic Region 1 indicates no sediment surveys available for reservoirs over 1.23×10^{-2} km^3 in this region (*SI Appendix*). (*C*) Agricultural revenue lost (in million USD) at HUC 4 scale due to soil salinization (color coded). (*D*) Ratio of nonnative to native fish species (color coded) and total number of observed nonnative species (text).

shallow—but accelerating—rate of decline in firm yield as active storage capacity decreases (Fig. S2). Firm yield for large reservoirs (>1.2 km^3, storage capacity) has already diminished by $\approx 1.9\%$ relative to yield at original capacity, and up to 6.25% for small reservoirs (1.2 $km^3 >$ storage capacity > 0.12 km^3). The absolute decline in firm yield since dam closure was not significantly different in the East and West for the reservoirs we analyzed (Table S1) except for small reservoirs, in which decline in absolute firm yield was marginally higher in the East (Fig. 2*E*). Although the differences in sediment related reductions in firm yield across the country were not generally significant in eastern relative to western reservoirs, estimated reductions in the absolute volume of firm yield losses in the West even for the small number of structures analyzed here are formidable. Estimated reductions in firm yield in the five large reservoirs we analyzed west of the 100th meridian (firm yield volume ≈ 0.584 $km^3 \cdot y^{-1}$) are larger in sum than maximum annual conveyance by the Los Angeles Aqueduct (≈ 0.25 $km^3 \cdot y^{-1}$) and Moffat Tunnel diversion to Denver (≈ 0.43 $km^3 \cdot y^{-1}$), and equivalent to 60% and 32% of the annual conveyance of the Salt River Project (≈ 0.97 $km^3 \cdot y^{-1}$) and Central Arizona Phoenix Project (≈ 1.85 $km^3 \cdot y^{-1}$), respectively.

Focus Area 3: Impact of Salt Loads in Croplands on Agricultural Revenue. Salinity is a worldwide threat to the sustainability of irrigated agriculture (17). Both the accumulation of salt and the extent of salt-affected soils are more prevalent in the West (Fig. 3*C* and Fig. S3). Total estimated revenue losses experienced by the agricultural sector are ≈ 2.8 billion US dollars (USD) annually. Estimated revenue losses are nearly an order of magnitude higher in the West (2.55 billion USD $\cdot$ y^{-1}, West vs. 267 million USD $\cdot$ y^{-1}, East). Crop yields and revenue have been disproportionately affected in western watersheds, particularly in regions with extensive areas of vegetable crops and orchards (Fig. 3*C*). Revenue losses are ≈ 60-fold higher per acre of cropland in the West (Fig. 2*F*).

Focus Area 4: Biodiversity and Invasion of Native Fish Faunas. The sustainability of fresh water supplies can be measured in terms of human water security and the capacity of freshwater ecosystems to support biodiversity (18). These two sustainability goals are not mutually exclusive—biodiversity provides valuable ecosystem services ranging from the food and economic benefits of inland fisheries (19) to the maintenance of water quality (20) and regulation of gas exchange between freshwater ecosystems and the atmosphere (21). Discharge magnitude and variation determine biodiversity in rivers across the globe (e.g., refs. 22 and 23), and dams, water diversions, and human appropriation of streamflow homogenize this variation (24), thereby altering key components of biodiversity, including food chain length (25) and the number of nonnative species, especially fishes (26, 27).

The proportion of all species that are nonnative provides a proxy for the impact of freshwater infrastructure on native biodiversity because dams and reservoirs facilitate invasion by nonnative fishes by creating new habitat (e.g., still reservoirs rather than flowing water) and altering the flow and temperature regime in dam "tailwaters" (26, 28, 29). Further, this ratio is one of four drivers used in broad-scale analyses of threats to human water security and biodiversity (18, 30). This ratio is higher in the West (Figs. 2*G* and 3*D*), and this is not a byproduct of higher native species richness in the East, because the absolute number of nonnative species is also higher (Fig. S4). Thus, dominance of western fish faunas by nonnative fishes results from higher absolute numbers of established nonnative fishes and low species richness of native fishes (Fig. 2*G*). Moreover, of the 25 most widespread nonnative fishes west of the Mississippi River drainage,[§] 56% (14 of 25) are piscivores native to lakes or rivers in hydrologic regions east of the 100th meridian with a less variable hydrologic regime, and 6 of these 25 are capable of eating not only native insectivores but also nonnative piscivores on the basis of body and gape size (Table S2). Eastern faunas not only dominate the species roster in western rivers, but they likely occupy one or more unique trophic levels at the apex of food webs in heavily modified western rivers. This artificial increase in food chain length is due in part to a reduction in discharge variability below dams (24, 25).

Civilization, If You Can Keep It. The central theme of *Cadillac Desert* is that the hydroclimate of the American West is not generous enough to sustain cities and agriculture, especially in the Southwest. Below we attempt to quantify this claim in two ways. First, we estimate agricultural water footprints of all large (>100,000 in size) US metropolitan statistical areas (MSAs) in the East and West. Our water footprints explicitly consider the net transfer of virtual water needed to feed the local population. Second, we estimate the total appropriation of surface water by humans for a seven-region area constituting the Desert Southwest. We estimate human appropriation of surface water for this "superregion" under all possible combinations of the following scenarios: using current withdrawals (as in Fig. 3*A* but at a larger resolution) or total water demand including the virtual water required for food production; and using Census 2000 population estimates, or assuming a doubling of the Census 2000 population.

Disproportionately large water footprints of cities in the US Southwest. Agricultural water footprints are the volume of water needed to meet the food demand for a city or region (31). Here, we normalize the water volume by runoff to find the equivalent land area to supply the water demand, analogous to a "carbon footprint" (32). Total water footprints based on water withdrawals are captured in Fig. 3*A*, where WSI indirectly represents the fraction of a subregion's land area necessary to generate the streamflow to sustain those withdrawals. Here we estimate net agricultural water footprints of the 332 largest US MSAs [>100,000 in population as of 2000 (33)]. Virtual water in food includes water transpired during production [via actual evapotranspiration (AET), i.e., "green water" (14)], is higher in arid regions with higher prevailing rates of evapotranspiration, and is ≈80% of all consumptive water use worldwide (14). Net virtual water represents the difference between virtual water import and export, or alternatively, the difference between the virtual water in locally grown food and the virtual water locally consumed. We define a virtual water footprint (VWF) of a city as the land area necessary to capture the streamflow required to satisfy the net virtual water transfer (i.e., to grow the additional crops needed to feed the population of that city that are not grown locally). Thus, our virtual water footprints differ from WSI in two ways: (*i*) they quantify the total land area equivalents of streamflow needed to feed cities via local agriculture, and (*ii*) they allow us to quantify net virtual trade in terms of import of virtual water to cities (positive VWF) and export of virtual water from watersheds with extensive crop area (negative VWF). Cities in the Desert Southwest United States had disproportionately high net water import (large positive VWF) (Fig. 4*A*). Urban areas with the top five total positive VWF (indicating net imports of virtual water) were Los Angeles, Las Vegas, Phoenix, New York, and Riverside, in that order. The VWF of Los Angeles is larger than the combined VWF of the eight largest VWFs east of the 100th meridian, including New York, Chicago, Dallas, Detroit, Philadelphia, Houston, Boston, and Washington, DC. Combined VWF for these eight metro areas is 206,585.5 km^2, compared with 214,922 km^2 for the Los Angeles metropolitan area. Watersheds exporting the most virtual water in the form of food products typically hosted smaller cities, many in the corn belt (Fig. 4*B*); subregions with the highest net virtual water export were those hosting Wichita (KS), Sioux Falls (SD), Omaha (NE), Havasu City (AZ), and Colorado Springs (CO), in that order. The virtual water demand of these smaller population centers is dwarfed by water used for agriculture in their watersheds, which is exported as food products. Average VWFs were positive west of the 100th meridian (indicating net import) and negative east of the 100th meridian (indicating net export; Fig. 2*H*). Western cities with net positive VWF had 7-fold larger footprints than cities with net positive VWF east of the 100th meridian (Fig. 2*H*). Western watersheds also export 1.7-fold more virtual water than watersheds dominated by cropland east of the 100th meridian (Fig. 2*H*), although this latter difference is not significant (Table S1). In summary, western cities have much larger virtual water footprints, largely owing to the more arid climate, and western crop lands export at least an equal magnitude of virtual water as cities and croplands east of the 100th meridian. Some but not all of the virtual water exported from productive farmland in the western United States (e.g., Central and Imperial valleys of California) offsets large footprints of cities in the desert Southwest, because these farmlands produce table vegetables, tree fruit, and nuts for much of the United States.

Human appropriation of streamflow in the US Southwest. Six major watersheds in the US Southwest are connected by aqueducts and water transfers (Fig. 4*B*). Water from the upper Colorado basin is diverted across the continental divide to the South Platte, Arkansas, and Rio Grande rivers for municipal use by front-range cities as well as agriculture. Snowmelt from the upper Colorado basin is collected lower in the basin and diverted to Las Vegas, central and southern Arizona, and southern California. Snowmelt from the Sierra Nevada is diverted to San Francisco and Reno and to cropland in the southern Central Valley of California via the Central Valley Project (CVP). Finally, snowmelt from the northern Sierra Nevada and water from Trinity River in California's Northern Coast Range is diverted south to the Central Valley (via the CVP), some portion of which reaches southern California via the State Water Project of California. The resulting human-engineered watershed connects streamflow generated in the mountains of Colorado and California to cities in at least six states, representing a combined urban population of more than 50 million, and to one third of all western croplands.

Here we quantify the human appropriation of streamflow in this superregion (Fig. 4*B*). The simplest index of human appropriation is WSI, or withdrawals normalized to MAF across the superregion (*SI Appendix*). Humans currently appropriate the equivalent of 76% of MAF in this superregion (WSI 0.76; Fig. 4*B*). This number is equivalent to >90% of streamflow when we use the virtual water demand for agriculture instead of the actual withdrawals associated with current agricultural practices to calculate WSI (Fig. 4*B*). This "virtual WSI" accounts for all water needed to grow crops to sustain the entire population in the superregion, assuming food is grown within and no food is transported out of the super region (i.e., "regional food production"). Higher virtual WSI suggests that much higher appropriation of streamflow would be

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[§] Here we focus on hydrologic regions 13–18, quantifying prevalence of nonnative fishes in 8-digit hydrologic unit code basins or accounting units. We chose a finer resolution for this analysis to illustrate the comprehensive nature of fish invasion in western watersheds. At this finer level of resolution, we can record not only whether a particular nonnative fish is present in a 4-digit subregion but also how widespread it is within that subregion.

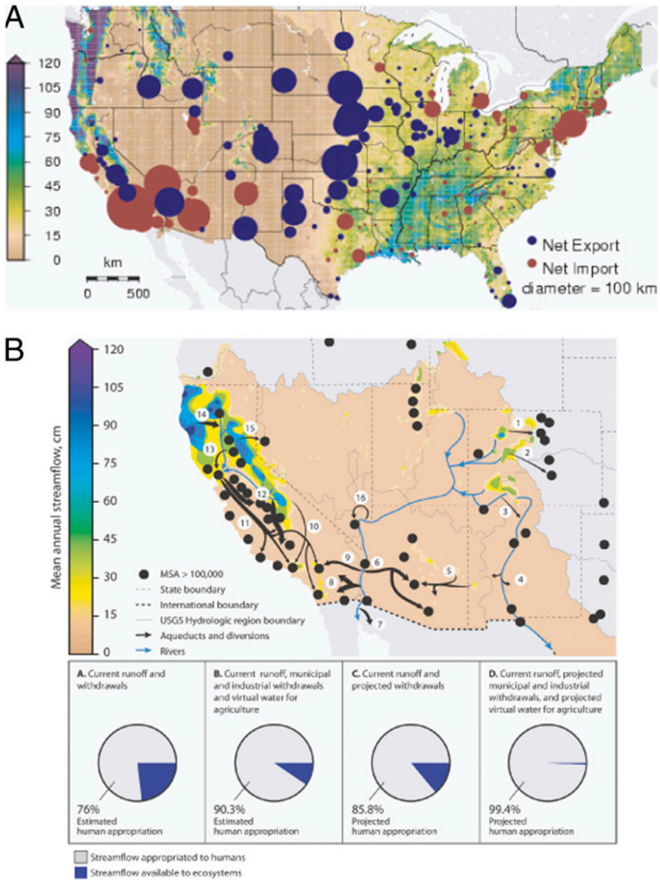

Fig. 4. Water footprints for agriculture and human appropriation of streamflow by urban areas in the US Desert Southwest. (*A*) Net virtual water footprints of metropolitan statistical areas >100,000 in size. Footprints represent the land area equivalent of streamflow generation required to grow the food to feed the MSA population (following ref. 45); positive numbers (blue) indicate net export (i.e., the MSA's hydrologic subregion produces more food than is required by the MSA population), and negative numbers (red) indicate net import (the MSA requires more food than is produced within the local hydrologic subregion) for each MSA. See *SI Appendix* for more details. (*B*) Appropriation of streamflow by large urban areas (Census 2000 MSAs >100,000 in size) under a population doubling scenario of these cities. Map shows the paucity of streamflow across five southwestern USGS hydrologic regions (Regions 13–16 and 18) and the natural and engineered causeways for this streamflow. Pie charts show proportion of streamflow appropriated by large urban areas in the same five-hydrologic-region area under four scenarios. Scenario A is the current water scarcity index (WSI = W/MAF) for the entire five-region area using USGS water use data from 2000 (W). Scenario B estimates the capacity for streamflow to support municipal and industrial withdrawals in Scenario A in addition to the virtual water needed for regional production of all food. The difference in human appropriation between Scenarios A and B highlights the degree to which the Desert Southwest imports streamflow (contained in food) from more distant hydrologic regions. Scenarios C and D project human appropriation of streamflow under a regional doubling scenario of all MSAs >100,000 in size in 2000, assuming only changes in W associated with population increase (*SI Appendix*). In Scenario C, projections are based on water use data (in Scenario A), whereas in Scenario D, projections are based on municipal and industrial withdrawals and estimated virtual water for agriculture. All scenarios rely on current VIC streamflow estimates (MAF, based on average annual climate forcings from 1950 to 1995). Arrow width is proportional to the magnitude of water diversion associated with numbered major water projects in the Southwest: (1) Duchesne River Diversion, (2) Blue, Fraser, and Williams Fork River diversions, (3) Frying Pan and Eagle River diversions, (4) San Juan River diversion, (5) Middle Rio Grande River diversions, (6) Salt River Project, (7) Central Arizona-Phoenix Project, (8) Colorado River flow exiting United States to Mexico (1.85 $\mathrm{km}^3 \cdot \mathrm{y}^{-1}$) as mandated by The Mexican Water Treaty of 1944, (9) All American Canal, (10) Colorado River Aqueduct, (11) Boulder Canyon Project, Lake Mead, (12) Los Angeles Aqueduct, (13) State Water Project, California Aqueduct, (14) Central Valley Project, (15) Tuolumne River diversion, (16) Truckee River diversions, (17) Central Valley Project: Trinity River diversion.

required for the superregion to persist on locally grown food alone and that there are likely important, but not as of yet quantified, ecological tradeoffs between water footprints associated with regionally produced agriculture and carbon footprints associated with food imports from agricultural lands outside the superregion.

Finally, population in the Cadillac Desert superregion is projected to increase significantly over the next 25–40 y (all projections available from the US Census Bureau; ref. 34). For example, the population of the state of California is projected to grow by 50% by 2050, the population of southern Nevada is projected to grow by as much as 57% by 2030, and the Phoenix metropolitan area (here defined as Maricopa County) and population centers on the Front Range of the Rocky Mountains of Colorado are projected to double by 2050 and 2040, respectively. This suggests that population doubling is possible in many population centers in the superregion within a century. Hence, we estimated WSI and virtual WSI as above, but assuming twice the population in the superregion. Using a conservative (more recent) trend for the relationship between population and water use, we estimate that humans will withdraw ≈86% of current MAF under a population doubling (WSI 0.86). Withdrawals could be as high as 99.4% of current MAF according to the extrapolated virtual water demand required for regional food production (virtual WSI 0.99; Fig. 4*B*).

Discussion

John Wesley Powell provided the earliest sketch of sustainable development in the western United States. Powell's conclusion in 1876 was that water scarcity would place limits on the growth of a new civilization in the region (3). Marc Reisner pursued this conclusion in *Cadillac Desert* a century after Powell's explorations (5). Reisner's diagnosis was that the water demands of agriculture and growing western cities were at odds and precariously dependent on static conditions—optimistic estimates of streamflow, unchanging reservoir storage capacity, and soils buffered against high salt loads. In this article we use data and methods unavailable in Reisner's time to reevaluate this diagnosis. We find that the characteristics and impacts of dams and reservoirs differ considerably between the eastern and western United States, suggesting that the Cadillac Desert envisioned by Marc Reisner has a strong scientific basis. Specifically, the US west of the 100th meridian is characterized by (*i*) low mean annual streamflow; (*ii*) large reservoirs spaced more distantly within river networks, but storing a more than 4-fold higher proportion of mean annual streamflow than in the East; (*iii*) 3-fold higher surface water withdrawals as a proportion of streamflow; (*iv*) net virtual water footprints at least seven times the area of those of eastern cities; (*v*) large reservoirs with estimated minimum lifespans exceeding 1.5–2 centuries that have nevertheless already experienced losses in firm yield greater in volume than the annual conveyance of critical water delivery systems (e.g., Los Angeles Aqueduct); (*vi*) >60-fold greater reductions in agricultural revenue due to inefficient irrigation practices and soil salinity; and (*vii*) faunas with nearly six times the ratio of nonnative to native fishes than those in the East. Our storyline, although hopefully more measured, is in line with the one Reisner crafted in 1986.

Interaction Between Reclamation and Climate Change. Our synthesis of water resources data ignores important interactions with climate change. Increased temperatures, higher water demand by crops, greater rainfall variability, reduced snowpack and streamflow, earlier snowmelt and peak streamflow timing, and a doubling of major urban populations are very likely scenarios in the next 100 y. Less certain but likely scenarios include reduced average annual precipitation in the southwest United States and climate/population-induced water withdrawal increases. Our analysis provides some insight about interactions between water storage systems, climate change, and population growth scenarios.

First, continued sediment accumulation will result in lower active storage and further reductions in yield of water from reservoirs. Reductions in firm yield due to sediment will be exacerbated by declines in streamflow, increases in variability, and changes in the timing of peak streamflow associated with climate change. Second, agricultural revenue losses due to salinization are likely to rise. Increasing temperatures would increase crop water demand and crop transpiration, leading to greater soil concentration of salts. Seasonal shifts and reductions in western water supply will require greater reliance on saline/brackish or nonrenewable fresh groundwater as a source for irrigation water. This double squeeze, from both supply and demand sides, is expected to increase soil salinization in much of the West. Third, invasion of rivers by nonnative fishes is ongoing. Native species in heavily invaded ecosystems will become increasingly threatened by nonnative species and flow regimes further altered by climate change.

In closing, we note that the capacity for water to support cities, industry, agriculture, and ecosystems in the US West is near its limit under current management practices. For an urban population double the Census 2000 size, we estimate that water withdrawals necessary to meet municipal, industrial, and agricultural demand will exceed 86% of the current streamflow across parts of seven hydrologic regions in the southwest United States (Fig. 4*B* and *SI Appendix*). Our estimate of human appropriation is >99% of the streamflow generated by this region if we include the water needed to produce all food to feed a doubled population in the region (Fig. 4*B*). These estimates are conservative for two reasons. First, our population doubling scenario does not include supply reductions due to climate change. Second, we assume conservative increases in water withdrawals as the urban population grows. Even these most-conservative estimates suggest that renewable freshwater resources will not comfortably support a population beyond two times the current levels in the western United States while still providing adequate flows to maintain vital ecosystems.

To reclaim freshwater sustainability in the Cadillac Desert, we suggest an initially modest target of a 16% reduction in the fraction of streamflow withdrawn, or WSI = 0.6 before the realization of a projected population doubling across the entire geographic region (Fig. 4*B*). This improved regional WSI represents a compromise between reductions that would alleviate water stress altogether (WSI 0.4) and those that would significantly diminish already insufficient freshwater resources in river and delta ecosystems (WSI >0.8). Meeting this target will require a regional water conservation policy coordinated across seven US states addressing at a minimum: (*i*) continued improvements in urban water use efficiency, (*ii*) implementation of desalinization by coastal cities, (*iii*) continued improvements in land-use practices that minimize erosion and sediment infilling of the region's reservoirs, (*iv*) technological advances increasing water application efficiency during irrigation, (*v*) modified crop portfolios that include only salt tolerant and cash crops, (*vi*) effective reallocation of salvaged surface water to ecosystems as farmlands are retired and cities shift to desalinization, and (*vii*) endorsement of market-based rather than government-subsidized water pricing for all uses except those that fulfill the most basic daily human needs. Further, Reisner's book *Cadillac Desert* and our analyses do not consider the impact of water use on groundwater reserves. A regional policy of freshwater sustainability should bridge this gap and (*viii*) implement aquifer storage and recovery and artificial recharge schemes for water storage and management, and (*ix*) endorse only judicious use of groundwater with minimal impact on surface flows in pursuit of our suggested target (WSI 0.6). This regional policy of freshwater sustainability will impose a cost, and this cost—as Reisner noted—will most likely include more expensive water at the tap and on the farm.

Materials and Methods

Macroscale Hydrology. We used a macroscale hydrologic model—the Variable Infiltration Capacity (VIC) model (35, 36)—to quantify patterns in mean annual streamflow volume (km^3) across the coterminous United States at a resolution of 1/8 degree using observed meteorological forcings from 1950 to 1999 (37). We used the VIC model to estimate streamflow (as opposed to available data) because the VIC model provides estimates of virgin flow, whereas empirically measured streamflow includes the effects of withdrawals and river regulation by dams. In contrast to previous continental-scale applications of the VIC model (37–39), the current version was implemented with seasonally frozen soils, improving energy and water balance estimates during the winter season (40, 41). The VIC model was calibrated to monthly naturalized and observed streamflow for 12 watersheds within six major representative hydrologic regions across the coterminous United States for a 10-y period and then evaluated for the remaining (independent) observational period of 10–40 y, between 1950 and 1999. Model bias was low and positive on average (9.2% ± 5.9% of naturalized or observed streamflow) with reasonable variation across basins (Table S3).

Patterns of Infrastructure. Using data from the National Inventory of Dams we summed the total number and storage capacity of reservoirs in each USGS subregion. We then estimated the average number of dams per 100 km of river length [according to USGS's HYDROGL020 layer (US National Atlas Water Feature Areas)] (42) or dam density. We also quantified the total storage capacity relative to mean annual streamflow (*relative* storage capacity) for each subregion using streamflow estimates from the VIC model (Fig. 1). We then made East vs. West comparisons in this section and all others to follow at the watershed, or USGS four-digit hydrologic code (HUC 4) subregion resolution. For all East vs. West comparisons, we used geographic centroids of HUC 4 subregions to determine their location relative to the 100th meridian.

Sediment Infilling. We quantified infilling rates, reservoir storage capacity losses, and lifespans using the RESIS-II database (43). This database includes repeat bathymetric surveys for >1,200 reservoirs in the United States. We estimated single structure storage capacity losses from closure to present (2010). Total capacity losses for hydrologic subregions were then estimated by multiplying the subregion's total reservoir capacity [from the National Inventory of Dams (NID)] by the minimum observed proportion of capacity lost (from RESIS-II). We expressed this capacity loss as a proportion of the subregion's mean annual streamflow (i.e., *relative* capacity loss).

Firm Yield Analysis. For 24 reservoirs in the RESIS-II database ranging in size from 0.04 to 35.5 km^3, we estimated the change in firm yield via sequent peak analysis based on our estimates of current active storage and observed monthly streamflow data from nearby USGS stations.

Agricultural Revenue Losses to Salinity. We estimated revenue losses as a result of diminished crop yields in saline soils for all 204 hydrologic subregions in the coterminous United States. We identified salt-affected soils using the nationwide State Soil Geographic Database (STATSGO). We then estimated revenue losses according to nationwide crop type and soil salinity maps and data on crop salt tolerances, crop yields, and prices.

Fish Invasion. We cataloged patterns of invasion by nonnative fishes using the USGS Nonindigenous Aquatic Species (NAS) database (44) and NatureServe's Distribution of Native Fishes by Watershed database (45). For nonnative fishes in the NAS dataset, we used only established, locally established, and stocked nonnative species in the NAS dataset to avoid spurious single sightings of nonindigenous species that might inflate our estimates of invasion. We recompiled presence/absence data at the resolution of hydrologic subregions in the lower 48 states and estimated α diversity for native, nonnative, and all (native and nonnative) fishes in each subregion (Fig. S4).

Water Footprints. To estimate a water footprint for each city, we used the annual per capita water requirements based on a published average US diet (46). We also calculated per capita crop water use for each subregion using estimates of AET from cropped areas under natural rainfall together with known quantities of irrigation water withdrawals. Per capita values were multiplied by the MSA population size from the 2000 census (US Census Bureau). The difference in virtual water demand and supply was normalized by streamflow depth from the VIC model to estimate the land area required to capture the net virtual water demand.

Extrapolation of Human Appropriation of Streamflow Under Population Doubling. To extrapolate water use and human appropriation of streamflow under a population doubling scenario, we developed a regression relationship between total US population size and total annual water withdrawals. The slope of this relationship at the time of publication of Cadillac Desert was $\approx$2, indicating a doubling in water extraction with population growth. Estimates of water withdrawals over the last 25 y (1980–2005) indicate that withdrawals have increased much less dramatically with population (slope = 0.23 per unit population). We extrapolate WSI and virtual WSI under a population doubling scenario for the superregion assuming a constant relationship between water use and population (slope = 0.23) over time frames consistent with population doubling (40–90 y). We recognize the perils of linear extrapolation of current water rates and thus rely on the more conservative, flatter relationship between population and water withdrawals to estimate future WSI.

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