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Kai Duan^{1,2,*} , Peter V Caldwell³, Ge Sun⁴, Steven G McNulty⁴, Yue Qin⁵ , Xiaohong Chen¹ and Ning Liu⁴¹ School of Civil Engineering, Sun Yat-Sen University, Guangzhou, People's Republic of China² Southern Marine Science and Engineering Guangdong Laboratory (Zhuhai), Zhuhai, People's Republic of China³ Center for Integrated Forest Sciences, USDA Forest Service, Otto, NC, United States of America⁴ Eastern Forest Environmental Threat Assessment Center, USDA Forest Service, Research Triangle Park, NC, United States of America⁵ College of Environmental Science and Engineering, Peking University, Beijing, People's Republic of China

* Author to whom any correspondence should be addressed.

E-mail: duank6@mail.sysu.edu.cn**Keywords:** inter-basin water transfer, efficiency, water stress, climate change, adaptationSupplementary material for this article is available [online](#)**Abstract**

Inter-basin water transfer (IBT) is widely used to mitigate water shortage at the cost of compromising water availability in water-exporting regions. Yet, we do not know how efficient are the IBTs in alleviating inter-regional water stress in a changing climate and water supply-demand context. From a socio-hydrological perspective, we here quantify the efficiency of more than 200 IBTs across the United States by a Stress Relief Index that measures the impact of water redistribution on the overall water stress level. 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, we show that 29% of the IBTs could be considered socially inefficient by 2010 as they shift water stress from water-receiving to water-exporting and downstream regions. Future stress escalations induced by growing population, declining runoff, and increasing demands for energy production and irrigation will alter IBT efficiency disproportionately. The inefficient IBTs would amount to 32% and 35% by the end of the 21st century under the scenarios of representative concentration pathway (RCP) 4.5 and RCP8.5, with 7 ~ 16 IBTs reaching a tipping point that their role in the water system could switch from alleviating to aggravating the overall water stress. Our results indicate that the evolving climatic and socioeconomic status can largely affect transfer efficiency, highlighting the need of basin-level adaptation strategies for sustainable use of the IBTs.

1. Introduction

Inter-basin water transfers (IBTs) have played a critical role in securing freshwater supply in many water deficient regions (Shiklomanov 2000, Yevjevich 2001, Liu and Zheng 2002). IBTs are designed to alleviate regional water stress by diverting surface water from a 'water rich' area to highly stressed regions, and potentially reduce the detrimental impacts caused by unsustainable local water uses (e.g. groundwater overdraft) (de Graaf *et al* 2019). Worldwide, 500 billion out of the estimated 42 trillion m³ (1.2%) of renewable water resources are redistributed by IBTs annually (Shiklomanov 2000), such as the

South-to-North water transfer project in China and the Snowy Mountains Scheme in Australia (Ghassemi and White 2007, Zhang *et al* 2020). In the United States, 22 billion m³ of water is transferred each year via over 200 IBTs, with the annual transfer magnitude ranging from 500 m³ to 4 billion m³ per IBT (Petsch 1985, Mooty and Jeffcoat 1986). The transferred water only accounts for 1% of surface freshwater resources (2.1 trillion m³ yr⁻¹) and 6% of surface water demands (356 billion m³ yr⁻¹) in the U.S. (Duan *et al* 2018), but it is an important source of freshwater for arid or densely populated areas. One example is southern California, where over 80% of the surface freshwater resources comes from

the 8 billion $\text{m}^3 \text{yr}^{-1}$ of water transferred from the San Joaquin River and Colorado River (Ashoori *et al* 2015, Duan *et al* 2019), supporting a population of 13 million in the Los Angeles Metropolitan Area and over nine million acres of farmland production for both local consumption and global trade (Hoekstra and Chapagain 2011, Mount and Hanak 2016).

The adequacy of surface freshwater resources at the country or regional scales can be interpreted by the water stress index (WS) defined as the ratio of off-stream water demand (water withdrawal or water use) to water availability (Wada *et al* 2011, Pedro-Monzonis *et al* 2015). The level of water stress is usually considered high when the ratio exceeds 0.4 due to the concern for sufficient instream water uses for navigation, hydropower generation, and ecological and environmental demands (Vörösmarty *et al* 2000, Oki *et al* 2001, Richey *et al* 2015). The aqueducts of IBTs are artificially integrated into the river networks, and disrupt the upstream-downstream flow passage due to water withdrawals in one basin and return flows in another. Such artificial modification to the natural hydrological system alters water balance in hydrologically connected drainage basins and influence downstream environments, which subsequently reduces water stress in the water-receiving basin at the cost of compromising water availability in the water-exporting basin.

Individual IBTs across the globe have been well studied from various perspectives of hydrology (Long *et al* 2020), water management (Gohari *et al* 2013, Barnett *et al* 2015), economics (Zhao *et al* 2015), and ecosystem conservation (Davies *et al* 1992, Grant *et al* 2012, Vargas *et al* 2020). However, two considerable gaps remain in our understanding of the IBTs' role in water stress alleviation. First, most of the previous studies have focused on the impact of individual IBTs, while the aggregate hydrological impacts of multiple IBTs have been rarely quantified at high spatial resolutions due to a lack of standardized and systematic data collection at national or continental scales (Emanuel *et al* 2015). For example, Long *et al* (2020) reported that water transferred through the South-to-North water transfer project accounted for 40% of groundwater storage recovery in Beijing; Zhao *et al* (2015) argued that water transfer cannot mitigate water stress in China, but the results were based on water stress evaluated coarsely at the provincial level (30 provinces) and the hydrological connections among regions were not considered. Second, little is known about the potential variations in the IBTs' role under the compound influence of dynamic hydroclimatic condition and water supply-demand context. For example, Emanuel *et al* (2015) examined the effectiveness of water transfer projects in the United States by comparing the transfer magnitudes to streamflow in water-exporting and receiving regions without considering the spatiotemporal differences in water demand. Although the

physical characteristics of drainage basins (e.g. topography, soil properties) can be assumed to remain static within the time scale of interest to water managers, pre-transfer water availability and water stress is constantly changing driven by environmental and anthropogenic stressors such as the changes in climate, population, water use efficiency, and economic and energy structures (Vörösmarty *et al* 2000, Maupin *et al* 2014). The nonlinear response of downstream water availability to the combined impacts of water transfer, climate change, and water-use behaviors in upstream areas could be highly complex for large basins. It is important to understand whether the IBT infrastructure could fulfill its role efficiently in a changing environment.

Here we present a dynamic water stress model and a set of efficiency metrics based on a high-resolution geography of water transfer, water use and availability, analyzing the role of IBTs in stress alleviation in historical and future contexts. We compiled historical records of 228 IBTs that transferred water across the 2009 8-digit hydrologic unit code (HUC-8) watersheds in the conterminous United States (CONUS), and projections of watershed runoff, population, water withdrawal, and consumptive water uses under future scenarios of climate change and adaptation in the 21st century. We consider explicitly how the topology of river networks and off-stream water uses determine the character of IBTs in sustainable water supply. We hypothesize that the large-scale climate change and associated adaptation strategies would alter regional water availability and water demand from both hydrological and socioeconomic aspects, potentially resulting in spatially diverse changes in IBT efficiency in water stress alleviation.

2. Methods

2.1. Data

2.1.1. IBTs

The location and transfer magnitudes of IBTs in 1973–1982 were collected from survey questionnaires in the eastern (Mooty and Jeffcoat 1986) and western (Petsch 1985) United States. Among the 256 IBTs originally identified in the reports, 23 were excluded due to the lack of transfer magnitudes and another five were excluded because they were associated with transboundary river basins (Emanuel *et al* 2015). The remaining 228 IBTs include 122 projects in the east and 106 in the west. Although dated, this database is the most comprehensive national-scale data of IBTs with detailed flow volumes (Dickson and Dzombak 2017, 2019), and has been widely used for national water resource assessments (Emanuel *et al* 2015, Brown *et al* 2019, Duan *et al* 2019).

2.1.2. Historical population and water use

Historical data of population and water uses were obtained from the water census reports compiled by

the U.S. Geological Survey (Solley *et al* 1998, Maupin *et al* 2014). The water use datasets were rescaled from counties (3109 counties) to HUC-8 watersheds based on weighted areal averages. Water withdrawal and consumption were linearly interpolated within each five-year reporting interval to generate a continuous time series of water demand to be compared to the variations in water availability (Duan *et al* 2018).

2.1.3. Reference scenarios of water demand and supply in the 21st century

Two reference scenarios of future water demand and supply were used to investigate the response of IBT efficiency to climate change and socioeconomic adaptation. An intermediate water stress (IS) scenario and a high water stress (HS) scenario were created based on the trajectory of a series of climatic (e.g. precipitation, temperature, radiation) and socioeconomic (e.g. population, energy structure, water use efficiency) factors to represent a future with and without climate change mitigation strategies, respectively (Duan *et al* 2019). The IS scenario was driven by climate change under the representative concentration pathway (RCP) 4.5 scenario, intermediate population growth, and power generation complying with the Clean Power Plan (CPP). Meanwhile, the HS scenario was driven by climate change under the RCP8.5 scenario, fast population growth, and power generation without the CPP. The CPP is a U.S. Environmental Protection Agency (EPA) program issued under the Clean Air Act (42 U.S.C. §7401) that aims at a reducing carbon emission from fossil fuel plants and extending tax credits for renewable energy. Energy structure and energy consumption was projected based on the Annual Energy Outlook provided by the Energy Information Administration of U.S. Department of Energy. Climate projections from 19 Global Climate Models (GCMs) of the fifth phase of the Coupled Model Inter-comparison Project (CMIP5) (<http://maca.northwestknowledge.net/>) was collected to enable a robust quantification of the major uncertainties from model structure. Future population were obtained from the Integrated Climate and Land-Use Scenarios v1.3 datasets compiled by the EPA (www.epa.gov/iclus/iclus-downloads). Water demand and consumption of surface freshwater was simulated by extrapolating the past trends with consideration of future demographic, socio-economic, and climatic disturbance on thermoelectric (NETL 2011), irrigation (Döll 2002), and domestic water uses. More details can be found in Duan *et al* (2019) and Brown *et al* (2013).

2.2. Dynamic water stress model

We developed a dynamic water stress model to investigate regional water availability and stress levels in various contexts of climate, water uses, and water transfers. The HUC-8 level watershed water

balance was simulated by a previously validated monthly eco-hydrological model—the US Department of Agriculture Forest Service (USDA-FS) Water Supply Stress Index (WaSSI) model (Sun *et al* 2011, Caldwell *et al* 2012). WaSSI was developed to capture land-cover specific hydrological processes and water balance components in the CONUS. Monthly precipitation and temperature for the period of 1961–2010 from the Parameter-elevation Relationships on Independent Slopes Model dataset (<http://prism.oregonstate.edu/>) were used to drive the WaSSI model for historical runoff simulation. Monthly precipitation, temperature, solar radiation, wind speed, and specific humidity derived from 19 CMIP5 GCMs were used to project runoff under future scenarios of RCP4.5 and RCP8.5.

Regional water availability was simulated by accumulating and routing streamflow through the river networks across the CONUS (Duan *et al* 2018). We assumed that water withdrawal, consumption, and transfer would occur uniformly in each watershed, while the return flows, the transferred water, and the residuals of the accumulated flow would be discharged simultaneously to surface water at the inlet of the next downstream watershed. A total of 18 777 upstream-downstream water connections among the HUC-8 watersheds were identified based on the geospatial attributes of streams at different hierarchical levels obtained from the National Hydrography Dataset (<http://nhd.usgs.gov/data.html>).

We further defined four scenarios of regional water availability to disentangle the independent impacts of each IBT and consumptive water uses on water supply and water stress at each watershed, including ‘natural’, ‘post-IBT’, ‘post-consumption’, and ‘post-consumption&IBT’ streamflows. ‘Natural’ streamflow (TF_m) represents a natural state of maximum water availability without anthropogenic disturbances, as

$$TF_m = LF + \sum_{i=1}^N UF_i \quad (1)$$

where LF is runoff generated from local watershed; UF_i represents water flow accumulated from the i th upstream watershed. ‘Post-IBT’ (TF_t) and ‘post-consumption’ (TF_c) streamflow represents regional water availability disturbed by the water transfers and upstream consumptive water uses respectively, as

$$TF_t = LF + \sum_{i=1}^N UF_i \pm \sum_{j=1}^M T_j \quad (2)$$

$$TF_c = LF + \sum_{i=1}^N UF_i - \sum_{i=1}^N C_i \quad (3)$$

where T_j is the magnitude of water transferred in or out of the watershed through the j th IBT project; C_i

is water consumption that occurs in the i th upstream watershed. Similarly, 'post-consumption + IBT' streamflow (TF_{ct}) represents water availability under the combined influence of upstream water uses and IBTs, as

$$TF_{ct} = LF + \sum_{i=1}^N UF_i - \sum_{i=1}^N C_i \pm \sum_{i=1}^M T_j. \quad (4)$$

IBT-induced variations in regional water availability with and without the influence of upstream water uses are quantified by comparing the simulations of TF_{ct} to TF_c and TF_t to TF_m , respectively.

2.3. Quantification of IBT efficiency

'Efficiency' is usually evaluated by weighing the benefit against the cost (Colby 1990). 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 supply, we here suggest two sets of simple metrics to consistently evaluate IBT impact on regional water supply and its efficiency.

2.3.1. Extent metrics

Due to the upstream-downstream water dynamics among hydrologically connected watersheds, an IBT could impact a much larger area besides the watersheds exporting and receiving the transferred water. We used six metrics to evaluate the extents of positive and negative impacts of each individual IBT on water supply, including land area and population positively/negatively impacted by the transfer, and changes in the coverage of highly stressed area and population caused by the transfer (SI appendix, table S1 available online at stacks.iop.org/ERL/17/044050/mmedia).

2.3.2. Efficiency metrics

We developed two simple indices using only water availability and water demands to assess IBT efficiency: (a) 'Natural efficiency' is measured by difference between transfer-in ratio and transfer-out ratio (DIO). Transfer-in ratio (TI) is the ratio of transfer magnitude to the mean annual streamflow in the water-receiving watershed, reflecting the degree of benefit for water supply in the destination region. Transfer-out ratio (TO) is the fraction of mean annual streamflow removed by an IBT from the water-exporting watershed, reflecting the cost of water availability reduction and ecosystem disturbance in the source region. DIO is calculated as

$$DIO = TI - TO = \frac{T}{TF_m(r)} - \frac{T}{TF_m(e)} \quad (5)$$

where TI and TO represents the ratio of transfer magnitude of an IBT to regional 'natural' renewable

freshwater availability in the water-receiving watershed ($TF_m(r)$) and water-exporting watershed ($TF_m(e)$), respectively.

(b) 'Social efficiency' is measured by Stress Relief Index (SRI), indicating the combined impacts of per unit transferred water on overall water stress across the areas that are in and downstream of water-exporting or receiving watersheds. The benefit/cost are measured by IBT-induced decrease/increase in regional water stress multiplying the impacted population, as

$$SRI = \frac{\sum_{i=1}^N [\lambda_i \times P_i \times (-\Delta WS_i)]}{T} \quad (6)$$

where T is transfer magnitude of the IBT; P_i and ΔWS_i are the population and the IBT-induced change in water stress in the i th watershed. λ_i is the weighing factor for the i th watershed that can be adjusted to differentiate water management priorities. Higher λ_i could be implemented for regions involved with extreme water shortage, vulnerable ecosystems, or endangered aquatic species. Here λ_i is set to be the constant one to facilitate a consistent comparison of climate change impact across the country. ΔWS is calculated as

$$\Delta WS = WD \times \left(\frac{1}{TF_{ct}} - \frac{1}{TF_c} \right) \quad (7)$$

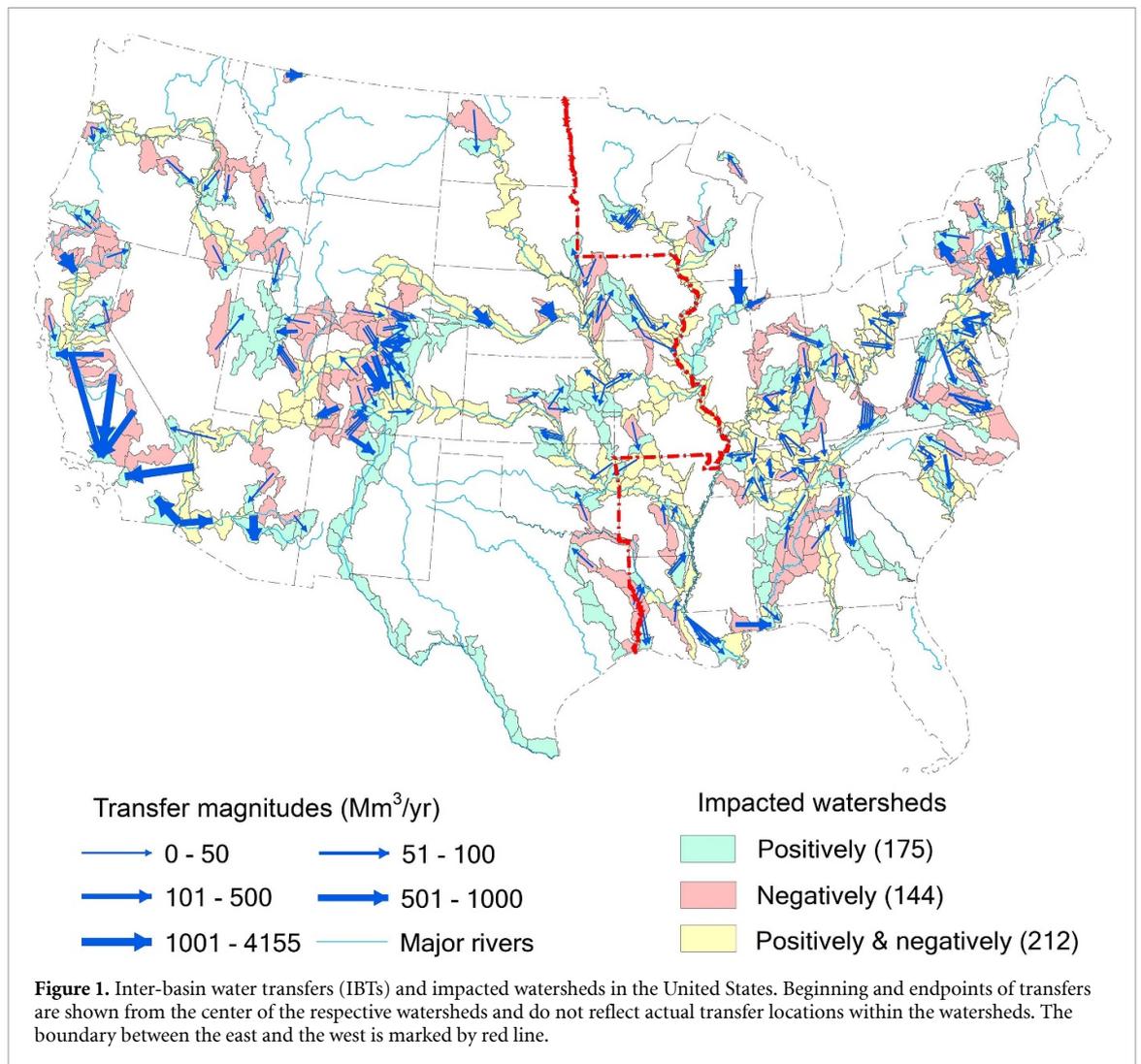
where WD is off-stream water demand.

Both indices measure efficiency by weighing the positive impacts of an IBT on water supply against the negative impacts. Therefore, a larger value of DIO or SRI indicates a higher efficiency of an IBT in remedying water scarcity. DIO and SRI may be either positive or negative, with a negative value suggesting that the IBT is inefficient in a certain hydrological and water-use context.

3. Results

3.1. Spatial extents of IBT impact on regional water supply

We identified 150 and 145 watersheds directly receiving and supplying water of IBTs, respectively (figure 1). The number of involved watersheds increase to 387 (water-receiving) and 356 (water-supplying) respectively when downstream influence of water transfer is considered. The extents of positively impacted land area and population of individual IBTs varied from 1.2×10^3 to 1.2×10^5 km² and from 1200 to 8.5 million people, whereas the negatively impacted area and population also varied widely from 0.7×10^3 – 1.3×10^5 km² and from 1900 to 4.9 million people (figures 2(a) and (b)). We found that the negatively affected area of 112 IBTs exceeded



the corresponding positively impacted area, including 58% (71 out of 122) in the east and 39% (41 out of 106) in the west. The negatively impacted population also exceeded the positively impacted population in 69 (57%) eastern IBTs and 38 (36%) western IBTs, respectively. These results suggest that nearly half of these existing IBTs compromised water supplies for either a larger area or population.

We cross-compared historical water stress under the four scenarios of regional water availability (equations (1)–(4)). Discrepancy among these scenarios suggests only a slight IBT-induced change in the coverage of highly stressed land area, either with (14.8%, 1.2×10^6 km²) or without (14.3%, 1.1×10^6 km²) the influence of upstream water consumption. Meanwhile, the corresponding proportion of highly stressed population was reduced from 18.5% to 17.6% and from 18.3% to 17.3% (figure 2(c)). We identified 12 most influential IBTs in Colorado, California, and New York that had relieved 2.3 million people from HS. These results confirmed the crucial role of IBTs in facilitating water supply for densely populated regions.

3.2. IBT efficiency in 1981–2010

Various hydroclimatic conditions and water uses led to diverse efficiency of the IBTs across the country in 1981–2010. On multi-decadal average, TI and TO (figure 2(d)) varied greatly from $1.4 \times 10^{-5}\%$ to $1.2 \times 10^4\%$ and from $1.9 \times 10^{-6}\%$ to 65%, respectively. Most of the IBTs with large TI or TO (7 IBTs with a TI larger than 100%; 9 out of 12 IBTs with a TO larger than 10%) were located in the west due to the dry climate and large transfer magnitudes (see reference numbers and details in SI appendix table S2). There were 96 IBTs (55 in the east and 41 in the west) with TO exceeding TI, a condition suggesting an inefficient IBT. The least naturally efficient IBTs include three projects in New York (e.g. IBT#17E Delaware Aqueduct) and one in Nebraska (#15W Loup River power canal) that removed as much as 29%–58% of the streamflow from the water-exporting watersheds.

SRI evaluations show that IBTs with small transfer magnitudes can also be deemed efficient as they benefit considerable downstream populations. Several transfers (<10 Mm³) located in Illinois (#68E

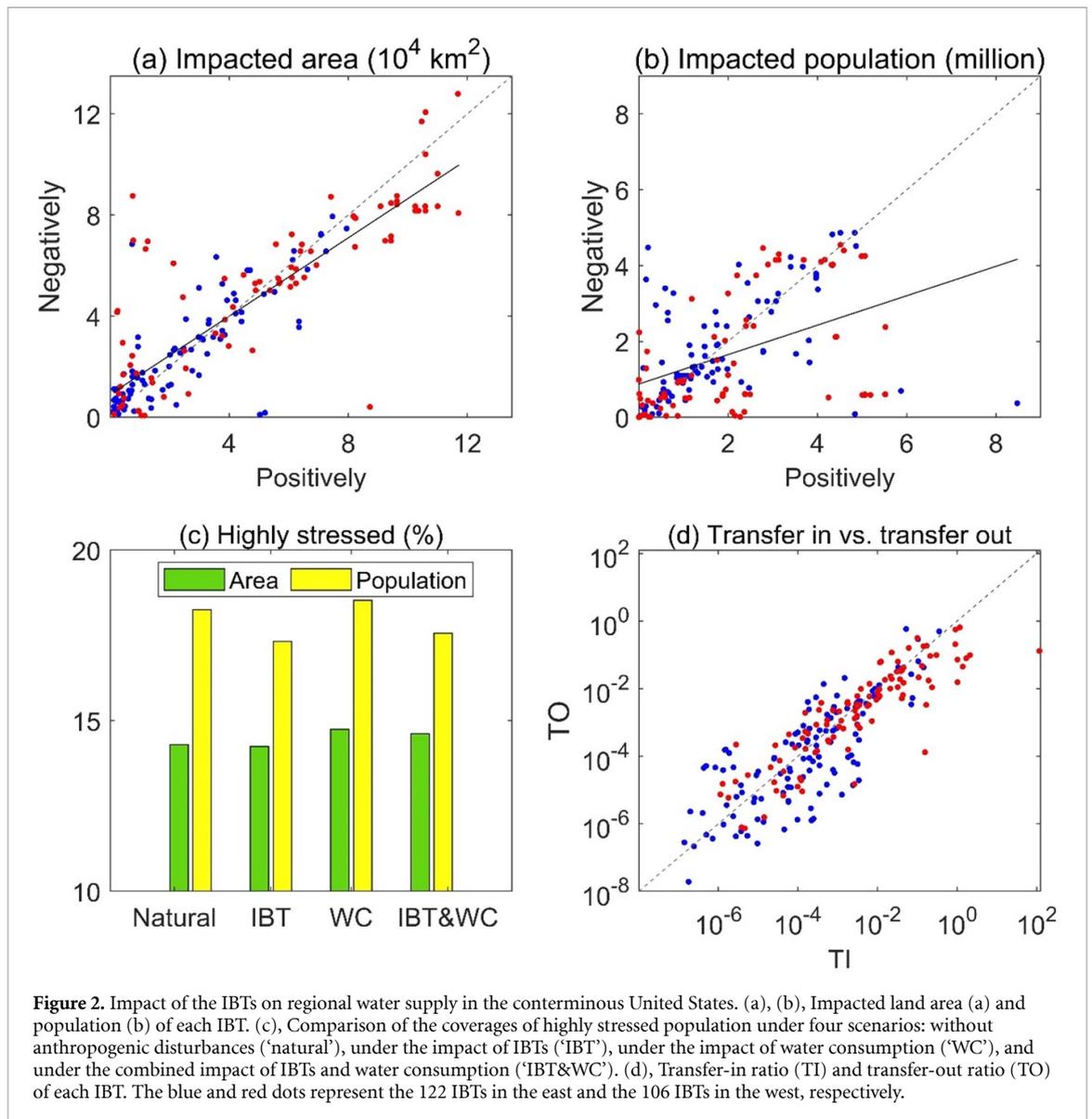


Figure 2. Impact of the IBTs on regional water supply in the conterminous United States. (a), (b), Impacted land area (a) and population (b) of each IBT. (c), Comparison of the coverages of highly stressed population under four scenarios: without anthropogenic disturbances ('natural'), under the impact of IBTs ('IBT'), under the impact of water consumption ('WC'), and under the combined impact of IBTs and water consumption ('IBT&WC'). (d), Transfer-in ratio (TI) and transfer-out ratio (TO) of each IBT. The blue and red dots represent the 122 IBTs in the east and the 106 IBTs in the west, respectively.

City of Highland Distribution lines), Wyoming (#6W City of Cheyenne Stage 1 Diversion), and Nevada (#79W Alfred Merritt Smith conveyance) were ranked among the most efficient IBTs with the overall reductions in water stress exceeding 1.0 (thousand people Mm^{-3}). Meanwhile, the negative SRI values indicate 67 inefficient IBTs (43 in the east and 24 in the west). The smallest SRI (-1.8 thousand people Mm^{-3}) was found in the IBT transferring water from the Sierra Nevada to southern California through the Los Angeles Aqueduct (#111W). This project decreased water supply for 3 million people downstream by removing water from upland areas.

Contradictory results between natural and social efficiency (i.e. $\text{DIO} \times \text{SRI} < 0$) were found at 55 IBTs (figure 3(a)). Such inconsistency reflects different perspectives on the role of IBTs in local and basin-level water systems. While DIO reflects the ratios of transfer magnitude to streamflow in the source and destination watersheds, SRI varies with the relevant

population and the aggregate hydrological response to variations in climate and water uses. Over a short period of time, annual variation in SRI is mainly controlled by the temporal variability of the dry and wet spells since socioeconomic status is relatively stable. For instance, higher efficiency at the three largest IBTs in California (figure 3(b)) coincided with the drought years of 1995–1997 and 2001–2003 (Robeson 2015).

3.3. Future IBT efficiency under climate change

3.3.1. Response of IBT efficiency

With current transfer routes and volumes, future climatic and socioeconomic changes would enhance or suppress IBT efficiency disproportionately across the CONUS (figure 4). Multi-model average results suggest increasing signal at over half of the IBTs, accounting for 50% (IS) and 54% (HS) by DIO and 54% (IS) and 61% (HS) by SRI. In particular, increasing SRI would cover more than 70% of the 106 western IBTs due to the significant rise in pre-transfer water stress

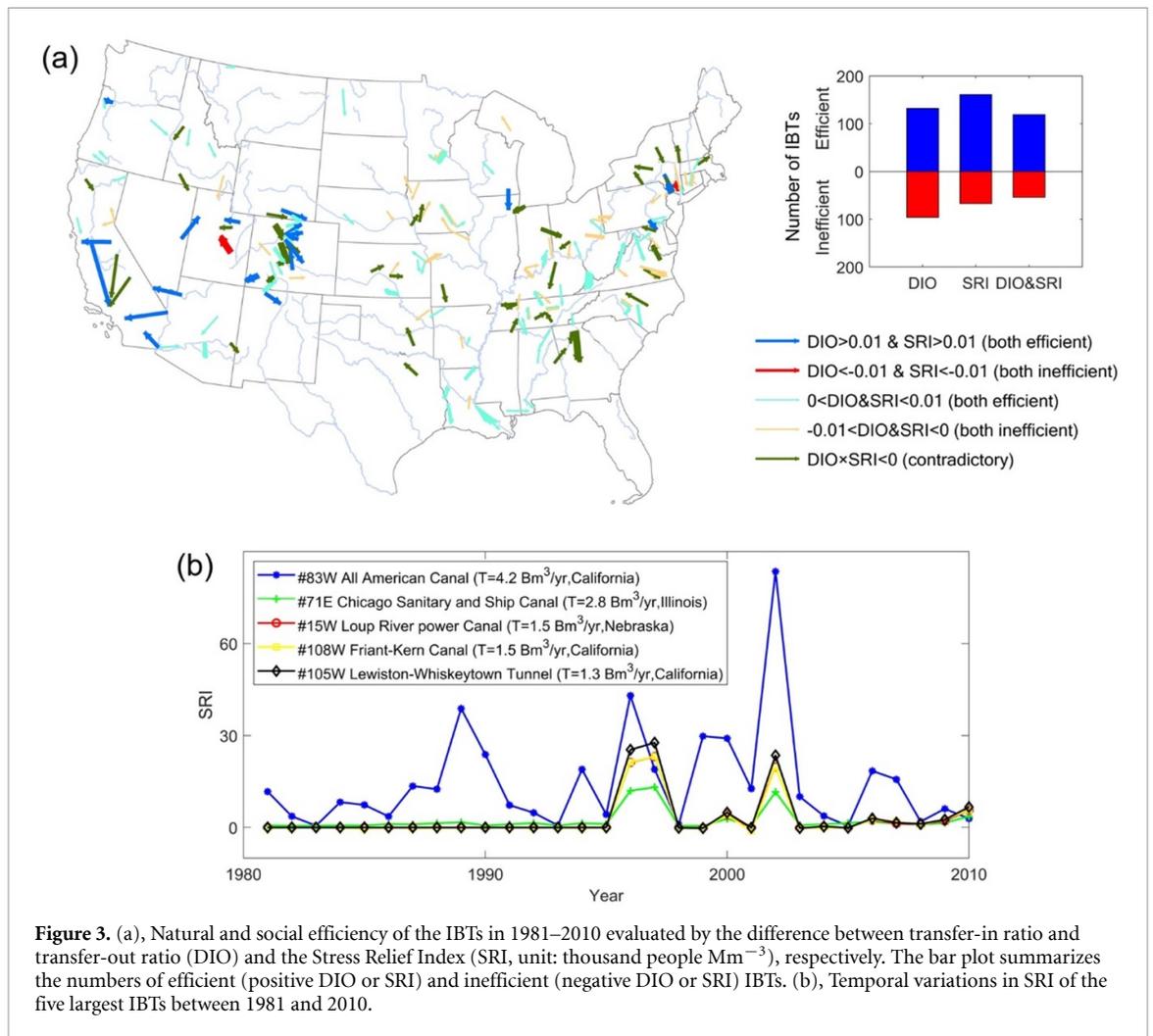


Figure 3. (a), Natural and social efficiency of the IBTs in 1981–2010 evaluated by the difference between transfer-in ratio and transfer-out ratio (DIO) and the Stress Relief Index (SRI, unit: thousand people Mm^{-3}), respectively. The bar plot summarizes the numbers of efficient (positive DIO or SRI) and inefficient (negative DIO or SRI) IBTs. (b), Temporal variations in SRI of the five largest IBTs between 1981 and 2010.

in the regions benefited from the IBTs. Discrepancy between the changes in DIO and SRI is widely found in the upstream areas of large rivers such as the Colorado River and the Rio Grande River, suggesting higher degree of dependence on the transferred water when downstream effects of the changing environment are considered. However, extensive decrease in efficiency is also expected. The proportion of naturally inefficient IBTs would slightly decrease from 42% to 41%, yet socially inefficient IBTs would increase from 29% to 32% (IS) and 35% (HS).

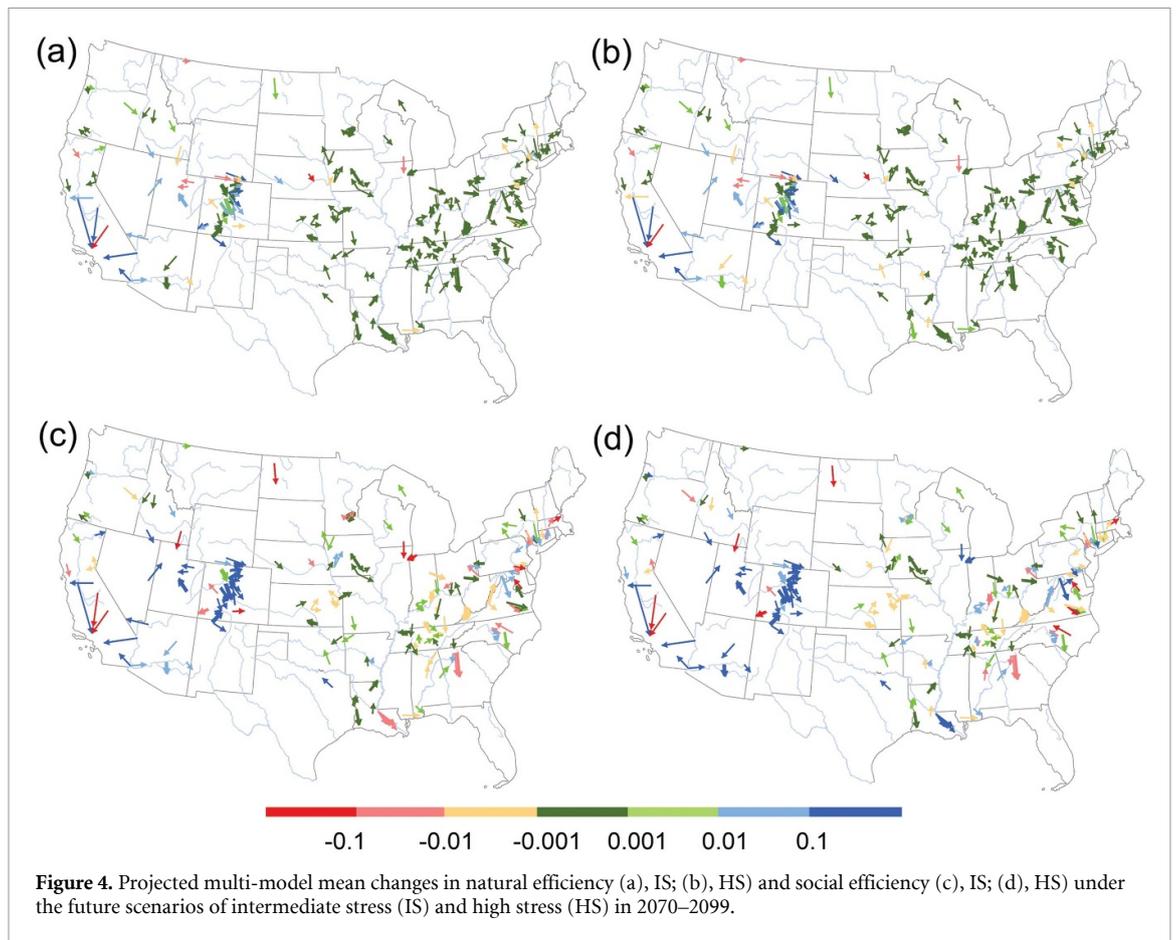
Multi-model means in post-transfer water stress suggest more frequent escalations to HS at water-exporting watersheds (9 under IS and 12 under HS) than that at water-receiving watersheds (4 under IS and 8 under HS) (figure S3). Downgrade from high stress to lower stress levels can only be expected at 1–3 water exporting/receiving watersheds. Such results imply that some water-exporting regions may not be able to afford the transfers in the farther future, yet the transferred water may be insufficient to remedy the worsening water shortage at water-receiving regions.

Future efficiency response shows divergent trends among historically efficient and inefficient IBTs

(figure 5). 46% (IS)–57% (HS) of the changes in DIO and 50% (IS)–63% (HS) of the changes in SRI suggest increasing signals in efficient IBTs and decreasing signals in inefficient IBTs. The IBTs are expected to shift towards a pattern of ‘efficient gets more efficient and inefficient gets more inefficient’ as climate change intensifies. This is probably associated with the shift of hydrological cycle under global warming that partially leads arid regions to become drier, such as the western CONUS. Particularly, 7 (IS) to 16 (HS) IBTs across the central (e.g. #62 W Montezuma Valley Irrigation Company Canal 2 in Colorado) and southeastern (e.g. #62E Cobb County Water System in Georgia) CONUS are expected to switch from efficient to inefficient (i.e. from positive to negative SRIs), while the opposite switch can only be found in 2 (IS)–4 (HS) cases. Efficiency change of these IBTs are expected to reach a tipping point that their role in the water system would switch from alleviating to aggravating the overall water stress.

3.3.2. Driving forces of potential efficiency change

We examined the relative roles of drivers of efficiency change from the historical period of 1981–2010 to the



future period of 2070–2099. Future changes in natural efficiency are resulted from terrestrial water balance shifts induced by climate change. Across IBTs with increasing and decreasing DIO, streamflow variations at water-receiving and water-exporting watersheds are projected to dominate the changes in natural efficiency, with the relative contributions reaching 70% (IS)–78% (HS), respectively.

SRI change was decomposed into the independent effects of population (including the subsequent changes in domestic water use), runoff, and thermoelectric and irrigation water uses (including the impacts of changing water demand and upstream water consumption) (figure 5). Population growth and migration are likely to be the largest driver, accounting for 41% (IS)–52% (HS) of SRI change based on the multi-model mean results. For example, large increases in SRI are projected in the southwest as population expands in water-receiving areas. However, the spatially inhomogeneous population growth could compromise IBT efficiency. The proportion of IBTs where the negatively affected population exceeds the benefited population would remain around 47% under the IS scenario, but increase to 62% under the HS scenario (figure S4). Runoff variations can explain 36% (IS)–39% (HS) of the increases in SRI and 33% (IS)–34% (HS) decreases. Impact of runoff

variation on efficiency tends to be enhanced through the aggregation of upstream flows across large river basins (e.g. the Rio Grande, Gila, and Colorado Rivers), where availability of upstream flow is identified as the most influential factor on water stress in downstream watersheds (Duan *et al* 2019).

The drop of water demand for energy production in water-exporting areas would be a major driver of efficiency increase when climate change adaptation measures are implemented. Its relative contribution reaches 37% at the IBTs switching from inefficient to efficient under the IS scenario (e.g. #27 W Springfield Pipeline in Missouri). Variations in thermoelectric water use can explain 13% (IS)–7% (HS) of the SRI increase and 25% (IS)–12% (HS) of the decrease in terms of the national average. The averaged contributions of irrigation water use are generally small (2%–6%) for IBTs with either increasing (3%–6%) or decreasing SRI (2%–5%). However, growing evaporative demand in water-receiving region could be a dominating driver of efficiency rise, such as the St. Mary Canal (#4 W) in Montana (64%–82%). Contributions of thermoelectric and irrigation water uses are consistently larger under the IS scenario, suggesting that adaptation practices could impact IBT efficiency extensively through curbing water withdrawal and consumptive uses.

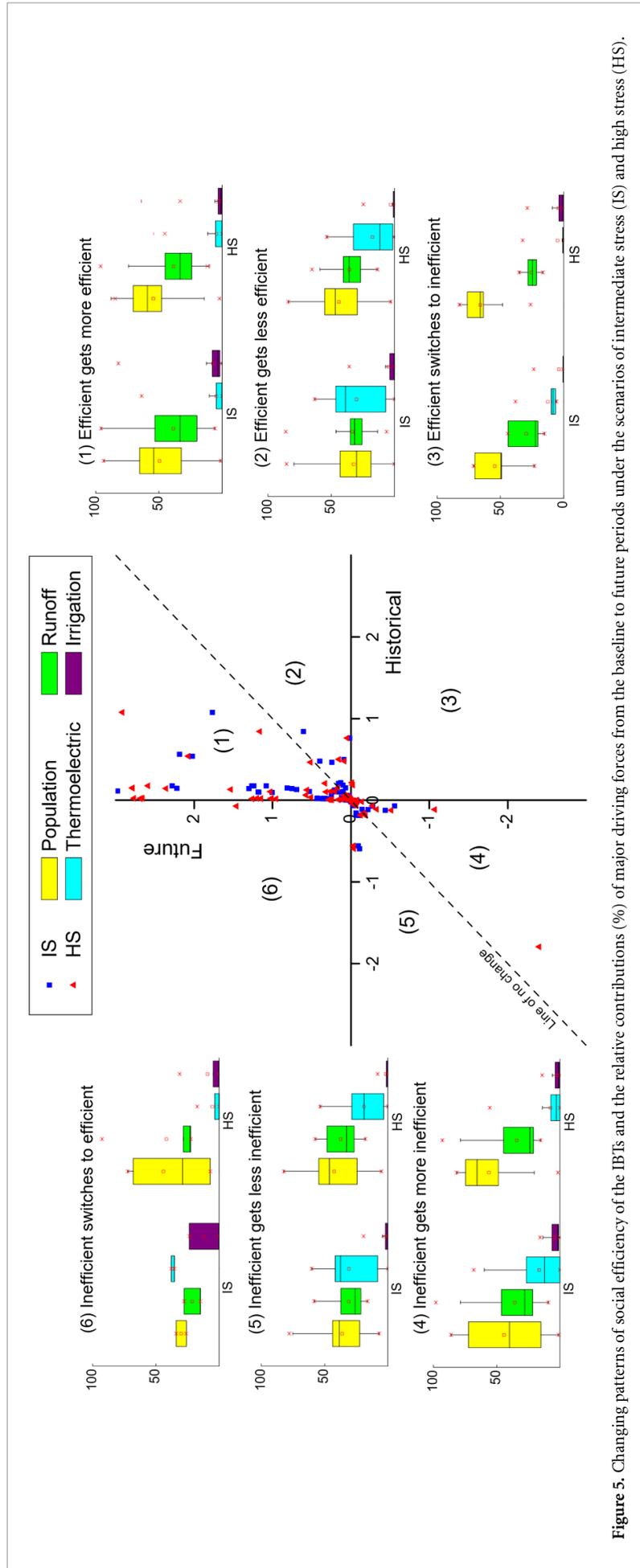


Figure 5. Changing patterns of social efficiency of the IBIs and the relative contributions (%) of major driving forces from the baseline to future periods under the scenarios of intermediate stress (IS) and high stress (HS).

4. Discussion and summary

The value of water is not the same for communities under different water stress levels. Although the IBTs are designed to divert water from where it is to where it is needed, they inevitably ‘rob Peter to pay Paul’ in a water-stressed world and may even cause environmental consequences (Webber *et al* 2017). Our analysis highlights that IBT efficiency in relieving water stress is constrained by topography, population distribution, and upstream-downstream water connections (i.e. stream flows, water withdrawals, and return flows). These results provide a reasonable evaluation for resource management at different administrative levels by helping to understand the role of IBTs in the water systems. Upland transfers should be dealt with particular caution for their potentially amplified downstream influences. Overlooking the downstream impacts of water transfers or not evaluating their efficiency in a dynamic supply-demand context could lead to misleading guidance for water and land managers.

The results support our hypothesis that future climatic and socioeconomic changes would lead to spatially diverse changes in IBT efficiency in water stress alleviation. The projected decline in efficiency and post-transfer stress levels raise the question of the sustainability of current IBTs in a fast-changing environment. Increased dependence on transferred water and stress escalation in water-exporting watersheds will lead to a higher cost to externalize water stress, and probably a higher risk to trigger conflicts over water rights (Doremus 2011). Population growth in water-receiving areas would be a major driver of efficiency rise, but future inhomogeneous increases in population could render 15% more IBTs obsolete as the suffered population exceeds the benefited population. Efficiency of IBTs in the arid western United States, particularly across large river basins, is more likely to be enhanced by the widespread decline in water availability (Milly and Dunne 2016, Duan *et al* 2017). Nevertheless, the increasing proportions of inefficient IBTs reveal the vulnerability of IBT efficiency to climate change from both the aspects of water demand and supply. Discrepancy between the two future scenarios demonstrate that adaptation strategies can significantly affect IBT efficiency by altering upstream water availability and pre-transfer water stress.

Several limitations and caveats apply to our study. Besides the uncertainties involved with the multidisciplinary datasets, we did not consider the role of groundwater supply and its interactions with surface water flows. We have excluded groundwater in the stress evaluations to highlight the impact of surface water redistribution by the IBTs. There is evidence that highly stressed basins collocate with regions of relatively low groundwater recharge rates across the globe, and groundwater resources are unlikely to

de-emphasize the stressed basins in the long term (Qin *et al* 2019). However, the benchmark of pre-transfer water stress would be different when incorporating groundwater and saline water uses in the tabulation. The societal reliance on the IBTs could vary with the potential changes in groundwater management policy and the ratio of groundwater use to the total water demand, particularly in regions experiencing considerable changes in groundwater accessibility (Fang and Jawitz 2019). Also, the local moisture recycling disturbed by human activities may affect regional water stress to various extents, such as the enhanced evaporation due to irrigation practices (Kang and Eltahir 2018) and increased open water area in reservoirs and aqueducts.

This study presents an integrated simulation-evaluation framework to assess the large-scale response of IBT efficiency to the nonstationary climatic and socioeconomic contexts. We have focused on demonstrating how the changing environment would challenge the IBT infrastructure and regional water management (Milly *et al* 2008). Further research on the interactions between IBTs and environmental stressors and compilation of an updated IBT inventory with information on the utilization of the transferred water and the operation strategies of IBT projects are warranted. Improved national survey of natural and anthropogenic water cycles, proper measures curbing water uses, and a flexible water transfer strategy coordinating with the environmental changes will be vital for achieving a sustainable use of the IBTs.

Data availability statement

The data that support the findings of this study are available upon reasonable request from the authors.

Code availability

All computer code used in this paper is available upon request from the authors.

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Author contributions

K D designed the study and performed the analysis. P C, G S, S M, Y Q, X C, and N L provided critical

insights on the results interpretation. K D wrote the initial draft, and all authors contributed comments and edits to finalize the paper.

Conflict of interest

The authors declare no competing interests.

ORCID iDs

Kai Duan  <https://orcid.org/0000-0002-0808-7580>

Yue Qin  <https://orcid.org/0000-0003-1664-4516>

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