JOURNAL OF THE AMERICAN WATER RESOURCES ASSOCIATION
Vol. 54, No. 3 AMERICAN WATER RESOURCES ASSOCIATION June 2018

IMPLICATIONS OF UPSTREAM FLOW AVAILABILITY FOR WATERSHED SURFACE WATER SUPPLY ACROSS THE CONTERMINOUS UNITED STATES[1]

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ABSTRACT: Although it is well established that the availability of upstream flow (AUF) affects downstream water supply, its significance has not been rigorously categorized and quantified at fine resolutions. This study aims to fill this gap by providing a nationwide inventory of AUF and local water resource, and assessing their roles in securing water supply across the 2,099 8-digit hydrologic unit code watersheds in the conterminous United States (CONUS). We investigated the effects of river hydraulic connectivity, climate variability, and water withdrawal, and consumption on water availability and water stress (ratio of demand to supply) in the past three decades (i.e., 1981–2010). The results show that 12% of the CONUS land relied on AUF for adequate freshwater supply, while local water alone was sufficient to meet the demand in another 74% of the area. The remaining 14% highly stressed area was mostly found in headwater areas or watersheds that were isolated from other basins, where stress levels were more sensitive to climate variability. Although the constantly changing water demand was the primary cause of escalating/diminishing stress, AUF variation could be an important driver in the arid south and southwest. This research contributes to better understanding of the significance of upstream–downstream water nexus in regional water availability, and this becomes more crucial under a changing climate and with intensified human activities.

(KEY TERMS: water supply; runoff; rivers/streams; simulation; time series analysis; planning.)

Duan, Kai, Ge Sun, Peter V. Caldwell, Steven G. McNulty, and Yang Zhang, 2018. Implications of Upstream Flow Availability for Watershed Surface Water Supply across the Conterminous United States. *Journal of the American Water Resources Association* (JAWRA) 54(3): 694–707. https://doi.org/10.1111/1752-1688.12644

INTRODUCTION

Surface and shallow subsurface runoff accumulates to streamflow in the river channels and constitutes the major part of renewable freshwater for human use (Oki and Kanae 2006). Besides human's basic needs for drinking and sanitation, much larger quantities of freshwater are required in modern economic activities, such as the thermoelectric plants cooling and irrigated agriculture. According to the most recent national water use report (Maupin et al. 2014), a total of 3×10^{11} m^3 surface freshwater was withdrawn from rivers and lakes in 2010 over the conterminous United States (CONUS). Meanwhile, the total available freshwater indicated by annual runoff has been varying around 2×10^{12} m^3 in the past century (U.S. Geological Survey [USGS] water watch, http://waterwatch.usgs.gov/index.php). Water demand was relatively small compared to the supply

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[1] Paper No. JAWRA-17-0104-P of the *Journal of the American Water Resources Association* (JAWRA). Received July 18, 2017; accepted February 27, 2018. © 2018 American Water Resources Association. This article is a U.S. Government work and is in the public domain in the USA. **Discussions are open until six months from issue publication**.

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at continental scale. However, there were many areas stressed by water shortage due to the uneven spatiotemporal distribution and the limited access to water resources (Vörösmarty et al. 2000; Schewe et al. 2014). Naturally, freshwater in the dynamic form of streamflow is only endowed to adjacent areas. Long-distance redistribution of water resources is costly, and faces the challenges of negative environmental consequences and water loss by leakage and evaporation. These facts make it critical to understand the geographic linkage of river networks, as well as the dynamics between upstream and downstream water users, before mapping water availability and scarcity.

The degree of water stress can be quantified by the ratio of water demand, estimated from the total offstream water use (i.e., water withdrawal) to water supply, defined as streamflow that local human populations sustainably have access to (Sun et al. 2008; Richey et al. 2015; Eldardiry et al. 2016). In previous evaluations based on basin-level or subbasin-level hydrological simulations, a frequently used assumption is that upstream flows are first consumed according to upstream users' demand and then the residuals complement downstream water availability (Vörösmarty et al. 2000; Oki et al. 2001; Döll et al. 2003; Caldwell et al. 2012; Schewe et al. 2014). However, upstream flows are susceptible to changing environment and behaviors of upstream users, such as climate change, water contamination, and conflicts and trades in water rights among upstream and downstream users (Foti et al. 2012; Grantham and Viers 2014; Munia et al. 2016). These factors may alter the magnitude and variability of runoff passage through river networks, and consequently affects water availability in middle-stream and downstream areas. As estimated by Oki et al. (2001), up to 1 billion people would have water resource-related stress if no upstream water was available for downstream areas.

Monitoring the changes in water stress and identifying the driving factors are essential for effective water resources planning and management in a rapidly changing world. Both water demand and supply are constantly changing due to changes in the environment and the socioeconomy. The possible driving factors for an increasing/decreasing stress include: (1) increasing/decreasing demand due to changes in population (Vörösmarty et al. 2000), economic structure (e.g., increasing/decreasing farmland and irrigation water use), energy structure (e.g., increasing/decreasing thermoelectric plants) (Moore et al. 2015), or water use efficiency (Maupin et al. 2014); (2) decreasing/increasing local water yield due to changes in climate background (Roy et al. 2012), land cover and land use (Sun et al. 2015), or other changes in underlying surface (e.g., topography, soil properties); (3) decreasing/increasing upstream flows due to the environmental changes in upstream areas or increasing/decreasing upstream withdrawals. Among the hydraulically connected watersheds, the changes in water yield and water use may lead to prolonged and accumulated effects on water supply in downstream areas.

The goal of this paper was to provide a retrospective assessment of water supply and water stress across the CONUS in the past three decades. Specifically, we address two questions: (1) To what extent did natural connectivity of the river network and upstream–downstream dynamics affect water availability and water stress? and (2) How did stress level change and what caused those changes? Unlike previous evaluations, the roles of local water resource and accumulated upstream flows in fulfilling water demand are discussed in detail. We explicitly model the water dynamics from upstream to downstream with constraints of river topology and offstream water use across the 2,099 USGS 8-digit hydrologic unit code (HUC-8) watersheds (http://water.usgs.gov/GIS/huc.html). We consider the stress levels with respect to renewable surface freshwater only. Groundwater and saline (or desalinized) water are excluded from the tabulation of both demand and supply aspects.

METHODS

Water Withdrawal and Consumption Data

County-level water use data have been compiled and published by the USGS every five years since 1985 (http://water.usgs.gov/watuse/data/). In this study, we collected water withdrawal data for the period of 1985–2010 and water consumption data for the period of 1985–1995, by sectors of public supply, domestic, irrigation, livestock, aquaculture, industrial, mining, and thermoelectric power. Due to the absence of census on water consumption after 1995, the consumptive water uses by sector in 2000–2010 were estimated by multiplying the consumptive rates (the ratio of consumption to withdrawal) obtained from the 1995 report (Solley et al. 1998) with water withdrawal in 2000–2010. The water withdrawal and consumption data were rescaled from county level (3,109 counties) to HUC-8 level (2,099 watersheds) based on weighted areal averages. In order to generate a continuous time series of water demand to be compared to observed annual runoff, water withdrawal and consumptive uses were linearly interpolated within each five-year reporting interval.

Watershed Water Balance Modeling

Due to the limited coverage of streamflow gauging sites, hydrological simulations are usually necessary for large-scale evaluations of water supply. We obtained monthly runoff at HUC-8 scale using an integrated water balance model (Water Supply Stress Index model, WaSSI) that describes hydrologic processes from precipitation to evapotranspiration (ET) and runoff discharge (Sun et al. 2011; Caldwell et al. 2012; Averyt et al. 2013; Duan et al. 2016; Duan, Sun, Zhang, et al. 2017). In the WaSSI model, temperature and watershed geography (elevation and latitude) are used to determine the proportions of rainfall and snowfall in monthly precipitation, as well as the rates of snow pack accumulation and melt (McCabe and Markstrom 2007). Potential ET (PET) is estimated by a suite of functions of available precipitation, Hamon's PET, leaf area index (LAI), and soil moisture for different land-cover ecosystems. The monthly processes of ET, infiltration, soil water recharge and discharge, and runoff generation are simulated for each land-cover type (2006 National Land Cover Database, https://www.mrlc.gov/nlcd06_data.php) within a watershed using the Sacramento Soil Moisture Accounting model (SAC-SMA) (Burnash 1995). The model inputs and parameters included monthly precipitation and temperature data obtained from the Parameter-elevation Relationships on Independent Slopes Model dataset (http://prism.oregonstate.edu/), temperature thresholds of the snow sub-model, parameters of ET sub-model derived from eddy covariance or sapflow measurements, parameters of SAC-SMA derived from soil properties, and spatial distributions of LAI and land cover in the CONUS.

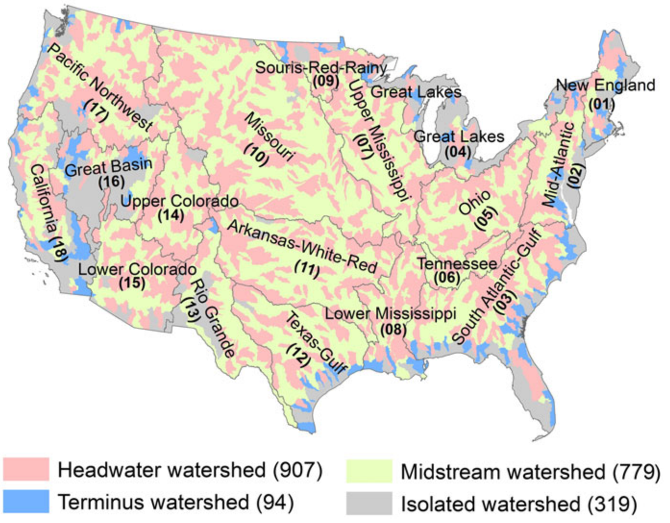


FIGURE 1. Hydraulic connectivity among the 2,099 8-digit hydrologic unit code (HUC-8) watersheds in the 18 water resource regions (i.e., HUC-2 watersheds) across the conterminous United States (CONUS). The numbers of "headwater," "midstream," "terminus," and "isolated" watersheds are marked with brackets in the legend.

Availability of Surface Freshwater Supply

Watershed-level surface freshwater supply consists of runoff generated from local precipitation and upstream flow accumulated from upstream areas. To rigorously quantify the availability of these two water resources, we simulated water accumulation through the stream networks based on the routing direction and hydraulic connectivity among the HUC-8 watersheds (Caldwell et al. 2012; Emanuel et al. 2015). The physical boundaries of watersheds and geospatial attributes of streams at different levels, ranging from 2,099 HUC-8 watersheds to 18 HUC-2 watersheds (i.e., water resource region, WRR, see Figure 1), were obtained from the USGS Watershed Boundary Dataset (http://nhd.usgs.gov/wbd.html) and National Hydrography Dataset (http://nhd.usgs.gov/data.html) on the ArcGIS platform (ESRI Inc., Redlands, CA). The outlet point for each HUC-8 watershed, i.e., the inlet of next downstream watershed, was considered as the exiting reach with the greatest cumulative drainage area. A total of 18,777 upstream–downstream connections were identified across the CONUS. We here reclassify the watersheds into four types (Figure 1) based on these connections: (1) "Headwater" watershed that is connected to downstream only; (2) "Midstream" watershed that is connected to both upstream and downstream; (3) "Terminus" watershed that is connected to upstream only; (4) "Isolated" watershed that is not connected to either upstream or downstream. These four types account for 907, 779, 94, and 319 of the watersheds (39%, 43%, 5%, and 13% of the CONUS area), respectively.

It can be assumed that "headwater" and "isolated" watersheds receive no water flow from outside, while "midstream" and "terminus" watersheds would receive a certain amount of water from the connected upstream areas under the influence of upstream human activities. We here investigate three scenarios of upstream flow availability for "midstream" and "terminus" watersheds:

1. **No upstream water supply**. It represents an extreme scenario that only the runoff generated within the watershed is accessible. Under this scenario, the total water supply (total flow, TF) equals the local water supply (local flow, LF) that can be simulated by the WaSSI model as precipitation (P) minus evapotranspiration (ET) and changes in soil moisture (S_{M}) and hydrologically connected snowpack (S_{P}) (Duan, Sun, McNulty, et al. 2017):

$$\mathrm{LF} = \mathrm{P} - \mathrm{ET} + \mathrm{d}S_{\mathrm{M}}/\mathrm{d}t + \mathrm{d}S_{\mathrm{P}}/\mathrm{d}t \tag{1}$$

2. **Maximum upstream water supply**. It represents a hypothetical natural state without human disturbances. The maximum surface freshwater supply can be calculated as

$$\mathrm{TF_m} = \mathrm{LF} + \sum\nolimits_{i=1}^{N} \mathrm{UF}_i, \tag{2}$$

where $\sum_{i=1}^{N}\mathrm{UF}_i$ is the total amount of LF accumulated from all the connected upstream watersheds.

3. **Post-consumption upstream water supply**. It represents a scenario with a given level of water withdrawal and consumption, where the total water supply can be calculated as

$$\mathrm{TF_c} = \mathrm{LF} + \sum\nolimits_{i=1}^{N}\mathrm{UF}_i - \sum\nolimits_{i=1}^{N}\mathrm{WW}_i + \sum\nolimits_{i=1}^{N}\mathrm{RF}_i, \tag{3}$$

where $\sum_{i=1}^{N}\mathrm{WW}_i$ and $\sum_{i=1}^{N}\mathrm{RF}_i$ are the total water withdrawal and return flow in the connected upstream watersheds, respectively. It was assumed that water withdrawal and consumption occur uniformly inside each watershed, and the return flows, as well as the residuals of the accumulated flow, were discharged simultaneously to surface water at the inlet of the next downstream watershed. In cases where the accumulated streamflow cannot meet the demand of withdrawal, the actual water withdrawal was set to equal the maximum water availability, and consumptive uses and the return flow discharged to downstream were reduced by the same ratio. $\mathrm{TF_c}$ represents a reasonable estimate of potential water supply with current hydrological condition and water consumption level. However, it should be kept in mind that the actual water availability could be affected by other anthropogenic factors, such as upstream flow regulation (e.g., dams), water diversions from/to other watersheds, accessibility limitation due to lack of infrastructure, and water quality deterioration from upstream uses. These factors are not currently represented in the modeling framework.

The effects of upstream water consumption on downstream water supply can be described by a coefficient of upstream flow availability, as

$$u = (\mathrm{TF_c} - \mathrm{LF})/(\mathrm{TF_m} - \mathrm{LF}) \tag{4}$$

As the value of coefficient u varies between 0 and 1, the post-consumption water supply falls into somewhere between LF (u = 0) and $\mathrm{TF_m}$ (u = 1).

Metrics of Water Stress

To quantify the sufficiency of local water resource and upstream flow in meeting water demand, we here suggest two indices of water stress. We define local water stress (LWS) as

$$\mathrm{LWS} = \mathrm{WD}/\mathrm{LF}, \tag{5}$$

where WD is the local water demand, estimated by subtracting saline water use and groundwater withdrawal from the total water withdrawal by all the sectors. Global water stress (GWS) is defined as the ratio of WD to post-consumption water supply:

$$\mathrm{GWS} = \mathrm{WD}/\mathrm{TF_c} \tag{6}$$

For the "headwater" and "isolated" watersheds, stresses evaluated by the two indices are identical. For the "midstream" and "terminus" watersheds, LWS reflects the vulnerability of water supply under an extreme situation that all the upstream flows are consumed or reserved by upstream users, while GWS represents the stress level where downstream users have full access to upstream flows after current consumptive uses. The difference between LWS and GWS indicates the uncertainty range of stress in response to upstream water availability, which could provide a reference for water planning and management at local levels.

Water stress is usually considered high if the ratio of water demand to water availability is higher than 0.4. A more detailed classification would include "high," "medium," "moderate," and "low" stress levels, with the ratio values being >0.4, between 0.2 and 0.4, 0.1 and 0.2, and <0.1, respectively (Vörösmarty et al. 2000; Oki et al. 2001; Richey et al. 2015). These thresholds were set with the concern that not all the water can be withdrawn for offstream uses. The water demands for ecological and environmental services, as well as instream uses for human society (i.e., navigation and hydropower), should also be met. In this study, we follow the previous criteria to map water scarcity across the CONUS using both LWS and GWS, and further define three stress regimes to address the degree of dependence on upstream flow:

1. "Unstressed," if LWS < 0.4, indicates that local water resource alone is sufficient to meet the demand of fresh surface water withdrawals;
2. "Upstream-stressed," if LWS > 0.4 and GWS < 0.4, indicates a high level of water stress when upstream flows are absent, but the stress can be markedly alleviated by the complement of upstream flow;

3. "Overstressed," if GWS > 0.4, indicates a high level of water stress even when water supply is complemented by upstream flow.

Detecting Trends and Identifying Driving Factors

Long-term trends in annual demand, supply, and stress during 1981–2010 were tested with the commonly used Mann–Kendall nonparametric rank-based method (Mann 1945; Kendall 1962). We here categorize the causes of trends in GWS into "demand induced," "demand & supply induced," and "supply induced" according to the significance of trends in WD, LF, TF, and GWS (Table 1). The "supply induced" trends are further classified to highlight the roles of upstream flow and LF. Given that the changes in demand and supply may drive the degree of water stress to change in either the same or opposite directions, the driving factor is only recognized if the trend is significant and consistent with the trend in GWS. For example, increasing demand is identified as the major driving factor for increasing stress only when there is either increasing trend or no significant trend in supply, otherwise it is identified as "demand–supply induced."

RESULTS

Water Stress Levels

Total water demand in the CONUS increased steadily from 1.9×10^{11} m^3/yr in 1950 to 3.9×10^{11} m^3/yr in 1980 owing to the growing population (Maupin et al. 2014). After reaching the peak in 1980, total demand during 1980–2005 was relatively stable around the level of 3.6×10^{11} m^3/yr, followed by a 13% downward shift from 2005 to 2010. On the other hand, total water availability ranged between 1.3×10^{12} (1988) and 2.6×10^{12} m^3/yr (1983) over the period of 1946–2010. The overall annual water stress (total demand/total supply) (Figure 2) has fluctuated between 0.09 (1950) and 0.28 (1977) over the past six decades. The stress level can be ranked as "medium" (0.2–0.4), "moderate" (0.1–0.2), and "low" (<0.1) in 12, 49, and 4 of the 65 years, respectively.

Although the stress level remained at the moderate level in most years at the CONUS scale, there was high regional diversity across the HUC-8 watersheds (Figure 3). Most of the western watersheds across WRR#10–18 were under "high" LWS (>0.4), which was consistent with the dry climate and the subsequently low LF. The exceptions were the wetter watersheds in the Pacific coast and the north of WRR#17 (Pacific Northwest) with LWS values below 0.1. In the central and eastern regions, the distribution of watersheds under high LWS largely agreed with that of areas demanding high water uses (over 1×10^9 m^3/yr). The difference between the magnitudes of LF and TF shows that the accumulations of streamflow fundamentally changed regional water availability, and led to clear downgrade in the stress levels evaluated by GWS compared to LWS.

Dependence on Upstream Water Supply

Figure 3f shows the spatial distributions of unstressed (LWS < 0.4), upstream-stressed (LWS > 0.4

TABLE 1. Patterns of trends in water stress (GWS) from 1981 to 2010 and the major driving factors.

Pattern	Trend	Major driving factor	Judging criteria
Demand induced			
11	Increasing	Increasing demand	$I(\mathrm{GWS}) = 1$ & $I(\mathrm{WD}) = 1$ & $I(\mathrm{TF}) \neq -1$[1]
12	Decreasing	Decreasing demand	$I(\mathrm{GWS}) = -1$ & $I(\mathrm{WD}) = -1$ & $I(\mathrm{TF}) \neq 1$
Demand–supply induced			
21	Increasing	Increasing demand & decreasing supply	$I(\mathrm{GWS}) = 1$ & $I(\mathrm{WD}) = 1$ & $I(\mathrm{TF}) = -1$
22	Decreasing	Decreasing demand & increasing supply	$I(\mathrm{GWS}) = -1$ & $I(\mathrm{WD}) = -1$ & $I(\mathrm{TF}) = 1$
Supply induced			
31	Increasing	Decreasing upstream flow	$I(\mathrm{GWS}) = 1$ & $I(\mathrm{WD}) \neq 1$ & $I(\mathrm{TF}) = -1$ & $I(\mathrm{LF}) \neq -1$
32	Increasing	Decreasing LF	$I(\mathrm{GWS}) = 1$ & $I(\mathrm{WD}) \neq 1$ & $I(\mathrm{TF}) \neq -1$ & $I(\mathrm{LF}) = -1$
33	Increasing	Decreasing upstream flow & LF	$I(\mathrm{GWS}) = 1$ & $I(\mathrm{WD}) \neq 1$ & $I(\mathrm{TF}) = -1$ & $I(\mathrm{LF}) = -1$
34	Decreasing	Increasing upstream flow	$I(\mathrm{GWS}) = -1$ & $I(\mathrm{WD}) \neq -1$ & $I(\mathrm{TF}) = 1$ & $I(\mathrm{LF}) \neq 1$
35	Decreasing	Increasing LF	$I(\mathrm{GWS}) = -1$ & $I(\mathrm{WD}) \neq -1$ & $I(\mathrm{TF}) \neq 1$ & $I(\mathrm{LF}) = 1$
36	Decreasing	Increasing upstream flow & LF	$I(\mathrm{GWS}) = -1$ & $I(\mathrm{WD}) \neq -1$ & $I(\mathrm{TF}) = 1$ & $I(\mathrm{LF}) = 1$

Notes: GWS, global water stress; WD, local water demand; TF, total flow; LF, local flow.

[1] $I(*)$ denotes the trend in variable * at the 5% significance level, and the values of 1, 0, and −1 indicate significant upward, insignificant, and significant downward trends, respectively.

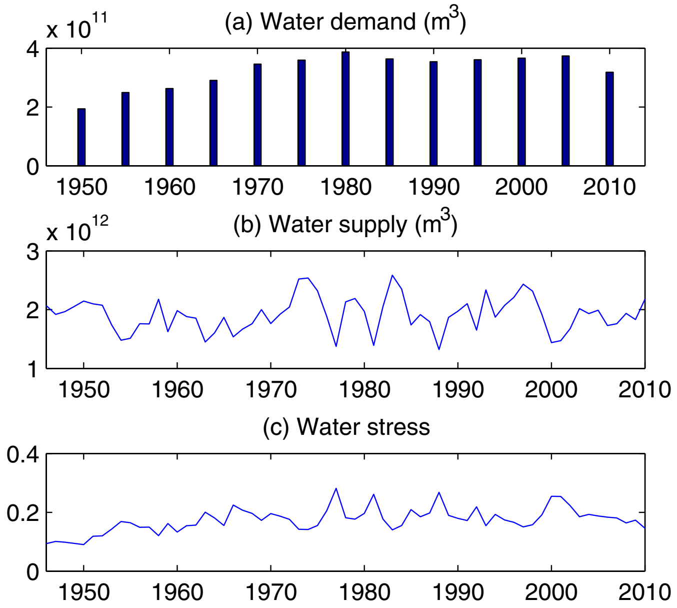


FIGURE 2. Overall changes in water demand (a), water supply (b), and water stress (c) in the CONUS between 1946 and 2010. Water demand data were obtained from the United States Geological Survey (USGS) reports from 1950 to 2010 (http://water.usgs.gov/watuse/data/). Water supply data at the CONUS level were derived from the USGS measurements at http://waterwatch.usgs.gov/index.php.

and GWS < 0.4), and overstressed (GWS > 0.4) watersheds. In the east, upstream-stressed areas can be mainly found in the Susquehanna (WRR#2, Mid-Atlantic), Ohio (WRR#5, Ohio), and Tennessee watersheds (WRR#6, Tennessee). These areas were mainly stressed due to dense population and large water use, but the complementary discharges from the tributaries could lower the stress levels to below 0.4. The western part of CONUS is hydrologically drier, and sufficient water supply is largely dependent on the accumulated water in the major rivers, such as Yellowstone, Platte, and Missouri River in WRR#10 (Missouri), Rio Grande and Pecos River in WRR#13 (Rio Grande), Colorado River in WRR#14–15 (Upper and Lower Colorado), and Snake River in WRR#17 (Pacific Northwest).

We cross-compared the coverages of watershed categories and stress types over the CONUS (Table 2). In total, we identified 213 out of the 2,099 watersheds as upstream-stressed, most of which were in the midstream of rivers. Meanwhile, there were 315 overstressed watersheds. It is worth noting that 274 out of the 315 (87%) were either "headwater" or "isolated" watersheds that had no access to natural upstream flow, while the other 41 watersheds were overstressed as inadequate upstream water would arrive in a normal year.

Variations in Stressed Area and Population

Figure 4 shows the coverages of LWS, GWS, and the three stress types over the last three decades. Approximately 67% of the CONUS area stayed unstressed from 1981 to 2010, but the other 33% have experienced stress to different degrees. Much larger variation ranges were detected in the coverage of "high" category (14% by LWS and 12% by GWS) than that of "moderate" and "medium" (<5%). While the coverage of upstream-stressed area was relatively stable (varying between 10% and 14% in area and between 11% and 16% in population), the overstressed area could expand from 9% to 21% (13%–26% in population). These results are consistent with the pattern shown in Table 2 that "headwater" and "isolated" areas, which accounted for over 80% of overstressed watersheds, could be more vulnerable to variations in water supply/demand due to the limited source of water supply. For example, local climate variation could cause recurrent switch between the states of unstressed and overstressed in accordance with the wet/dry cycles in some "headwater" or "isolated" watersheds, while the "midstream" and "terminus" areas generally have higher resilience to climate variability thanks to the complementary water from upstream. The spatial inhomogeneity of changes in water supply/demand in relevant upstream areas could offset some stress for downstream areas in extreme situations.

Historic Trends in Water Stress and Driving Factors

We also examined the multi-decadal trends in water stress and the roles of changing demand and local and upstream supplies. Though no significant trend can be found at the CONUS scale, there were a variety of trends across the watersheds (Figure 5). Water demand showed significant changes in more than two-thirds of the 2,099 watersheds, including 757 (36%) decreases and 614 (29%) increases. A significant decrease at WRR level can be found in the northeast (WRR#1,2,4,5) and northwest (WRR#14,16,17), with increases in the south (WRR#6,8,11,12). On the other hand, significant changes in LF and TF only occurred in approximately 10% of the watersheds. The increase in both LF and TF can be mainly found in the northeast (WRR#1,2) and Souris-Red-Rainy (WRR#9), while decreases were spread in the southwest from WRR#11 to WRR#17. It is worth noting that there were clearly more decreases in TF (160 watersheds) than in LF (128 watersheds) in the southern CONUS. The streamflow in the Arkansas, Canadian, Red, Brazos, and Pecos Rivers across WRR#11–13 showed widespread

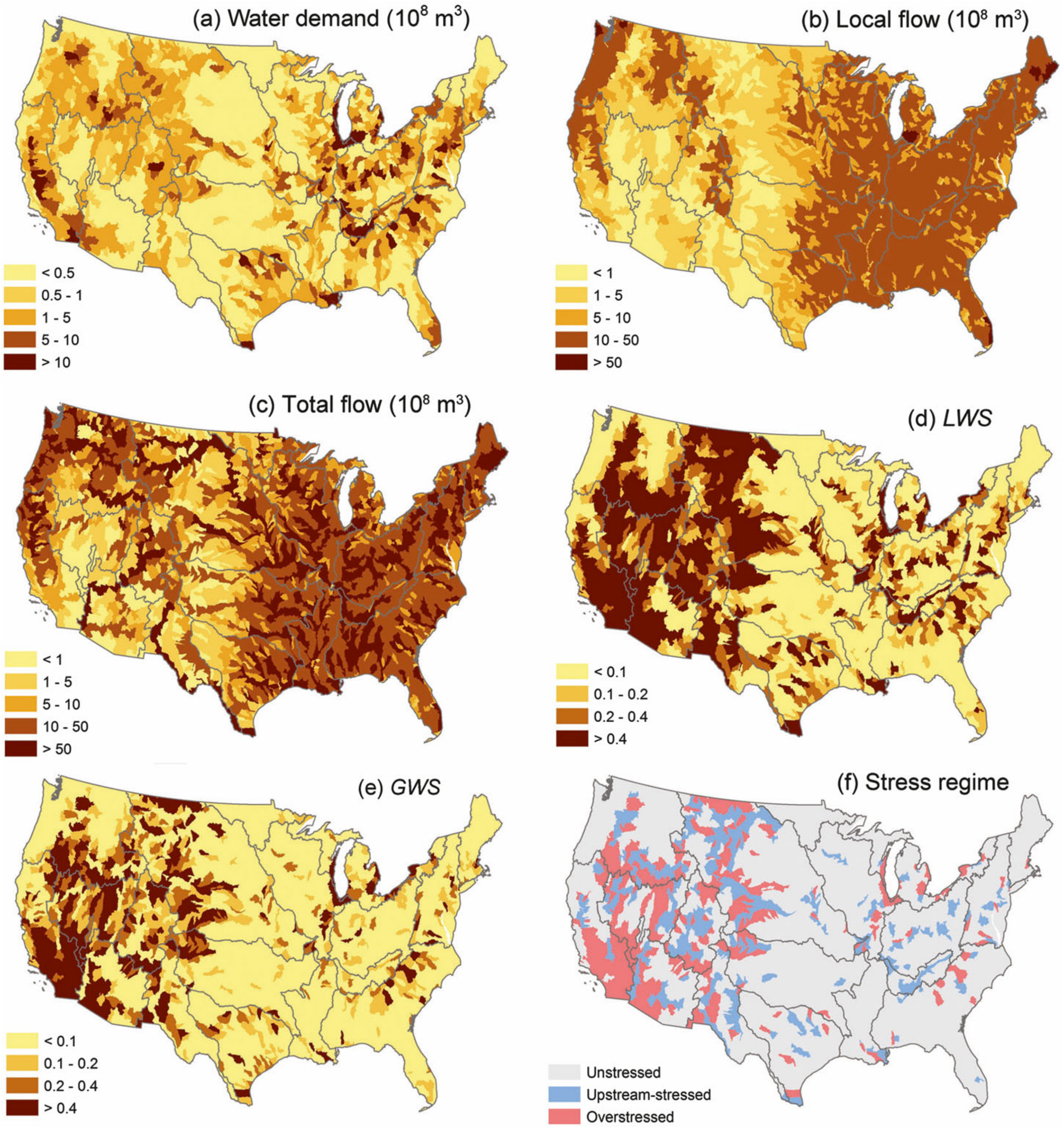


FIGURE 3. Spatial distribution of multi-decadal mean annual water demand (a), LF (b), post-consumption TF (TF_c) (c), local water stress (LWS) (d), GWS (e), and stress regime (f) across the HUC-8 watersheds during 1981–2010.

decreases as a result of declines in upstream flows, although not so significant in the catchment runoff.

The combination of changes in demand and supply has caused rising LWS and GWS in 377 (17% in area and 14% in population) and 400 (19% in area and 15% in population) watersheds, respectively. At WRR level, significantly higher stress can be found in Tennessee (WRR#6) and Texas-Gulf (WRR#12) along with increasing demand, and also in Lower Colorado

TABLE 2. Summary of area and population under different types of water stress in the CONUS.

	Area %				**Population %**			
Watershed category	**Unstressed**	**Upstream-stressed**	**Overstressed**	**Total**	**Unstressed**	**Upstream-stressed**	**Overstressed**	**Total**
Headwater	32 ± 1.6[1]	\	7 ± 1.6	39	23 ± 0.8	\	5 ± 0.6	28
Midstream	30 ± 1.5	11 ± 0.9	2 ± 0.8	43	19 ± 1.5	12 ± 1.1	4 ± 0.6	35
Terminus	3 ± 0.2	0.9 ± 0.2	1 ± 0.2	5	6 ± 0.7	2 ± 0.7	0.4 ± 0.2	8
Isolated	9 ± 0.8	\	4 ± 0.8	13	18 ± 2.1	\	10 ± 2.1	28
CONUS	74 ± 3.7	12 ± 0.9	14 ± 3.1	100	66 ± 3.8	14 ± 1.4	20 ± 3.0	100

[1] Mean ± standard deviation of annual results during the period of 1981–2010.

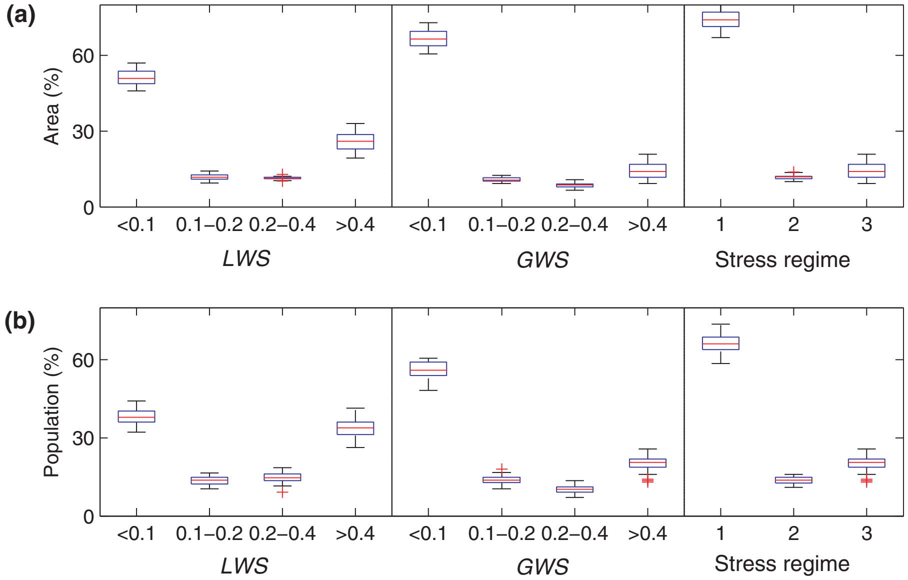


FIGURE 4. Variation ranges of water stressed area (a) and population (b) in the CONUS during 1981–2010. The stress levels categorized by LWS and GWS are denoted by "<0.1" (low), "0.1–0.2" (moderate), "0.2–0.4" (medium), and ">0.4" (high) in the x-axis, while the stress regimes are denoted by "1" (unstressed), "2" (upstream-stressed), and "3" (overstressed). The vertical spread of the box–whisker plots shows the different annual results monitored in the 30 years, with the boxes covering the ranges from 25% quartile to 75% quartile of the distributions (interquartile range) and the red lines within each box marking the median values. Points outside the whiskers are extreme outliers and marked by plus signs.

(WRR#15) along with decreasing water supplies. Decreasing trends in LWS and GWS covered 384 (17% in area and 28% in population) and 382 (17% in area and 28% in population) watersheds across the country. The results of both LWS and GWS suggest that the largest decreases in water stress were found in the northeast (WRR#1,2,5) and Souris-Red-Rainy (WRR#9), where there were significant changes in both demand and supply.

Increase in local WD has been the primary driver in 75% (i.e., 298 out of 400) of the increasingly stressed watersheds (pattern "11," Figure 6), which can largely be explained by the increasing population in these areas, such as the fast-growing cities in the states of Texas, Colorado, and North Carolina. Another 37 watersheds, mainly scattered in the southwest (WRR#11–15), were under increasing stress driven by both increasing demand and decreasing supply (pattern "21"). Decreases in supply accounted for 9% (36 out of 400) of the increasingly stressed watersheds across the western CONUS (WRR#11–18) (patterns "31"–"33"). In particular, the rising stress in 15 watersheds in south and southwest (WRR#11–13 and WRR#15) was dominated by the depletion of upstream flows (pattern "31"), which is consistent with the decreasing upstream flow (but not so in LF) in the Arkansas, Canadian, Red, Brazos, and Pecos Rivers (Figure 5b, 5c).

Decreases in demand also played a primary role in decreasing GWS, accounting for 84% (320 out of 382) of the stress-decreasing watersheds (pattern "12"). The widespread decreases in demand can be explained by the improvement of water use efficiency. Despite the ongoing increase in population, per-unit

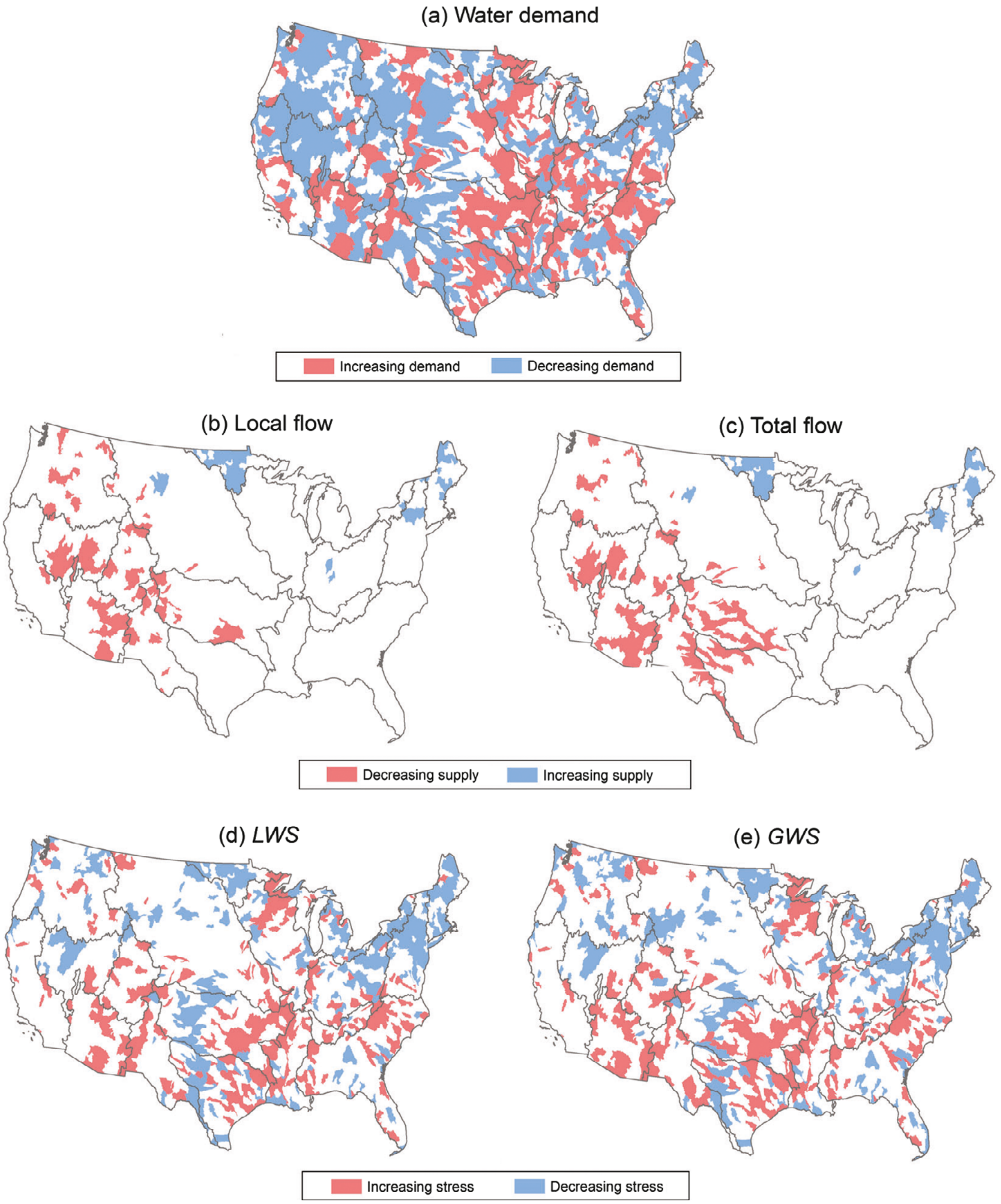
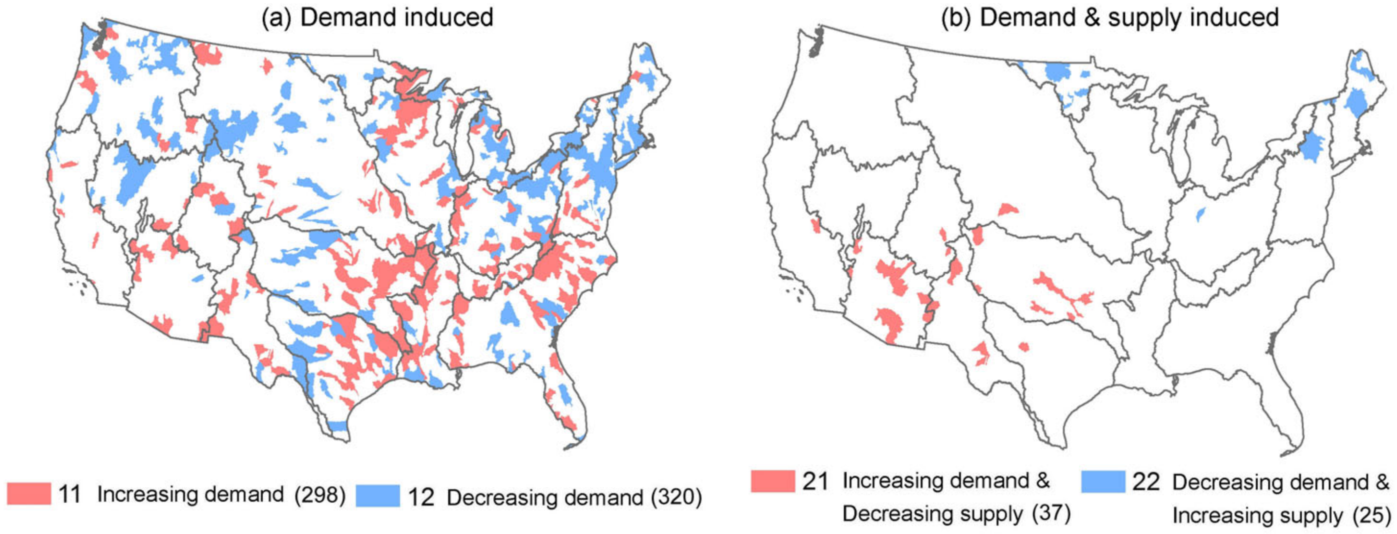


FIGURE 5. Trends in annual water demand, supply, and stress. (a–e) Trends in water demand (a), LF (b), TF_c (c), LWS (d), and GWS (e) across the HUC-8 watersheds during 1981–2010.

water use has been steadily dropping in industry and thermoelectric power over the past 45 years, while the efficiency in the other largest sectors including domestic, irrigation, and public supply has also been improved since 2000 (Foti et al. 2012; Brown et al. 2013). Decreasing demand dominated the changes in stress level in 14% of the land where 25% of the population resided in, suggesting that the changing efficiency has played a particularly important role in the densely populated areas. In another 25 watersheds in the northeast (WRR#1,2,5) and north (WRR#9), both decreasing demand and increasing supply have induced the decreasing stress (pattern “22”). The supply induced decrease can only be found in 11 watersheds in Souris-Red-Rain (WRR#9) (patterns “34”–“36”). In addition, there were significant trends in GWS in other 55 watersheds that did not fit in any of the above patterns. We considered these trends in GWS as a result of the combinations of different changes, but not being dominated by either factor, because no significant trend can be detected in either demand or supply in these areas.

Impact of Recent Consumptive Uses

Figure 7a, 7b summarizes the sensitivity of stressed area and population to the coefficient of upstream flow availability (u) on multi-decadal basis. With the coefficient u decreasing from 1 (maximum upstream water supply) to 0 (no upstream water supply), the coverage of “high” stress expands substantially from 14% to 26% in area and from 20% to 34% in population, while the coverages of “moderate” and “medium” stress both vary between 9% and 12% in area and between 10% and 15% in population. The coverages of stressed area were most sensitive to u at the ranges of 0–0.2. The evaluation under the



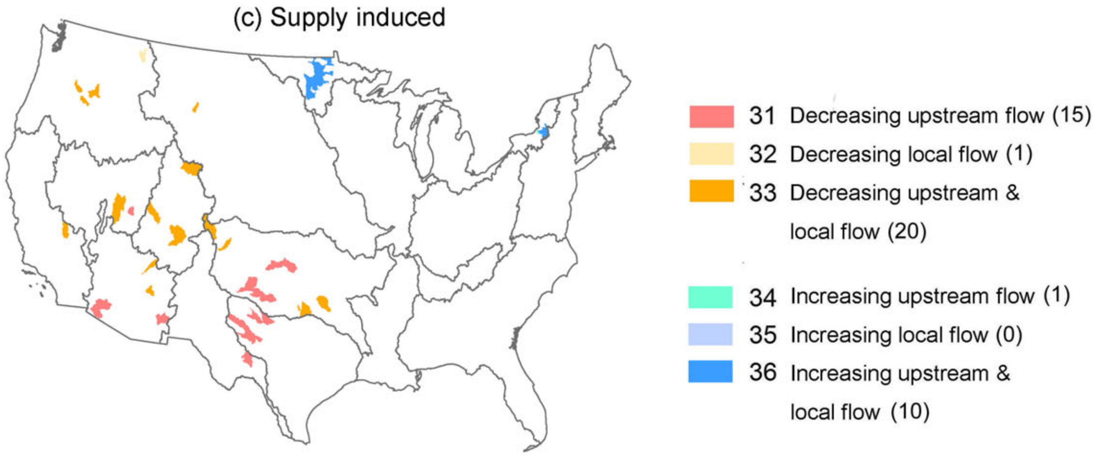


FIGURE 6. Major driving factors of trends in watershed-level GWS. (a–c) Demand induced stress change (a), demand & supply induced stress change (b), supply induced stress change (c). The patterns of trends “11–36” are explained in Table 1. The numbers of watersheds matching each pattern of trends are marked with brackets in the legend.

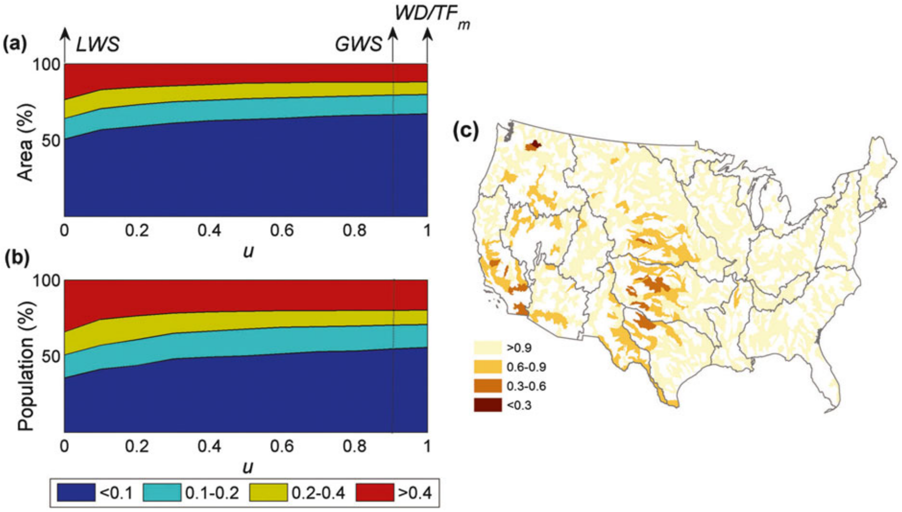


FIGURE 7. (a, b) Sensitivity of stressed area (a) and population (b) to the availability of upstream flow (coefficient u); (c) multiyear mean of coefficient u in each watershed in the period of 1981–2010. The proportions of area and population under different stress levels "<0.1" (low), "0.1–0.2" (moderate), "0.2–0.4" (medium), and ">0.4" (high) are estimated from 30-year mean annual values. The coverages of stressed area and population evaluated by LWS, GWS, and WD/TF$_m$ correspond to the u values of 0, 0.9, and 1, respectively.

scenario of post-consumption upstream water supply corresponds to the u value of 0.9. In other words, the recent consumptive uses caused a decline in upstream water availability equivalent to 10% on a national average.

There were only slight differences (<1%) in the multi-decadal mean coverages of stressed area with (i.e., GWS, equals WD/TF) and without consumptive uses (i.e., WD/TF$_m$). However, water consumption could be a critical cause of upstream flow depletion (Figure 7c) that led to escalating stress. For example, 9 out of the 15 watersheds that matched pattern "31" (Figure 6) would show either decreasing or insignificant trends in water stress if water consumption was not considered, indicating that the intensified upstream consumption has dominated the rise of stress. Meanwhile, the trends in the other "supply induced" watersheds (patterns "32–36") were generally consistent under these two circumstances, suggesting that climate variation in local or upstream areas was probably the main cause of decline in water supply.

DISCUSSION

Implications

This study represents the first attempt to consistently quantify water stress with concern of upstream flow availability at a fine watershed scale across the CONUS. The novelty and merits are the efforts in mapping the degree of water scarcity and its variations under multiple driving factors in the context of upstream–downstream dynamics. It should be kept in mind that this assessment is performed from a hydrological perspective. Water supply "in reality" is largely determined by the status of laws and policies of the water right system (Grantham and Viers 2014), as well as regulations of dams and reservoirs (Nilsson et al. 2005) and interbasin water transfers (Emanuel et al. 2015) through water rights trading. However, our goal was not to report the history of water allocation and management, but to provide a benchmark of the availability of local and upstream flows at a high spatial resolution, and to specify their roles in securing water supply. Our identification of the spatiotemporal patterns of water supply stress has broad implications for both academic research and policy making. Different management strategies for regions with different hydraulic connectivity and stress types are warranted to prepare us for future environmental and anthropogenic changes. For example, upstream-stressed areas are probably more vulnerable to upstream changes such as droughts and water quality deterioration. Sufficient infrastructure for water conservation and storage, and prospective monitoring with concern of distinct source areas are crucial for more effective water management. Overstressed areas, on the other hand, rely on the improvement of water use efficiency and the expansion of sources of water supply, such as updating irrigation system, rain harvesting, interbasin water transfer, and water reclamation.

Comparison with Previous Evaluations

Our results agree with previous assessments that the southwest and major metropolitan areas were generally under more severe water stress (Roy et al. 2005; Foti et al. 2012), and overstressed areas covered around 14% of the CONUS land (Moore et al. 2015). However, there are also differences among these estimates due to inconsistencies in data (e.g., data source, spatial and time scales, gap-filling approach) and modeling method. The relationship between water demand and supply has been interpreted with various indices to quantify the degree of water supply stress (or described by a similar term such as "water vulnerability" or "water scarcity"), such as the ratio of total water use to streamflow (Vörösmarty et al. 2000; Oki et al. 2001), the ratio of total water use to streamflow plus pumped groundwater (Sun et al. 2008), and the ratio of consumptive water use to runoff (Moore et al. 2015). Compared to the prior work, this study addresses not only the degree of water scarcity but also the roles of upstream–downstream dynamics and historic variations in the key factors. The 12% upstream-stressed areas identified in this study, as well as the spatially diverse role of upstream flow and its sensitivity to climate variability and water withdrawal, were relatively understudied. In future research, our results could be combined with scenarios of climate change, energy and economic structural reform, and water transfers to further evaluate their roles in stressing water supply.

Caveats

There are certain limitations in this evaluation that should be noted:

1. **Uncertainties in Data**. The spatiotemporal characteristics of stress evaluation are largely dependent on the resolutions of data and the principles of data assimilation. Data describing water demand and consumptive uses are collected by socioeconomic unit (e.g., county), while data of water availability are usually compiled at site or hydrologic-unit level. Rescaling of these datasets inevitably adds uncertainty to the results. Ideally, evaluations of water stress at finer spatiotemporal scales can reveal more useful information. However, data of water use and consumptions on social aspects are not easily available and are difficult to simulate, despite that the developments of hydrologic measurements and modeling techniques allow us to capture more details of the natural water cycles with a reasonable accuracy. In this case, the absence of water consumption census after 1995 makes the estimation of water consumption an important source of uncertainty in the evaluations of upstream flow availability and stress level. We could have simulated runoff and streamflow variation at a finer resolution of HUC-12 (over 82,000 watersheds) (Duan et al. 2016), rather than HUC-8 (2,099 watersheds), but the large spatial gap between county-level (3,109 counties) water demand data and HUC-12 level water supply data would add error to the spatial disaggregation. Temporally, the stressed regions were identified on an annual basis. The climate variations at intra-annual scales may lead to higher occurrences of water stress than that evaluated from averaged estimates (Devineni et al. 2015; Scherer et al. 2015). However, such short-term stress triggered by climate variability can be largely alleviated by local water storage facilities (e.g., reservoirs).

   Water supply data based on hydrological modeling are also embedded with uncertainty. Due to the limited coverage of stream gauging sites, hydrological simulation tools are usually necessary for nationwide evaluations. The structure and parameters of the applied hydrologic model (e.g., estimates of PET and ET) may cause considerable uncertainty in the estimate of water availability (Bae et al. 2011; Bosshard et al. 2013; Duan and Mei 2014).
2. **Source of Water Supply**. We focused on surface freshwater in this study, while saline water and groundwater have also played different roles in water supply across the country. Saline water has been widely used in the states that border the Gulf of Mexico, Atlantic, and Pacific Oceans, accounting for 13%–20% of the total water use (including surface and ground water) in the country since the 1960s (Kenny et al. 2009; Maupin et al. 2014). Although much of the current saline water use is for once-through cooling in coastal power plants, more saline water use can be expected to secure water supply as the unit cost of desalination keeps dropping in the future (Zhou and Tol 2005). Groundwater is another important source (Richey et al. 2015), which has constituted 20%–25% of the total national freshwater withdrawal in recent decades. Our results imply that "upstream-stressed" areas could be more sensitive to the impact of return flows from upstream. The withdrawal and discharge of saline water and groundwater could alter the terrestrial water cycle in river systems and cause additional stress from the aspects of both water quantity and quality.

CONCLUSIONS

The results presented here demonstrate the effects of river hydraulic connectivity, climate variability, and human's water consumptive uses on water availability, and the subsequent effects on stress levels of sustainable water supply. We found that local water resource alone was sufficient to meet water demand in 74% (±3.7%) of the CONUS area (66% ± 3.8% of the population), while the remains included 12% (±0.9%) upstream-stressed area (14% ± 1.4% of the population) and 14% (±3.1%) overstressed area (20% ± 3.0% of the population). The historical variations suggest that upstream-stressed areas were generally more resilient to climate variability, because the inhomogeneous hydro-climatological changes in relevant upstream areas could offset each other. Overstressed areas were mostly located in headwater areas or isolated from other basins, where water supply was insusceptible to upstream activities but could be more vulnerable to local climate variation.

Recent consumptive uses caused an average 10% decline in the availability of upstream flow and a slight rise in the overall stress. In most regions, stress level was found to be insensitive to the recent magnitudes of upstream water consumption, while the increases/decreases in local water demand has been the primary driving factor of escalating/diminishing stress. However, depletion in upstream flow caused by climate variation and upstream consumption has acted as an important driver of stress escalation for some downstream areas, especially in the arid south and southwest.

Our findings contribute to better understanding of the water nexus among HUC-8 watersheds and its impact on water supply. The stress patterns and sensitivity to upstream flow availability identified by this study provide useful information for risk assessment in water resources planning and integrated management across administrative boundaries (i.e., counties or states).

ACKNOWLEDGMENTS

This work was supported by the National Science Foundation EaSM program (AGS-1049200) awarded to North Carolina State University (NCSU), and the Joint Venture Agreement between Eastern Forest Environmental Threat Assessment Center (EFETAC), U.S. Department of Agriculture Forest Service, and NCSU (16-JV-11330110-037).

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