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Evolving efficiency of inter-basin water transfers in regional water stress alleviation

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ABSTRACT

Inter-basin water transfer (IBT) is widely used to mitigate water stress by diverting water from a relatively water-rich region. However, it is unclear how the IBTs' role evolves with the dynamic hydroclimatic and socioeconomic circumstances. Here, we propose a new Stress Relief Index and an integrated water stress simulation framework to quantify the efficiency of 50 active IBTs across the conterminous United States in alleviating regional water stress. The IBTs vastly reduced the coverage of highly stressed area (8.7×10^4 km^2) and population (4.3 million people) during 1986–2015. The widespread (74%–80% of the IBTs) increasing IBT efficiency suggest that IBTs have been increasingly important in securing water supply in a drying climate. However, the complex combinations of changes in climate, water use behaviors in energy and food production, population, and transfer magnitudes caused divergent changes in IBT efficiency, revealing the challenges posed by streamflow depletion and spatial migration of water demand.

1. Introduction

Inter-basin water transfers (IBTs) have been widely constructed to mitigate regional water stress in dry environments or human population centers (McDonald et al., 2014; Snaddon et al., 1999). Worldwide, it was estimated that over 500 billion out of the 42 trillion m^3 renewable water were redistributed by IBTs annually (Shiklomanov, 2000). For example, the world's largest IBT project, South-to-North Water Transfer Project in China has transferred 50 billion m^3 of water to the North China Plain and Beijing Metropolitan Area in 2014–2021 (Liu and Zheng, 2002; Webber et al., 2017). The All American Canal provides around 4 billion m^3 of water per year for agricultural production in the southern California since the 1940s (Mount and Hanak, 2016; Petsch, 1985). These IBTs have played an essential role in sustaining the water-food-energy nexus and providing freshwater for various uses such as domestic supply, irrigation, energy production, navigation and shipping, and eco-environmental restoration (Dickson and Dzombak, 2019; Shumilova et al., 2018; Sternberg, 2016; Zhuang, 2016).

The degree of regional water stress or water scarcity is usually quantified as the ratio of freshwater demand (represented by local water withdrawal or off-stream water use) to the availability of renewable freshwater (i.e., streamflow discharge) (Oki et al., 2001; Pedro-Monzonís et al., 2015; Vörösmarty et al., 2000). The fast-changing environments have caused extensive changes in regional water stress from both the aspects of water demand and availability over the past decades (Chen et al., 2022; Roy et al., 2012; Sun et al., 2008). Global water demand has more than doubled in the second half of the 20th century due to the growing population and increasing water demand for food and energy production, particularly in developing economies such as India and China (Shiklomanov, 2000; Wada et al., 2011). In the United States, total water use reached its highest level in 1980 and dropped by 21% from 2005 to 2015, primarily thanks to significant decreases in water withdrawal for thermoelectric power generation (Dieter et al., 2017; Grubert and Sanders, 2018; Maupin et al., 2014). However, such national trends masked local challenges of water shortage caused by mixes of socioeconomic and climatic forces throughout the country (Warziniack et al., 2022). In addition, water withdrawal, climate change, and land management altered hydrological processes and thus the magnitudes and variability of river discharges (Sagarika et al., 2014).

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Such rapid changes in pre-transfer conditions of regional water stress complicate the evaluation of IBTs' role in the water resource systems (Khadem et al., 2021; Yan et al., 2012; Zhang et al., 2018, 2020). An important underlying assumption of IBT is that the value of water is not the same for communities under different water stress levels. Thus, diverting water from a relatively water-rich area to a water-stressed region is economically or socially beneficial overall. Based on the assumption that an IBT-induced increase and reduction in water availability would respectively constitute a positive and negative impact on regional water security, the efficiency of an IBT in alleviating water stress can be measured by weighing the benefit for water-receiving regions against the expense for water-exporting regions in terms of water stress level (Duan et al., 2022; Howe and Easter, 2013). However, the hydroclimatic circumstances and water demand in both water-receiving and exporting regions are ever-changing and can not be fully predicted when the IBTs are designed. The compound influence of dynamic hydroclimatic and socioeconomic context could challenge the necessity and efficiency of existing IBTs (Barnett et al., 2015; Gohari et al., 2013; Khadem et al., 2021; Zhao et al., 2015).

Hydrological models are useful tools to simulate changes in water stress and the impacts of changes in water availability and demand for sectoral water uses. Yet, the artificial networks of water diversion and the actual magnitudes of IBTs are difficult to be parameterized in modeling frameworks with limited data (Wada et al., 2014). In previous large-scale studies, the aggregate hydrological impacts of multiple IBTs were usually not considered or simplified due to a lack of standardized and systematic IBT data compilation (McDonald et al., 2014; Wada et al., 2013; Zhao et al., 2015). The nonlinear response of downstream water availability to the combined impacts of water consumption and diversions in upstream areas can be highly complex for large basins. Assessments derived from coarse representations of these processes could miss out on key aspects of upstream-downstream hydrological connections and fluctuations, particularly at the local level (Scherer et al., 2015).

Recently, there have been a few attempts to characterize IBT impacts on streamflow or water stress across the United States using IBT datasets compiled at a national scale. For example, Emanuel et al. (2015) examined the hydrologic favorability of 228 IBTs by comparing the mean annual transfer magnitudes in 1973–1982 to streamflow in water-exporting and receiving basins. Brown et al. (2019) projected future water shortage by modeling water yields and routing water flows through river networks and IBTs at the scale of 4-digit hydrologic unit code (HUC-4) basins (204 basins), setting transfer amounts equal to the mean annual diversions in 1980–1982. Duan et al. (2019; 2022) investigated how upstream-downstream connectivity and IBTs impacted water stress under historical and future climate change scenarios, assuming the transfer magnitudes would remain unchanged using data in 1973–1982. Liu et al. (2022) quantified the benefits of IBTs in redistributing water from forested land to drinking water intakes, using the average volumes of transferred water between 2001 and 2015. Nevertheless, these previous studies simplified the water transfer processes by using the mean annual transfer magnitudes in a particular historical period instead of continuous transfer volumes. At the same time, major efforts were put into understanding the long-term variations in climate and the response of runoff and sectoral water withdrawals to climate change. Annual variations of the IBT impacts were rarely detected or analyzed. Considerable gaps remain in our understanding of the IBTs' effectiveness in a changing environment.

This study aims to provide a retrospective assessment of the efficiency of IBTs in mitigating regional water stress in a dynamic hydroclimatic and water supply-demand context at the annual scale. We used an updated national survey of IBTs active in the conterminous United States (CONUS) in the last three decades. The evaluation of IBTs' role was integrated into a high-resolution simulation framework of regional water stress that characterized the natural (upstream to downstream) and artificial (water transfers and water uses) water connections across the 2099 8-digit hydrologic unit code (HUC-8) basins (http://water.usgs.gov/GIS/huc.html). The specific questions we aimed to answer were: (1) Does accounting for water redistribution by the IBTs significantly alter the estimate of regional water stress and water-stressed population? (2) How did the IBT-induced increase and reduction in water availability affect water stress and how did it vary annually from 1986 to 2015? (3) What factors have driven the efficiency of IBTs in water stress alleviation to change?

2. Data and methods

2.1. Data

2.1.1. Inter-basin water transfers

The first national database of IBTs in the CONUS was compiled based on a survey questionnaire by the U.S. Geological Survey (USGS), reporting HUC-8 basins the IBTs located in and the transfer magnitudes from 1973 to 1982 (Mooty and Jeffcoat, 1986; Petsch, 1985). The mean annual flow volumes have been widely used for national water resource assessments (Brown et al., 2019; Duan et al., 2019; Emanuel et al., 2015). Dickson and Dzombak (2017) built a 2016 inventory of IBT waterways crossing HUC-6 basins through geographical information analysis, however the volumetric flow data were not reported.

In this study, we used a new IBT database developed by the USDA Forest Service (Dobbs et al., 2022) with updated flow volumes and location information. Data was acquired from open records and questionnaires for major cities' water utility organizations, state-level water management authorities, management agencies of IBT projects, the USGS, and the U.S. Bureau of Reclamation. An IBT is identified when water is transferred across the HUC-8 basin boundaries. The database includes only transfers originating in surface water due to the difficulty in accounting for the origin location of the groundwater source. We selected 50 IBTs where the annual transfer magnitudes from 1986 through 2015 are available to facilitate a long-term analysis of IBT efficiency. The mean annual transfer magnitude of these IBTs ranges from 0.08 to 4206 million m^3/year (Fig. 1). The total transfer magnitude per year reaches 22.6 billion m^3 and accounts for over 6% of surface water demand in the CONUS (Duan et al., 2018). The transferred water has been an important source of freshwater for arid or densely populated areas such as southern California and the New York metropolitan area.

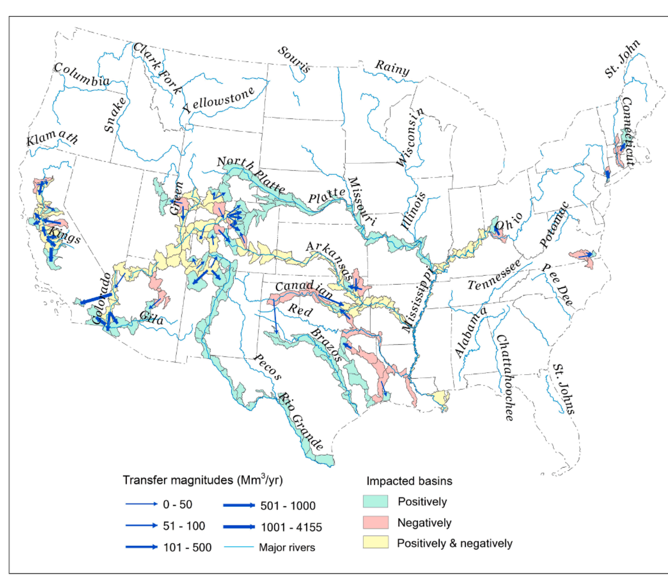

Fig. 1. Distribution of the 50 inter-basin water transfers (IBTs) and impacted basins. The transfer magnitudes were mean values in 1986–2015.

2.1.2. Water uses

The most comprehensive data on water withdrawal and consumption in the U.S. are reported every five years by the U.S. Geological Survey (USGS) as a part of the National Water Use Information Program (Dieter et al., 2017; Maupin et al., 2014; Solley et al., 1998). Historical (1985–2015) human population and sectoral freshwater use data were collected and rescaled from county (3109 counties) to HUC-8 basin based on weighted areal averages. The raw data were linearly interpolated within each five-year reporting interval to generate a continuous time series of annual water demand and consumptive uses to be integrated into the simulation of regional water availability (Duan et al., 2018). The classification of water-use sectors include commercial, domestic, irrigation for agriculture, livestock, aquaculture, industrial, mining, thermoelectric power generation, and public supply delivered to various users. Among the water-use sectors, thermoelectric power, irrigation, and domestic uses (including public delivered and self-supplied) have remained the largest in recent decades and accounted for over 80% of total water withdrawals (Dieter et al., 2017; Maupin et al., 2014).

2.1.3. Runoff

We used monthly runoff simulations of the USGS Water Balance (UWB) model (McCabe and Wolock, 2011b) to represent the amount of renewable freshwater generated within each basin from 1986 through 2015. The UWB model uses an accounting procedure to compute the allocation of water among hydrologic cycle components, including climatic water supply (precipitation) and demand (potential evapotranspiration), snow accumulation and melt, soil moisture storage, and partitioning of precipitation into actual evapotranspiration and runoff delivered to streams and rivers. The UWB model parameters were taken from parameter sets developed in previous studies (McCabe and Markstrom, 2007; McCabe and Wolock, 1999, 2011a), including a parameter that specifies the fraction of precipitation that becomes direct runoff, temperature thresholds that determine the proportions of rainfall and snowfall in precipitation, a snow melt factor that determines the melt rate of snowpack, and a parameter that specifies how much surplus water becomes runoff in a month. The parameters of soil moisture storage capacity were derived from the gridded water-capacity values of the State Soil Geographic dataset (http://www.soilinfo.psu.edu/) and by assuming a one-meter rooting depth (McCabe and Wolock, 2011b). The climate inputs driving the model are monthly temperature and precipitation data obtained from the Parameter-elevation Regression on Independent Slopes Model (PRISM) dataset (http://www.ocs.orst.edu/prism/). Climate data for all the 4×4 km grid cells (481,639 PRISM cells) in CONUS were used to estimate monthly runoff generated in each cell, and then the gridded runoff was aggregated to HUC-8 basins.

2.2. IBT impact on regional water stress

2.2.1. Simulation of IBT impact on water availability

The impact of IBT on regional water stress was quantified using the dynamic water stress model (Duan et al., 2022) that disentangles the independent effects of each IBT and upstream consumptive water uses on water availability across water-exporting and receiving basins and downstream. Regional water availability within basin y at time t was simulated by routing streamflow through the river networks and IBT aqueducts as follows:

$$TF_{CT,y,t} = LF_{y,t} + \sum_{i=1}^{N} UF_{i,y,t} - \sum_{i=1}^{N} C_{i,y,t} \pm \sum_{j=1}^{M} T_{j,y,t} \tag{1}$$

$LF_{y,t}$ is runoff generated in basin y and $UF_{i,y,t}$ represents water flows accumulated from the i^{th} upstream basin. The sum of LF and UF represents the natural state of maximum water availability without anthropogenic disturbances. $C_{i,y,t}$ is water consumption that occurs in the i^{th} upstream basin, calculated as water withdrawals minus return flows. $T_{j,y,t}$ is the transfer magnitude of the j^{th} IBT that diverts water into or out of basin y or an upstream basin. Across the CONUS, we identified 18,777 upstream-downstream hydrological connections at the HUC-8 level based on the hierarchical geospatial attributes of streams obtained from the USGS National Hydrography Dataset (http://nhd.usgs.gov/data.html) and the Watershed Boundary Dataset (https://datagateway.nrcs.usda.gov/). The 2099 HUC-8 basins were thus categorized into 907 "headwater", 779 "midstream", 94 "terminus", and 319 "isolated" basins. Water withdrawal, consumptive uses, and diversion were assumed to occur uniformly in each basin, while the return flows, the transferred water, and the residuals of the accumulated streamflow would be discharged simultaneously to surface water at the inlet of the next downstream basin. Neither within-basin water retention due to wastewater treatment nor reservoir storage was considered.

It can be assumed that an IBT-induced increase and reduction in water availability would respectively constitute a positive and negative impact on water supply. The spatial extents of positive and negative impacts of each IBT on the water resources system were measured by the land area and population of the water-receiving and exporting basins and downstream, respectively. IBT-induced variations in regional water availability were estimated by comparing the simulation of TF_{CT} driven by IBTs of interest to the benchmark of pre-transfer streamflow with (TF_M) or without (TF_C) the influence of water uses, as:

$$TF_{M,y,t} = LF_{y,t} + \sum_{i=1}^{N} UF_{i,y,t} \tag{2}$$

$$TF_{C,y,t} = LF_{y,t} + \sum_{i=1}^{N} UF_{i,y,t} - \sum_{i=1}^{N} C_{i,y,t} \tag{3}$$

2.2.2. Efficiency of IBT in water stress alleviation

By weighing the positive and negative impacts on regional water supply, efficiency of an IBT in mitigating water stress was measured by the Stress Relief Index (SRI) as:

$$SRI = \sum_{i=1}^{N} \left[w_i \cdot P_i \cdot WD_i \cdot \left(1 / TF_{C,i} - 1 / TF_{CT,i}\right)\right] \Bigg/ \left(T \cdot \sum_{i=1}^{N} w_i\right) \tag{4}$$

where P_i and WD_i are the population and off-stream water demand in the i^{th} IBT-impacted basin; T is the transfer magnitude; w_i is the weighting parameter for the i^{th} impacted basin. SRI reflects the difference between benefit and cost of an IBT in terms of IBT-induced decrease and increase in regional water stress multiplying the potentially impacted populations. As water stress is shifted from water-receiving to water-exporting regions to various degrees, a larger value of SRI indicates a higher efficiency of an IBT in remedying water scarcity, while a negative SRI implies that the IBT could be inefficient when the cost for water-exporting regions is fully considered.

We modified the SRI index proposed in Duan et al. (2022) to a weighted average formula that measures mean stress alleviation per basin. Thus, the efficiency of IBTs with different topography and extents of downstream effects is comparable. The weighting parameter w can be used to differentiate regional priorities of water management. For instance, higher weights could be applied for regions directly relying on the transferred water, or regions involved with extreme events, vulnerable ecosystems, or endangered aquatic species. We here focus on analyzing three sets of SRIs that represent different perspectives on the extent of IBT impact and prioritization for water managers:

- SRI-Local. w is set to be one for the water-exporting and receiving basins. For the basins downstream of an IBT, if any, w is set to be zero, and thus the long-distance downstream impact of water diversions is neglected.

- SRI-Downstream. Equivalent weight ($w = 1$) is applied for the water-exporting and receiving basins and all the downstream basins. IBT impact on water supply is assumed to be extended consistently by the river systems regardless of the downstream distance.
- SRI-Prioritization. Larger weights are applied for the water-exporting/receiving and downstream basins that are experiencing higher pre-transfer water stress (i.e., *WD/TFc*). Following the commonly used classifications of water stress levels (Oki et al., 2001; Vörösmarty et al., 2000), high, medium, and low water stresses are identified when the ratio of water demand to water availability is over 0.4, between 0.2 and 0.4, and smaller than 0.2, respectively. Correspondingly, w is set as 2, 1, and 0.5 for the basins with high, medium, and low pre-transfer water stress, respectively.

While SRI-Local focuses on the water demand-supply relations at the source and destination basins, SRI-Downstream and SRI-Prioritization vary with the aggregate hydrological response to climate and water uses variations and indicate the combined impacts of per unit transferred water on the overall water stress condition.

2.3. Detection and attribution of trends

To quantify the recent trends of SRI, we performed Linear Least Squares Regression analysis using SRI as the dependent variable and year as the independent variable. The regression slope was defined as the trend of SRI (i.e., annual change). Historical trends in SRI were attributed to the variations in water demand, water availability, population, and transfer magnitudes. Similar to the previous studies of Piao et al. (2015) and Duan et al. (2017), the relative contributions of individual driving factors were detected based on the difference between two modeling experiments (S1 and S2). In simulation S1, SRI is evaluated using inputs varying from 1986 to 2015. In simulation S2, the driving factor of interest is held constant as in 1986 while the other factors are all varied. The independent effects of the *i*th driving factor on SRI trend is calculated as:

$$E_i = V_{S1} - V_{S2,i} \tag{5}$$

where V_{S1} and $V_{S2,i}$ are the trends of SRI identified from the simulations of S1 and S2, respectively. V_{S1} represents the combined effect of variations in all the driving factors on SRI trend, and can be decomposed into the independent effects of each individual factor (E_i) and the effect of interactions among them (E_{Int}):

$$V_{S1} = \sum_{i=1}^{N} E_i + E_{\text{int}} \tag{6}$$

The relative contribution (%) of the *i*th driving factor on SRI trend is then quantified by the relative weight, as

$$C_i = 100 \times |E_i| \Big/ \sum_{i=1}^{N} |E_i| \tag{7}$$

3. Results

3.1. IBT impact on regional water availability and water stress

3.1.1. Spatial extents of individual IBTs' impact

Besides 41 water-receiving basins and 31 water-exporting basins where the origin and destination points of the 50 IBTs were located, water availability at 163 and 109 basins were positively and negatively impacted by the IBTs when downstream influence was considered, respectively. The spatial extents of land area and population (Fig. 2) that were benefited from individual IBTs varied from 488 to 1.2×10^5 km^2 and from 8500 to 6 million people, respectively. Most of the large IBTs were constructed in the dry west, where river network density is relatively low and regional water supply relies heavily on flows accumulated in large rivers (e.g., the Rio Grande, Gila, San Joaquin, and Colorado Rivers). However, these projects also compromised water availability for comparable or even larger areas due to removing water from upland basins. The negatively impacted area and population ranged from 708 to 9×10^4 km^2 and from 8500 to 3.6 million people. The relationship between positive and negative impacts shows that the positively and negatively impacted land areas of the IBTs are well correlated ($y = 0.7x+1.0$, $R^2 = 0.9$). The negatively affected area of 50% IBTs exceeded the corresponding positively impacted area (those above the 1:1 line in Fig. 2b). Meanwhile, a majority of the IBTs were designed to redistribute water to more densely populated regions, yet the negatively impacted population also exceeded the positively impacted population from 17 IBTs.

3.1.2. IBT impact on water stress

We cross-compared regional water stress in 1986–2015 across the 2099 HUC-8 basins using mean annual natural (TF_M), post-IBT (TF_T), post-consumption (TF_C), and post-consumption&IBT (TF_{CT}) streamflow as water availability (Fig. S1). Pre- and post-transfer water stress were evaluated by the ratio of water demand to TF_C and TF_{CT}. Then, the combined effects of all the IBTs on water stress with and without the influence of upstream water uses (Fig. 3) were identified by comparing the results derived from TF_T to TF_M and TF_{CT} to TF_C, respectively. Across the water-exporting/receiving basins, the IBTs would decrease the coverage of highly stressed land area and population by 1.2×10^4 km^2 (3.4%) and 2.7 million people (13.1%) under the background of natural streamflow. Such IBT-induced decreases expanded to 2.5×10^4 (2.8%) and 3.6 million people (8.9%) with all the impacted downstream basins being accounted for. Consumptive water uses compromised downstream water availability and thus highlighted the role of IBTs in the water supply systems, particularly for the highly stressed communities that were distributed across the Connecticut, Platte, Arkansas, Canadian,

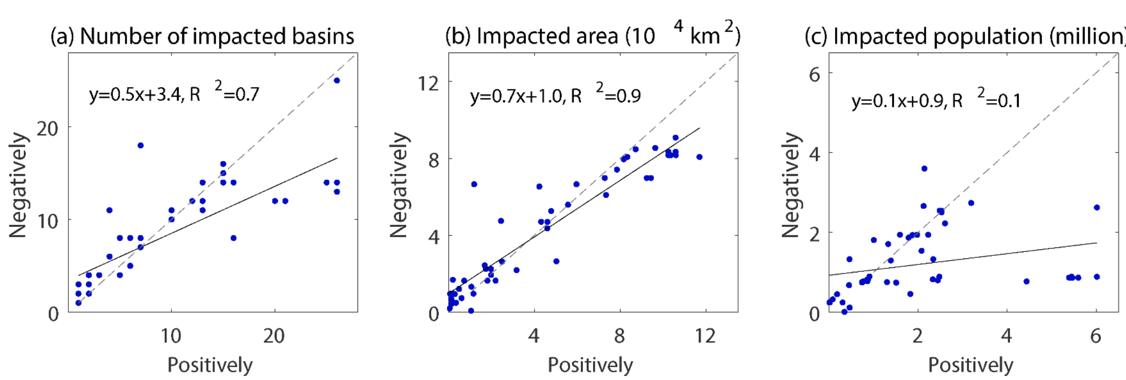

Fig. 2. Spatial extents (**a**, Number of HUC-8 basins; **b**, Land area; **c**, Population) of the positive and negative impacts on water supply of the 50 IBTs in 1986–2015.

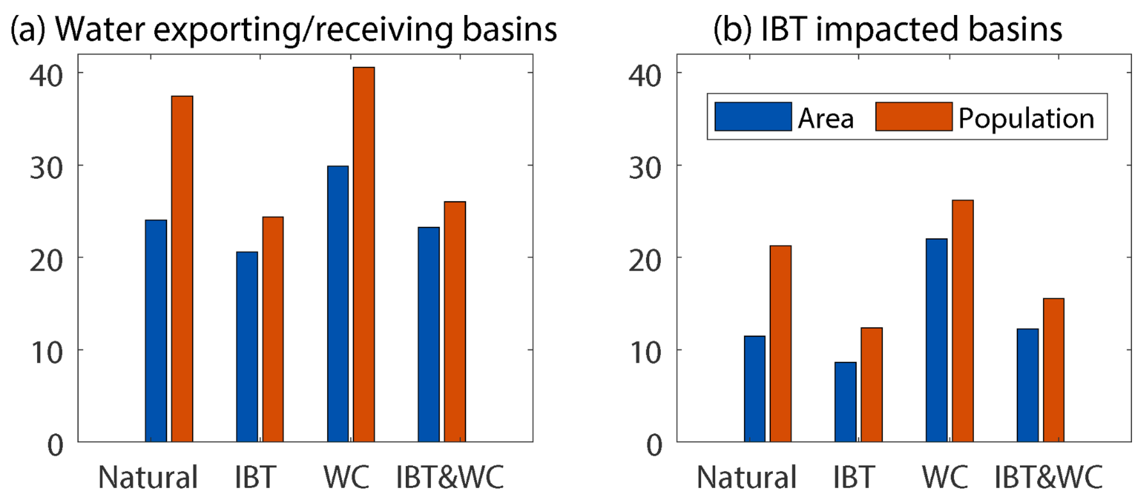

Fig. 3. Proportions (%) of highly stressed (>0.4) land area and population over the water exporting/receiving basins (**a**) and the IBT impacted basins (**b**). Water stress is evaluated using the mean annual streamflow under four scenarios: without anthropogenic disturbances ('Natural'), under the impact of IBTs ('IBT'), under the impact of upstream water consumption ('WC'), and under the combined impact of IBTs and upstream water consumption ('IBT&WC').

Brazos, Green, Gila, and Kings River basins. In the context of upstream water consumption in 1986–2015, the IBTs reduced the coverage of highly stressed land area and population by 2.3×10^4 km^2 (6.6%) and 3.0 million people (14.5%) in the water-exporting/receiving basins, and by 8.7×10^4 km^2 (9.7%) and 4.3 million people (10.7%) over the IBT impacted basins.

3.1.3. *IBT efficiency in water stress alleviation*

Multi-decadal mean SRI-Local (Fig. 4) suggests that 82% of the 50 IBTs efficiently alleviated regional water stress during 1986–2015, yet the IBT-induced escalation of water stress at water-exporting basins surpassed the stress reduction at water-receiving basins across the other 18% IBTs. Results of SRI-Downstream and SRI-Prioritization show that 96% of the IBTs were efficient as the extended impacts on downstream regions are incorporated, except for two cases in Virginia and Arizona where both SRI-Downstream and SRI-Prioritization were negative values close to zero (-3.4×10^{-4} and -2.3×10^{-5}). The evaluated IBT efficiency generally increased from SRI-Local to SRI-Downstream and then to SRI-Prioritization, with the average efficiency reaching 0.29, 0.63, and 1.0 (unit: thousand people · Mm^{-3}). The largest SRI-Local (3.0) and SRI-Downstream (9.3) were found in lower Colorado, supplying water for southern California. The highest SRI-Prioritization (16.2) was identified at the IBT transferring water from upstream of Arkansas to the upper Platte basin due to its far-reaching influence on highly stressed regions.

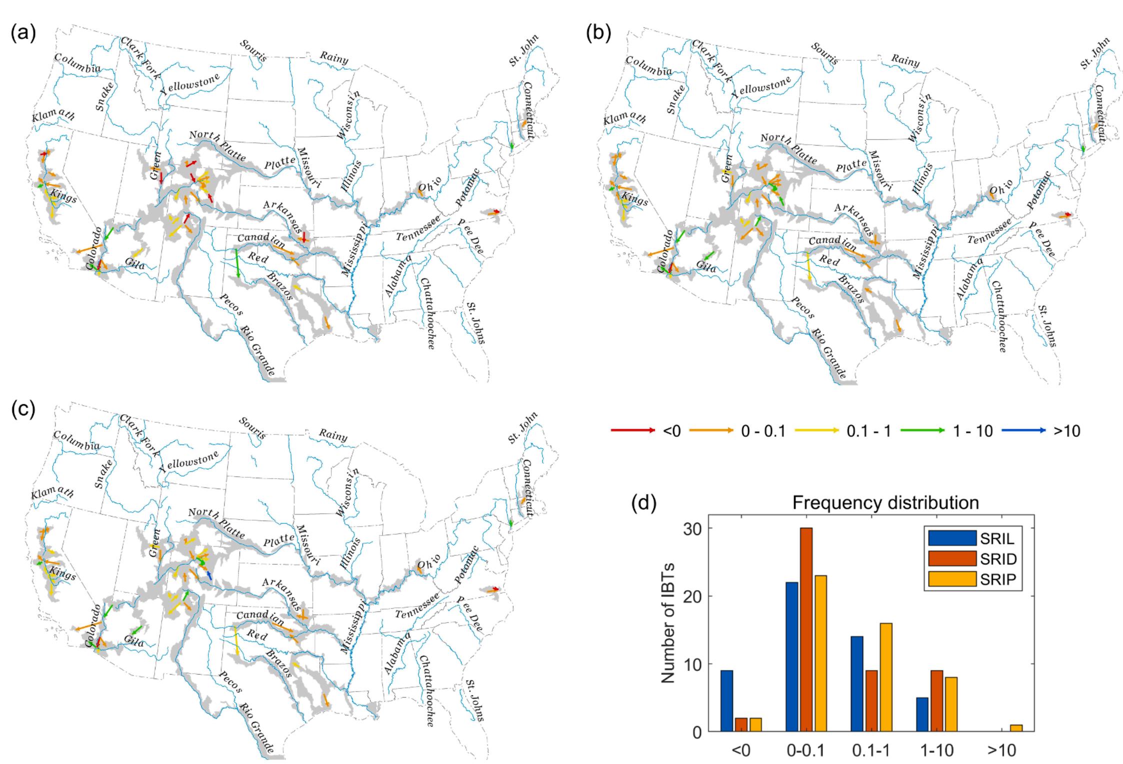

Fig. 4. Mean efficiency of the IBTs in water stress alleviation through the period of 1986–2015. The IBT efficiency was evaluated by: (**a**) SRI-Local (SRIL); (**b**) SRI-Downstream (SRID); (**c**) SRI-Prioritization (SRIP). (**d**) Frequency distribution of mean efficiency. The unit of SRI is thousand people· Mm^{-3}.

3.2. Temporal trends in 1986–2015

3.2.1. Water supply-demand context

Freshwater withdrawal in the CONUS increased steadily from 1950 to 1980 along with the growing population and reached its peak in 1980. During 1980–2005, the total annual withdrawal fluctuated around 4.7 $\times$ 10^{11} m^3 and then decreased to 4.2 $\times$ 10^{11} m^3 in 2010 and 3.9 $\times$ 10^{11} m^3 in 2015 (Fig. S2-S3). The drop in freshwater withdrawal was largely caused by decreases in thermoelectric water withdrawals (Dieter et al., 2017), and covered 60% of the IBT impacted HUC-8 basins. Meanwhile, total water yield varied significantly between 1.4 $\times$ 10^{12} (1988) and 2.5 $\times$ 10^{12} m^3 yr^{-1} (1998) over the period of 1986–2015. Significant decreases in streamflow at the significance level of 5% (p-value<0.05) were mainly found in southern California and the Rio Grande River basin, accounting for 9% of the IBT impacted basins. Water stress at the CONUS scale fluctuated between 0.16 (2015) and 0.34 (1988) and remained "medium" in most of the years. However, the HUC8-level evaluation revealed that high stress covered a wide range of the western and central CONUS. The generally drying trend in the Colorado, Gila, and Rio Grande River basins over the southwest caused increasing regional water stress despite the decreasing water demand. In the central CONUS, the increasing demand and decreasing streamflow both aggravated the water stress level across the Arkansas, Canadian, Red River basins.

3.2.2. Trends in IBT efficiency

The annual variations in IBT efficiency are largely controlled by the temporal variability of the dry and wet spells in streamflow, while the socioeconomic status is usually evolving progressively. The linear trends in SRI were not significant at the significance level of 5% at a majority of the IBTs, which is consistent with the insignificance of trends in streamflow. However, significant trends can also be identified at 30% ~32% of the IBTs from the northeast to the southwest (Fig. 5). Significant decreases were detected at two eastern IBTs transferring water from the Connecticut and Ohio River basins. Meanwhile, increasing signals, including 13~14 significant and 23~27 insignificant trends, prevailed in the central and southwestern CONUS, particularly in the states of Texas and California, indicating that regional water supply has been increasingly dependent on the IBTs over the past three decades.

Distributions of the p-value suggest similar spatial patterns among evaluations of the three SRI indices, and the discrepancy was mainly found in upland IBTs that transferred water across the upstream areas of Colorado, Platte, Canadian, and Brazos River basins. However, trend slopes suggest that the changing rate tends to be amplified from SRI-Local to SRI-Downstream and then to SRI-Prioritization at the ten most efficient IBTs, where the mean SRI-Downstream and SRI-Prioritization in 1986–2015 exceeded 1.0 (thousand people $\cdot$ Mm^{-3}). Such results demonstrate that the changing environment can exert a larger influence on IBT efficiency when the widespread downstream impacts are considered or the highly-stressed regions are prioritized in the evaluation.

3.3. Driving forces of IBT efficiency change

We attributed the efficiency change of the IBTs from 1986 to 2015 to the impacts of climate, water use behavior, population growth or migration, and the regulation of transfer magnitudes (Fig. 6). Climate-induced runoff variation was identified as the largest driving force of efficiency change at 44~52% of the IBTs. The impact of water use behavior surpassed the other driving factors at 24%~30% of the IBTs. Particularly, drops in water demand at the water-receiving basins dominated the two significant decreasing trends in IBT efficiency, with the relative contribution reaching 80%~82% and 40%~46%. The IBTs where efficiency change was mainly controlled by the variations in population and transfer magnitudes also accounted for 4%~12% and 22%~24% of the IBTs, respectively. Comparing the three SRI indices, the relative contribution of climate in altering SRI-Local is generally larger than SRI-Downstream and SRI-Prioritization, with mean values reaching 38%, 34%, and 34%. This can be explained by the spatially diverse changes in streamflow (Fig. S3) that buffers the climatic impact

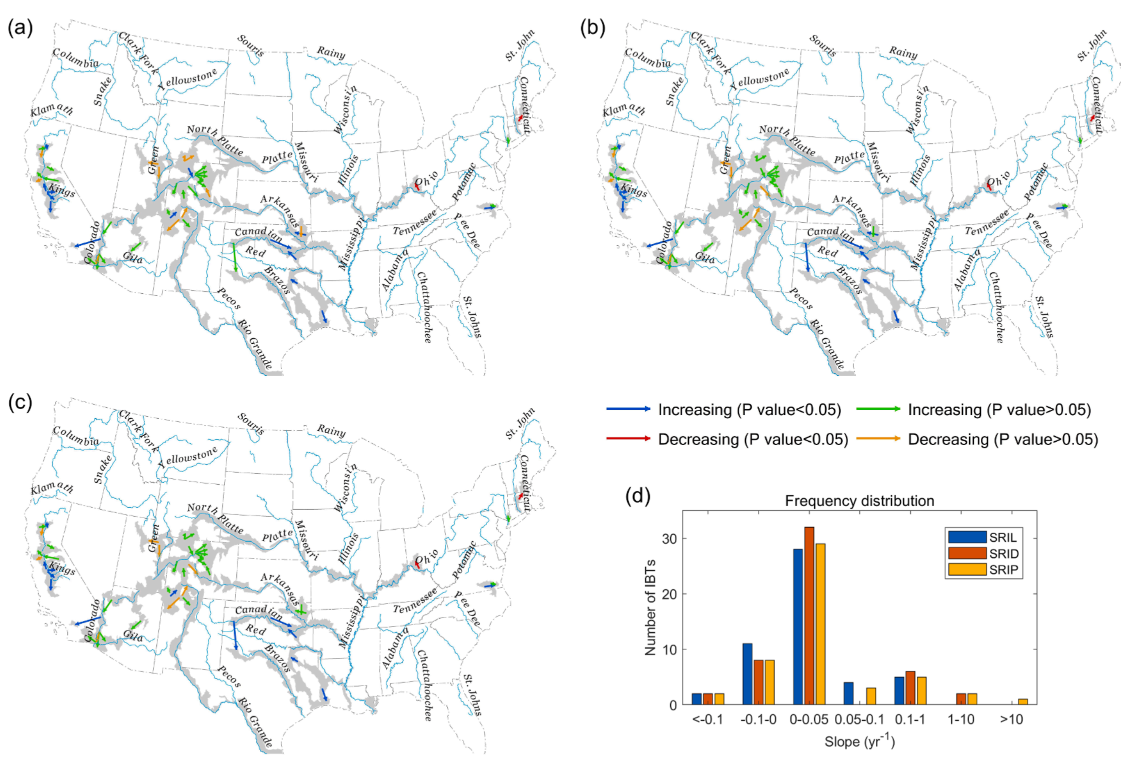

Fig. 5. Spatial distribution of the trend in IBT efficiency during the period of 1986–2015. The IBT efficiency was evaluated by: (**a**) SRI-Local (SRIL); (**b**) SRI-Downstream (SRID); (**c**) SRI-Prioritization (SRIP). (d) Frequency distribution of trend slope.

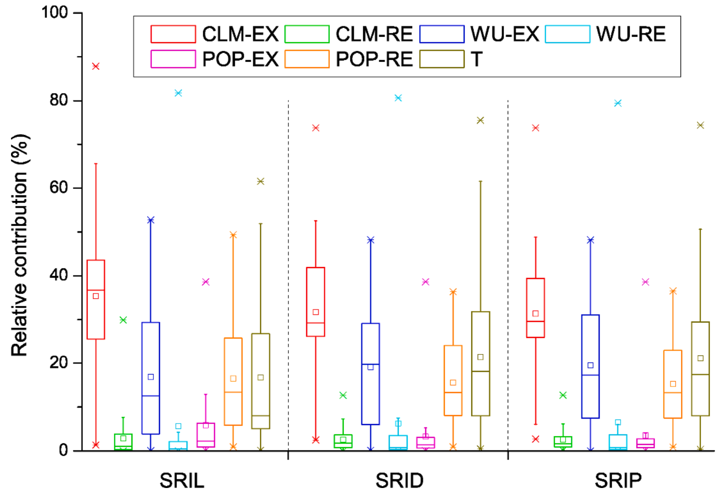

Fig. 6. Relative contributions (%) of the driving forces to the trend in IBT efficiency during the period of 1986–2015. The IBT efficiency were evaluated by SRI-Local (SRIL), SRI-Downstream (SRID), and SRI-Prioritization (SRIP). Trends in IBT efficiency were attributed to the changes in climate (CLM), water use (WU), population (POP) in water-exporting regions (-EX) and water-receiving regions (-RE), and transfer magnitude (T).

on regional water stress when non-local water is tabulated into water availability. On the other hand, SRI-Downstream and SRI-Prioritization tend to be more sensitive to water use behaviors and transfer magnitudes, as their influence on larger spatial extents are accounted for.

The outliers in Fig. 6 suggest that the relative contributions of the driving forces varied widely at different IBTs due to the complex hydrological and socioeconomic changes across the IBT impacted regions. We further examined the role of driving forces from the water-exporting/receiving and downstream basins and demonstrated three representative regional patterns of efficiency change across the CONUS (Fig. 7). Decreasing water demand, primarily for thermoelectric power generation, was identified as a major driving factor in the northeast. For instance, the decreasing demand in water-receiving regions dominated the decrease in efficiency of the Quabbin Aqueduct transferring water from the Connecticut River to the state of Massachusetts. While the relative contribution of decreasing demand reached 79%~82%, the wetting climate and increasing streamflow at water-exporting regions also reduced IBT efficiency.

In the central CONUS, particularly in the state of Texas, streamflow depletion at water-exporting and downstream basins was a major factor which explained up to 46% of IBT efficiency change. However, decreasing streamflow also occurred widely across water-receiving regions, which enhanced IBT efficiency along with the increasing water demand and population. In the southwest, the drying climate and declining streamflow at water-exporting regions have weakened the capacity to supply transferred water. Contrarily, the decreasing water demand in water-exporting regions, mainly the drop in irrigation water use, potentially reduced the cost of water transfer and rendered the IBTs more efficient. For example, the decreasing water demand and streamflow at water-exporting regions of the IBT transferring water from the

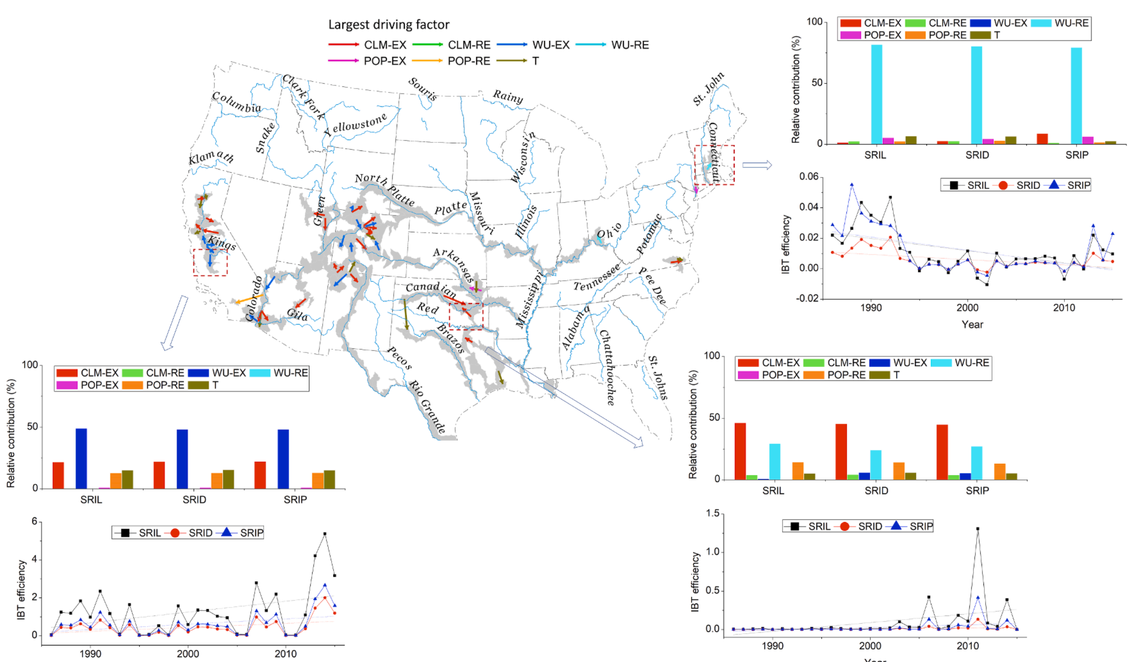

Fig. 7. Trends and driving forces of the IBTs' efficiency change during the period of 1986–2015. IBT efficiency were evaluated by SRI-Local (SRIL), SRI-Downstream (SRID), and SRI-Prioritization (SRIP). Trends in IBT efficiency were attributed to the changes in climate (CLM), water use (WU), population (POP) in water-exporting regions (-EX) and water-receiving regions (-RE), and transfer magnitude (T).

Kings River to southern California explained 48% and 22% of the changes in IBT efficiency, respectively.

4. Discussion

Quantification of IBTs' efficiency in water stress alleviation and its interactions with environmental stressors is fundamental to our understanding of adaptive water management under global change, and is needed to enable decision-makers to build, remove, or renew water transfer infrastructure in a sustainable way. Among the factors confining the efficiency of an IBT, the underlying basin characteristics such as topography are relatively stable within the time scale of interest to water managers and IBT operators, while climatic and socioeconomic conditions often experience considerable variations. For example, water availability in the water-stressed southwestern US is expected to continue declining in the 21st century and would further affect the sustainability of the IBT projects widespread in these regions (Duan et al., 2019; Schewe et al., 2014; Seager et al., 2013). Water use in the US reached its lowest level in 2015 in the past four decades, and is projected to change by as much as $-8\% \sim +235\%$ in the next half century under different climate and socioeconomic scenarios (Warziniack et al., 2022). Such changes in consumptive water use and shift in spatial distributions of water demand will continue to pose substantial challenges for IBT management.

IBT impacts are well recognized by a broad range of research fields, yet the assessment criteria tend to be prescriptive and subjective (Kibiiy and Ndambuki, 2015; Yan et al., 2012). General principles and qualitative criteria of IBT implementation have been frequently discussed. For example, the water-exporting region should not encounter water deficit in the present due to the transfer and the IBT should not hinder its future economic development (Cox, 1999); the IBT should be socially, environmentally, and economically sustainable (Gupta et al., 2008); the expected negative impacts of the IBT should be minimized and the expected benefits should be maximized (Kibiiy and Ndambuki, 2015). More detailed quantitative analysis has also been performed in a variety of case studies, aiming at a better representation of the comprehensive influence of IBTs (Roozbahani et al., 2020; Sinha et al., 2020; Yan et al., 2012). However, it is still challenging to account for multiple IBTs' independent and combined impacts on water supply or efficiency in mitigating water shortage in a consistent framework due to diverse circumstances of IBT projects and lack of data.

In this study, we presented a simple Stress Relief Index to weigh IBTs' positive impacts on water-receiving regions against the negative impacts on water-exporting regions from a socio-hydrological perspective. The evaluation of IBTs' role in affecting large-scale water resource systems was integrated into the dynamic simulation of regional water stress. The SRI index can be adapted to evaluate IBT efficiency at different spatial scales of interest, such as sub-basin, catchment, or communities, depending on the definition of "inter-basin" and spatial resolution of water transfer and water use datasets. Different weights can be conveniently applied for specific regions or water management agents to comply with public perception or policy decisions.

To the best of our knowledge, this study is the first to comprehensively detect and attribute the historical trends of IBT efficiency in alleviating regional water stress. While the general goals have been achieved, a few points should be addressed in further studies. First, the assimilation of hydroclimatic and socioeconomic datasets from multiple sources could cause uncertainties to various degrees. For example, the data on transfer magnitudes were collected from various levels of water managers (e.g., city, state, and federal government). While care was taken to minimize uncertainty in these data and considerable effort was expended to put all of the information into a consistent framework (Dobbs et al., 2022), the discrepancy in flow measurement and data compilation procedures among agencies providing these data could lead to errors when attempting to identify and compare spatial characteristics of IBTs at large scales. In addition, nationwide data on water withdrawals and consumptive uses are only compiled at the county scale. The gap between the spatial resolutions of hydrological modeling and water use data aggregates to the uncertainty in characterizing regional water availability (Liu et al., 2020; Scherer et al., 2015). Second, the attribution analysis did not fully consider the interactions among different driving factors of IBT efficiency change. For instance, climate change and variability affect regional water demand and water consumption rates across multiple water-use sectors (Brown et al., 2019; Schewe et al., 2014; Webber et al., 2016) and motivate the implementation and adaptation of IBT projects (Liu et al., 2022). Population growth and migration also alter the spatial distribution of water uses and long-term water planning (Kasprzyk et al., 2009). Third, the role of local water rights legislation and the other factors influencing IBT regulation strategies were not considered. We have focused on evaluating the role of IBTs in the water resource supply-demand systems with the reported transfer magnitudes, which were already constrained by a range of spatially-varying factors such as the water market, water rights laws, and the costs of operation and maintenance (de Andrade et al., 2011). Finally, instream water uses such as navigation, shipping, hydroelectric power generation, recreation, and environmental flows were not incorporated in the evaluations of water stress and IBT efficiency. The consideration of instream water uses and the environmental cost of water transfers could affect the measurement of IBTs' social efficiency (Davies et al., 1992; Snaddon et al., 1999; Vargas et al., 2020).

5. Conclusions

Freshwater has been transferred across basins through engineered aqueducts to alleviate water stress in highly stressed regions, but these transfers take a toll on water supply in water-exporting regions. This study examined the role of 50 IBTs across the United States in alleviating regional water stress through the period of 1986–2015 with an updated annual IBT dataset and an integrated simulation-evaluation framework. The following conclusions were drawn: (1) The spatial extents of land area and population benefited from the IBTs ranged widely from 488 to 1.2×10^5 km^2 and from 8500 to 6 million people, yet the negatively impacted population of 17 IBTs exceeded the positively impacted population when downstream effects were considered. (2) The IBTs significantly reduced the coverage of highly stressed land area and population by 8.7×10^4 km^2 and 4.3 million people over the IBT impacted basins. (3) The increasing efficiency over 74%−80% of the IBTs suggest that the IBTs have played an increasingly import role in securing regional water supply in a widespread drying climate. (4) While the decreasing water demand in water-receiving regions and the wetting climate significantly reduced the efficiency of water transfer in the northeast, the IBTs have been increasingly important in the central US due to streamflow depletion, increasing water demand, and increasing population across water-receiving regions. In the southwest, the decreasing water demand due to mainly irrigation water uses in water-exporting regions potentially reduced the cost of externalizing water stress and thus enhanced IBT efficiency, although the drying climate has weakened the capacity of supplying water transfer.

Our results demonstrate how climate change, growing population, water consumption for energy and food production, and regulation of transfer magnitudes have caused divergent changes in IBT efficiency. In this fast-changing era, we need to rethink the role of IBTs in water supply and the dynamic interactions between environmental stressors and the water systems to achieve sustainable management of IBTs. Adaptive management strategies from both water supply and demand aspects will be critical for planning and renewing these grand water infrastructures, and upland transfers should be dealt with particular caution for their uncertain and potentially amplified downstream influences.

CRediT authorship contribution statement

Kai Duan: Conceptualization, Methodology, Data curation, Writing – original draft. **Shen Qu:** Writing – review & editing. **Ning Liu:** Data curation. **Gladys R. Dobbs:** Data curation. **Peter V. Caldwell:** Writing – review & editing. **Ge Sun:** Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.resconrec.2023.106878.

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