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LETTER

Influence of basin characteristics on the effectiveness and downstream reach of interbasin water transfers: displacing a problem

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Abstract

Interbasin water transfers are globally important water management strategies, yet little is known about their role in the hydrologic cycle at regional and continental scales. Specifically, there is a dearth of centralized information on transfer locations and characteristics, and few analyses place transfers into a relevant hydrological context. We assessed hydrological characteristics of interbasin transfers (IBTs) in the conterminous US using a nationwide inventory of transfers together with historical climate data and hydrological modeling. Supplying and receiving drainage basins share similar hydroclimatological conditions, suggesting that climatological drivers of water shortages in receiving basins likely have similar effects on supplying basins. This result calls into question the effectiveness of transfers as a strategy to mitigate climate-driven water shortages, as the water shortage may be displaced but not resolved. We also identified hydrologically advantageous and disadvantageous IBTs by comparing the water balances of supplying and receiving basins. Transfer magnitudes did not vary between the two categories, confirming that factors driving individual IBTs, such as patterns of human water demand or engineering constraints, also influence the continental-scale distribution of transfers. Some IBTs impact streamflow for hundreds of kilometers downstream. Transfer magnitude, hydroclimate and organization of downstream river networks mediate downstream impacts, and these impacts have the potential to expand downstream nonlinearly during years of drought. This work sheds new light on IBTs and emphasizes the need for updated inventories and analyses that place IBTs in an appropriate hydrological context.

1. Introduction

The global water cycle has been modified by human activities that influence the distribution of water resources at local, regional and global scales (Postel *et al* 1996, Jackson *et al* 2001, Gordon *et al* 2005). Among the direct influences of humans on the global water cycle are interbasin transfers (IBTs) of surface water, which redistribute surface water flows among river basins to support a wide range of human activities and are among several options available to managers and policy-makers for alleviating water deficits and mediating drought impacts in the face of climate change (Gupta and van der Zaag 2008, Kasprzyk *et al* 2009). Worldwide, IBTs redistribute an estimated 500 billion m^3 of water annually (Shiklomanov 2000), the equivalent of about 1.3% of global continental discharge to oceans (Fekete *et al* 2002). In doing so, IBTs create artificial links in the global water cycle that alter the hydrologic balances of supplying and receiving drainage basins and influence downstream environments.

Individual IBTs have been well studied from planning and management perspectives (e.g., Draper *et al* 2003, Brandes *et al* 2005, Rodrigues *et al* 2014), and many impacts of individual transfers on various terrestrial and aquatic ecosystems have been documented (Davies *et al* 1992, Kingsford 2000a, Kennedy and Turner 2011). Still, little is known about the aggregate hydrologic impacts of IBTs at regional or continental scales (approximately 10^3 to 10^6 km^2) despite periodic calls for new research on these artificial linkages between basins and impacts on downstream flows (Davies *et al* 1992, Kingsford 2000b). Even less is known about the hydrological context in which these transfers take place, including the hydroclimatological conditions of the basins participating in transfers, the fractions of streamflow lost from or received by participating basins, and the roles of hydroclimate and basin organization in the persistence of downstream flow reductions.

Individual case studies of IBTs provide some general insight about how these management strategies affect water balances, yet a considerable gap remains in our understanding of how these transfers and their associated impacts are distributed across regions or continents. There are no detailed studies of the hydrological characteristics of IBTs at regional or continental scale due, in part, to a lack of standardized and systematic data collection at these scales. Given the impacts of ongoing droughts on water supplies in the US and elsewhere along with the continued influence of climate change on future water availability (Rajagopalan *et al* 2009, IPCC 2014), it is important to understand IBT characteristics and their potential impacts in aggregate, particularly if IBTs remain important parts of future water management strategies.

We performed a retrospective analysis of IBTs active in the conterminous United States between 1973 and 1982 using the only national inventory of IBTs ever compiled (Petsch 1985, Mooty and Jeffcoat 1986). We combined IBT data with outputs from a continental-scale hydrological model, driven by historical climate data, to situate IBTs in the context of the water balances of their supplying and receiving drainage basins. We assessed the hydrologic favorability of each IBT from a water balance perspective, and we evaluated the impact of IBTs on downstream flow conditions, demonstrating the capacity of hydroclimate and river network structure to mediate downstream effects of IBTs. We provide all of the inventory data, together with contextual information about flow routing, climate and modeled streamflow for each transfer, available as a single table in the supplementary materials.

2. Methods

We digitized print copies of the 1985–1986 IBT inventories (Petsch 1985, Mooty and Jeffcoat 1986) into a table of IBTs active from 1973 to 1982 in the conterminous United States (table S1). Of the 256 unique IBTs identified in these inventories, 23 did not report transfer magnitudes and were excluded from further analyses. For each of the remaining 233 IBTs, we identified the 8-digit US Geological Survey hydrologic unit code (HUC8) associated with both the source and destination, and where appropriate we updated original 1:100 000 HUC8 identifiers (Seaber *et al* 1987) with values from the more recent US Geological Survey Watershed Boundary Dataset (WBD 2015). The source and destination locations of each IBT were visually inspected to confirm correct WBD-derived HUC8 assignments, and components of only 3 IBTs (all located in California) were assigned new HUC8s due to differences between the original HUC8 boundaries and the WBD-derived HUC8 boundaries (e.g., Berelson *et al* 2004). Five additional IBTs were excluded from further analysis because their basins crossed international borders, preventing computation of areally standardized hydrologic fluxes.

The WBD-derived HUC8 dataset contained no information on flow routing (connectivity or direction). To analyze the impacts of IBTs on downstream surface water flows we developed an algorithm to add this information to the HUC8 dataset. First, we used GIS software (ArcMAP, ESRI Inc., Redlands, CA) to combine the WBD-derived HUC8 dataset with another geospatial dataset containing stream reaches and their physical attributes for the conterminous United States (NHDPlus, Horizon Systems Corp., Herndon, VA). Approximately 3 million stream reaches and 2099 HUC8s were combined in this step. Next, the exiting reach with the greatest cumulative drainage area was considered the true exit point for the HUC8 and the immediate destination of that reach (i.e. the adjoining HUC8 or an ocean) was identified as the destination of flow from the HUC8. Finally, the results of this analysis were compiled as a two-column table of from-HUC8s and to-HUC8s representing each connection (either directly adjacent or indirectly linked through a stream network) between HUC8s in the conterminous United States (18 777 connections). We joined this table to a HUC8 geospatial layer using ArcMap and Python scripting language, which allowed us to identify or select all HUC8s upstream or downstream of a given HUC8. Our Python-based selection tools are included as supplementary materials.

We used the USDA Forest Service's Water Supply Stress Index (WaSSI) hydrologic model (e.g., Caldwell *et al* 2012, Sun *et al* 2015) to simulate HUC8 water balances during the 1973–1982 inventory period. The WaSSI model estimates runoff generated in each HUC8 at a monthly time step and routes the runoff as streamflow through the river network. By default, WaSSI assumes natural surface water flows and ignores any anthropogenic alterations to the routing of runoff. A web-based version of the WaSSI model along with related tools and publications can be accessed through the Forest Service's Eastern Forest Environmental Threat Assessment Center's website (EFETAC 2015). We accounted for IBTs in WaSSI by subtracting the volume of each IBT from the routed flow of the supplying basin and adding this volume to the routed flow of the receiving basin. To determine the net impacts of all IBTs on all HUC8s, the WaSSI model was first used to calculate natural water flows for all HUC8s in the conterminous United States from 1973 to 1982. Hydroclimatic inputs were derived from the PRISM dataset (Daly *et al* 1994, PRISM 2015). The model was run again for the same time period with adjusted flows due to IBTs. The two model scenarios, one with IBTs and one without IBTs, were used to determine the fraction of flow diverted by IBTs for every HUC8 containing an IBT. We also determined the fraction of flow diverted in every HUC8 located downstream from an IBT. The aggregate model results assume there was no consumptive water use in the receiving HUC8s. To evaluate the impacts of individual IBTs on their respective source and receiving HUC8s, the WaSSI model was run through 228 additional iterations, once for each IBT.

In addition to identifying the basin water balance impacts of IBTs, the HUC8 routing tools were used to estimate the length of stream impacted by each IBT. The HUC8 routing exercise identified a single stream segment at the outlet of each HUC8. Using the stream segment routing attributes in the NHD, these outlet segments were connected to form mainstems within many downstream HUC8s. Mainstem lengths were determined by connecting NHD stream segments from the outlet to the inlet for each HUC8 (Caldwell *et al* 2012). Using a table of all mainstem lengths contained within each HUC8, an average mainstem length was calculated for each HUC8 that was impacted by an IBT. These impacted mainstem length calculations served as estimates of the actual stream lengths affected by IBTs. To ensure impacted mainstem length estimates were uniformly conservative, the mainstems of HUC8s containing IBTs were always excluded, leaving only the mainstems of downstream HUC8s. We used the Ohio River and Colorado River basins as examples to show how differences in hydroclimate and stream network structure affect the downstream impacts of hypothetical IBTs located in the headwaters of each basin.

3. Results and discussion

3.1. Hydrologic characteristics of IBTs and participating basins

The 228 IBTs in the national inventory transferred a total of 22 billion m^3 of water per year, on average, between 1973 and 1982, representing approximately 3.5% of total human water withdrawals for the conterminous United States during this period (Shiklomanov 2000), and approximately 1% of total estimated streamflow in recent years for the conterminous United States (Sun *et al* 2015). Although small in magnitude compared to total streamflow, these IBTs have major impacts on population growth, agriculture and industry in many parts of the country. Transfers were widespread geographically and spanned a range of magnitudes (figure 1) conforming to a lognormal distribution ($KS = 0.04$, $P = 0.84$) with a geometric mean of $1.57 \times 10^6\ m^3\ yr^{-1}$ (figure 2(A)). The ten largest IBTs accounted for over 70% of the total water transferred. Seven of these were located in the western United States (i.e., San Joaquin, Klamath, Colorado, Loup, and North Platte River basins) and three were located in the eastern United States (i.e., Hudson and Susquehanna River basins, and Lake Michigan).

Mean annual precipitation (MAP) estimated from PRISM data varied widely among supplying and receiving basins, ranging from about 150 mm yr^{-1} to over 2400 mm yr^{-1} during the 1973–1982 period and reflecting the diversity of climates in which IBTs are found. Among all IBTs, MAP was strongly correlated between supplying basins and receiving basins (Spearman $\rho = 0.85$, $P < 0.0001$), suggesting that IBTs generally transfer water between basins with similar annual precipitation (figure 2(C)); the median absolute difference in precipitation between supplying and receiving basins was only 8.9% (89 mm yr^{-1}) of the median MAP of all basins in the study. This result is consistent with the fact that supplying and receiving basins are often located in close proximity to one another (figure 1) and share similar hydroclimate conditions.

Using the WaSSI hydrological model, we estimated mean annual streamflow from each supplying and receiving basin during the years 1973–1982 in the absence of IBTs (hereafter, natural streamflow) (figure 2(D)). Most transfers were small relative to natural streamflow, with half of IBTs in the inventory consuming less than 0.04% of natural streamflow in supplying basins, and 78% of IBTs consuming less than 1% of natural streamflow in supplying basins. Twenty-five IBTs consumed more than 5% of the natural streamflow in their supplying basins.

Supplying basins had greater natural streamflow than receiving basins (Wilcoxon $P = 0.02$) in 59% of the IBTs (i.e., 135 of 228). Natural streamflows from supplying and receiving basins of all IBTs were weakly but significantly correlated (Spearman $\rho = 0.36$, $P < 0.0001$). Supplying and receiving basins shared similar mean annual runoff (natural streamflow per unit drainage area) resulting in strong correlations between supplying and receiving runoff among all IBTs (Spearman $\rho = 0.86$, $P < 0.0001$; figure 2(D)—inset). The strength of correlations for both precipitation and runoff between supplying and receiving basins suggests that in general, IBTs link basins with similar hydroclimatological conditions, with differences in streamflow between supplying and receiving basins driven largely by differences in drainage area. Strongly correlated runoff ratios (i.e., the mean annual runoff fraction of MAP) between supplying and receiving basins (Spearman $\rho = 0.80$, $P < 0.0001$; not shown) further suggest that supplying and receiving basins share similar hydroclimatic conditions. The

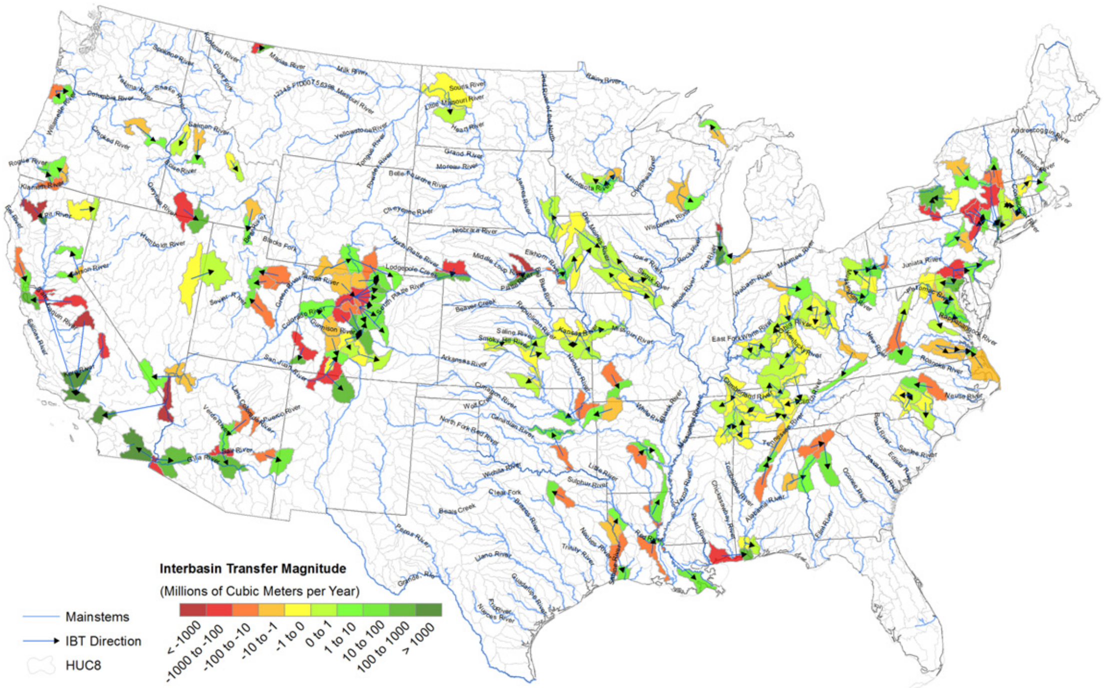

Figure 1. Interbasin surface water transfers (IBTs) in the conterminous United States from 1973 to 1982. Colors show net annual transfer magnitudes between 8-digit hydrologic units (HUC8s), and arrows point from source HUC8s to destination HUC8s.

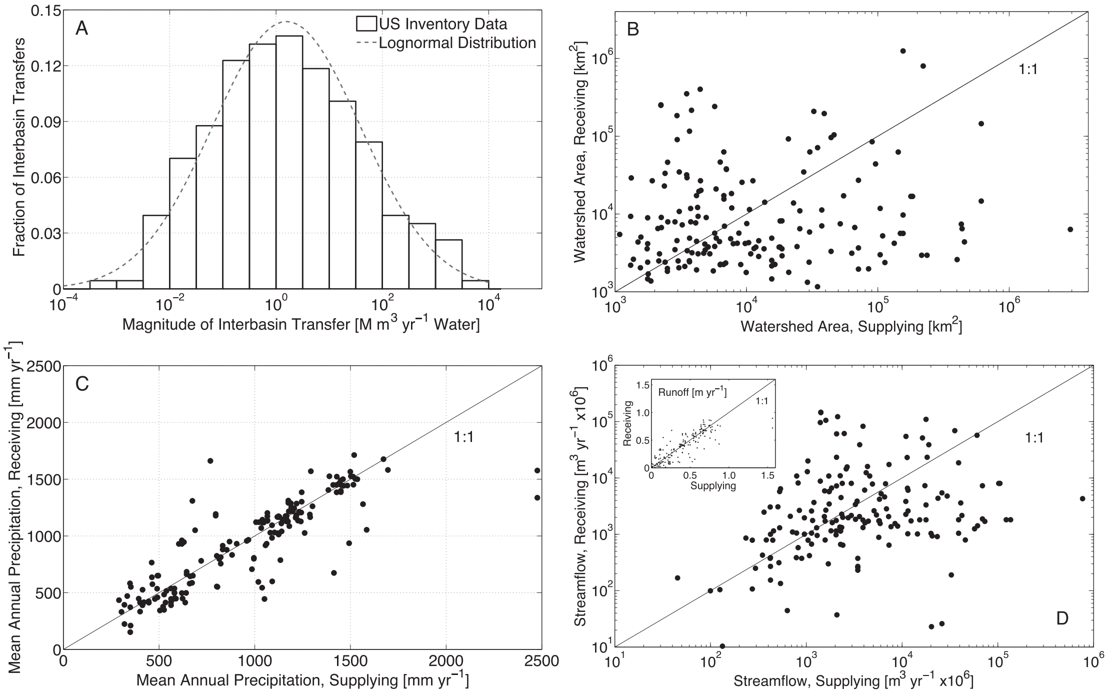

Figure 2. Hydrologic characteristics of 228 interbasin transfers and their associated supplying and receiving basins. Frequency distribution of transfer magnitudes (A). Each transfer is plotted separately in terms of the basin area (B), mean annual precipitation (C), modeled natural streamflow (D) and modeled runoff (D Inset) of its supplying and receiving basins.

same climate-related stressors that drive the development of IBTs may also limit their effectiveness at supplying water to other water stressed basins because supplying and receiving basins share similar hydroclimatic conditions and are often close in proximity to one another.

3.2. Comparing water balances in supplying and receiving basins

Each transfer affected the water balance of its supplying and receiving basin differently. We compared the fraction of mean annual streamflow removed by an IBT from its supplying basin to the fraction of mean annual streamflow gained by its receiving basin to quantify these differences. Transfers in which supplying basin streamflow exceeded receiving basin streamflow (occurring in 135 of 228 basins) were considered hydrologically advantageous since the proportion of streamflow transferred to the receiving basin was greater than the proportion of streamflow lost from the supplying basin. The remaining IBTs (i.e., 93 of 228) exhibited the opposite behavior and were considered hydrologically disadvantageous.

The distributions of transfer magnitudes between advantageous and disadvantageous groups were not significantly different (KS $= 0.09$, $P = 0.68$), suggesting that intra-basin water uses such as agricultural, industrial and other human water needs along with engineering or logistical concerns play a more prominent role in the planning and management of transfers (e.g. Gupta and van der Zaag 2008) than the actual hydroclimatic conditions of basins joined by IBTs. In other words, IBTs in the conterminous United States do not seek to minimize relative streamflow withdrawals from supplying basins while maximizing relative contributions to receiving basins. This type of optimization (minimizing the impacts of withdrawals while maximizing their relative contributions) would favor hydrologically advantageous IBTs over disadvantageous IBTs, yet the results suggest that no such optimization exists when considering the conterminous US as a whole. Clearly this type of hydrological optimization was not a design criterion for past IBTs, but water balance comparisons such as these have the potential to help guide the design of future IBTs as human populations grow and expand, and as in-stream ecosystem services become increasingly valued within supplying basins.

We examined and compared key features of hydrologically advantageous and disadvantage IBTs to better understand how basin characteristics and climatic conditions contributed to these classifications. The median supplying drainage basin area of hydrologically advantageous IBTs was nearly four times larger than the median supplying drainage basin area of disadvantageous IBTs (Wilcoxon $P < 0.0001$). Supplying drainage basins of hydrologically advantageous IBTs were typically larger than their own receiving drainage basins (Wilcoxon $P < 0.0001$), whereas the opposite was true for hydrologically disadvantageous IBTs (Wilcoxon $P < 0.0001$; figure 3(B)). These results suggest that many IBTs are hydrologically advantageous because they have large supplying basins, which tend to generate more streamflow than their smaller, receiving basins for similar climate conditions. Thus, IBTs with relatively large supplying basins are predisposed to classification as hydrologically advantageous.

Hydroclimatic conditions differed somewhat between advantageous and disadvantageous transfers. Supplying basins of hydrologically advantageous IBTs received significantly less precipitation (1-sided Wilcoxon $P = 0.04$) and had significantly less natural runoff overall (1-sided Wilcoxon $P = 0.02$) than supplying basins of hydrologically disadvantageous IBTs (figure 3(C)). These IBTs are hydrologically advantageous, despite having less precipitation and runoff than hydrologically disadvantageous IBTs, because their supplying basins are overwhelmingly larger than their receiving basins. In particular, for transfers originating in dry regions of the US (below the mean MAP for all basins studied), supplying basins are, on average, approximately ten times larger for hydrologically advantageous IBTs than disadvantageous IBTs. These results confirm that the larger supplying drainage basins of hydrologically advantageous IBTs offset the fact that they receive less precipitation than their hydrologically disadvantageous counterparts. Thus, drainage area and climate interact to cause differences in streamflow between supplying and receiving basins

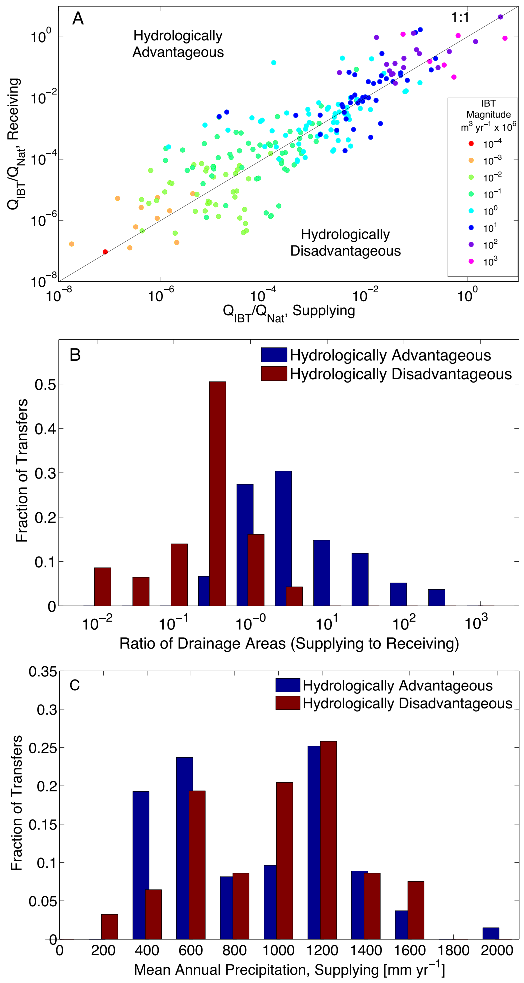

Figure 3. Characteristics of hydrologically advantageous and disadvantageous transfers. Hydrological advantage or disadvantage determined by comparing IBT magnitude as a fraction of natural streamflow received to the fraction of natural streamflow supplied (A). Distributions of the ratio of supplying to receiving drainage areas for hydrologically advantageous and hydrologically disadvantageous transfers shown (B) along with distributions of mean annual precipitation (MAP) for hydrologically advantageous and disadvantageous transfers (C).

that allow some IBTs to be more hydrologically advantageous than others.

3.3. Impacts of IBTs on downstream flows

The net impacts of IBTs have the potential to impact streamflow in downstream river reaches (figure 4(A)). Where IBTs are large relative to natural streamflow in the supplying basin, or where the supplying river passes through drier climates downstream, significant streamflow reductions may persist downstream of the supplying basin until surface water and groundwater inputs diminish the relative impact of the transfer. Streams in receiving basins may eventually gain water as a result of transfers, but up to 60% of the transferred water may be lost to consumptive uses (Shiklomanov 2000) and may never contribute to streamflow in the receiving basin. We limited further analysis to impacts downstream of supplying basins only because few data are available to estimate consumptive use of transferred water in the 1973–1982 inventory.

Comparison of WaSSI model scenarios with and without transfers revealed that most IBTs (i.e., 206 of 228) did not reduce the average long-term streamflow downstream of their supplying basins by more than 5%. This result pertains to the long-term, annual water balance during the 1973–1982 period and does not address impacts of IBTs on downstream environments that may be related to other flow characteristics (e.g., extreme high or low flows) or flow seasonality. The remaining 22 IBTs experienced long-term average streamflow reductions of at least 5% at distances up to 520 km downstream. These 22 IBTs are, on average, about two orders of magnitude larger than the other 206 IBTs in the inventory. They are located in diverse settings across the United States and include 18 transfers in the western US and four in the eastern US. Half of the 22 streams recovered to at least 95% of their natural streamflow within157 km of the withdrawal. For five of the IBTs, 95% natural flow recovery did not occur before streams reached their Atlantic or Pacific outlet. For streams in which flow recovered before reaching the ocean, we found a weak correlation between recovery distance and the fraction of natural streamflow removed by IBTs (Spearman $\rho = 0.48$, $P = 0.052$) suggesting that downstream flow recovery is not only affected by the relative magnitude of an IBT, but by other factors as well, including the geographic location of the IBT and its position within the topological drainage network.

We used WaSSI to simulate flows downstream of a hypothetical IBT in the headwaters (basins with approximately 1500 km^2 of upstream contributing area) of the Ohio and Colorado Rivers, two contrasting river systems, under a range of potential transfer magnitudes to understand how an IBT's position within a drainage network affects downstream flow recovery (figures 4(B) and (C)). These transfer magnitudes affected average downstream flows differently in each river system. The Ohio River system recovered its average natural streamflow (defined as 95% recovery) in a relatively short distance downstream of IBT withdrawals of varying magnitudes (figure 4(B)). For example, an IBT comprising 10% of natural flow in the Ohio River headwaters would reduce average flow by at least 5% for approximately 100 km downstream of the headwater basin, whereas an IBT comprising 50% of natural flow would affect downstream flow for approximately 310 km. Conversely, in the Colorado River headwaters, an IBT comprising 10% of natural flow affected downstream flow by at least 5% for approximately 175 km, and an IBT comprising 50% of natural flow affected downstream flow for at least 600 km (figure 4(C)). We also used WaSSI to simulate downstream impacts during the driest year in each basin for which complete datasets were available (1961 to 2012). We selected 1963 for the Ohio River (26% below long-term MAP) and 2002 for the Colorado River (34% below long-term MAP). During drought years, the same hypothetical IBTs produce much different patterns of downstream recovery (figures 4(D) and (E)). In the Ohio River basin, impacts extend from 100 km to over 400 km downstream (figure 4(D)). In the Colorado River basin, severe downstream impacts (<75% natural flow recovery) emerge for smaller IBT magnitudes, and these severe impacts extend much farther downstream (figure 4(E)).

Different recovery distances between the two basins can be explained in part by relatively high precipitation, runoff ratios, and drainage densities in the eastern United States (where the Ohio River is located) compared to the western United States (where the Colorado River is located). Together, basin physical characteristics and hydroclimatological conditions affect the distances over which streamflow recovers for an IBT of a given magnitude. As a result, the Ohio River represents a system whose recovery to 95% of natural flow is relatively resilient across a wide range of IBT magnitudes compared to the Colorado River, whose recovery is much less resilient across the same range of relative IBT magnitudes. Drought years emphasize this point further; downstream impacts along the Ohio River grow modestly during drought (figure 4(D)), whereas downstream impacts along the Colorado River expand severely and nonlinearly during drought (figure 4(E)). Thus, in basins where drought is expected to increase in frequency and intensity in response to climate change, IBT impacts on streamflow may emerge where no impacts existed previously, or their impacts may extend farther downstream.

The flow recovery patterns of these two rivers (figures 4(B) through (E)) may be considered descriptors of the resilience (e.g., Gunderson 2000) of these two systems to IBT-driven water losses during the 1973–1982 period. The downstream rate of recovery represents an alternate metric for assessing the sustainability (Poff *et al* 2003) of a water transfer that

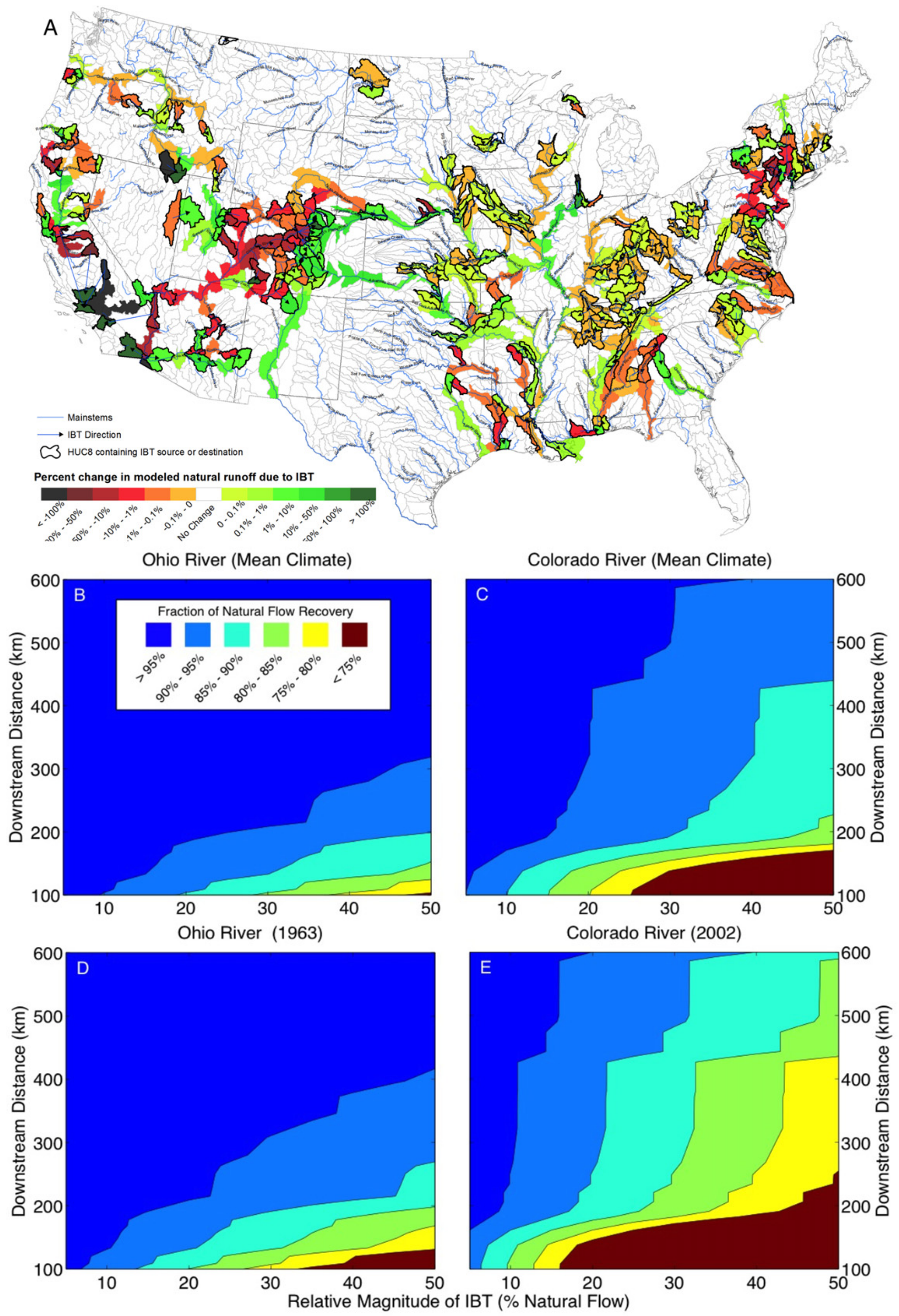

Figure 4. Impacts of interbasin transfers on downstream flows. Net impacts shown for HUC8s within the conterminous United States (A). For two major river systems, the Ohio River (B) and the Colorado River (C), downstream recovery as a fraction of natural streamflow is shown for a range of hypothetical transfers located in the headwaters of each river basin averaged over the years 1973–1982. Downstream recovery is also shown for years of extreme drought, including 1963 for the Ohio River (D) and 2002 for the Colorado River (E).

acknowledges the relationship between transfer magnitude, stream network topology and hydroclimatological conditions. With this in mind, the relatively low resilience of the Colorado River basin coupled with the number of actual IBTs in the basin (figure 4(A)) is noteworthy, given concerns about the sustainability of water supplies in this basin, which provides water to much of the southwestern United States (Rajagopalan *et al* 2009). Given the growing reliance on IBTs to meet human water demands along with increasing uncertainty in water supplies due to changes in climate, human populations and land use, it will become increasingly important to acknowledge that the impacts of IBTs on surface water flows (both individually and in aggregate) may propagate far downstream depending on the basin's hydroclimatological exposure and topological characteristics.

4. Conclusions and recommendations

IBTs are widespread across the US (figure 1). Given the relatively strong correlations between hydroclimatological variables in supplying and receiving basins (figure 2), managers and decision makers should consider that the same hydroclimatological drivers of water shortages in receiving basins may likely curtail water availability in supplying basins. In essence, IBTs are not simply transferring water to receiving basins; they are also transferring hydroclimatological characteristics of the supplying basins and potentially displacing problems associated with climate-related water shortages. Our results (figure 3) demonstrate that IBTs, overall, are not optimized with respect to relative streamflow gains and losses in the participating basins. Rather, location-specific human water needs and engineering constraints that determine characteristics of individual IBTs appear to dominate IBT characteristics at the continental scale. While water demand and engineering constraints will continue to motivate individual IBTs in the future, opportunities exist for planners to consider the broader hydroclimatological characteristics of the supplying and receiving basins when planning future transfer projects.

In aggregate, IBTs influence downstream flows significantly in some locations (figure 4(A)), particularly where climate and river network structure affect the resiliency of downstream flows to transfer losses from supplying basins (figures 4(B) through (E)). Relatively few IBTs in this study impacted average long-term flows downstream of the basin in which the transfer occurred. However, when present, downstream reductions had the potential to persist for long distances depending on interactions between basin network structure and hydroclimate. If, in the future, IBTs are employed as a means of mitigating hydroclimatological stressors associated with climate change (e.g., drought), decision makers need to understand the implications of displacing not only water but also water management problems associated with hydroclimatological conditions and climate change. We recommend new inventories and assessments of IBTs and other water management structures at regional and continental scales as a crucial first step toward clearer understanding of how IBTs and other water management activities are affected by basin characteristics and by climate, how these activities affect downstream flows, and how climate change may alter the effectiveness of IBTs in future water management portfolios.

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