# Quantifying the impacts of Interbasin Transfers on Water Balances in the Conterminous United States

by

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**ABSTRACT**

An estimated 22 billion cubic meters (18 million acre feet) of water were exported through interbasin transfers (IBTs) every year from 1973-1982. Humans depend on IBTs for drinking water, crop production, power generation, and countless industrial processes. As human populations grow and expand around the globe, demand for clean, fresh water will continue to increase, and IBTs will continue to be considered as options for delivering that water to places in need. Increased demand and a changing climate make the future of existing IBTs uncertain, particularly in the Southwest United States where the Colorado River's storage reservoirs are at risk of depletion by the end of the twenty-first century.  Using the USDA Forest Service's Water Supply Stress Index (WaSSI) model, updated USGS hydrologic datasets, and geographic information systems, this paper estimates, maps, and explores the impacts of IBTs on national water balances. Each IBT was classified as hydrologically favorable or unfavorable by comparing the fraction of natural runoff lost from the source sub-basin to the fraction of natural runoff gained in the receiving sub-basin, and downstream impacts on flow were estimated for all sub-basins in the conterminous United States. A quarter of all sub-basins were impacted by IBTs, whether gaining or losing water, and one third of those gained or lost more than one percent of their natural flow.

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# 1. INTRODUCTION

## *1.1 Overview*

An interbasin water transfer (IBT) is a manmade structure or series of structures used to divert water from one river basin to another, so that the water does not return to the source basin. Devices used to divert water include canals, pipes, and tunnels, and the water may move by gravity, siphon, or pump. Water is typically diverted for human consumption, irrigation, power generation, and industrial uses. Many IBTs are surrounded in controversy as the diverted water is not returned to the source basin, which can create water shortages for populations and ecosystems that once relied on that water.

One such example of a controversial IBT is the Lake Gaston Water Transfer, which diverts water from Lake Gaston in NC to Virginia Beach, VA. The IBT was completed in 1998, but the conflict between VA and NC began in the 1970s and continued for at least another decade after construction was completed (Cox, 2007). The transfer was relatively small compared to the source water supply, reducing the Roanoke River's downstream flows by 1% on average, and up to 4% during times of drought. Even this seemingly small transfer created complex issues for the numerous stakeholders, who included multiple cities, states, federal agencies, regional organizations, a power company, and others. Obtaining permits and funding were major obstacles to the project, and stakeholders' concerns included lake and fishing recreation, fisheries management, and water quality on both sides of the transfer. If a relatively small IBT like the Lake Gaston Water Transfer can generate decades of controversy, one might imagine the political, social, economic, and environmental impacts of much larger projects in much dryer regions. This case study of a modern IBT demonstrates the need for further research on IBTs to inform stakeholders and policymakers.

Climate change has implications for IBTs (Gleick, 1989; Reclamation, 2011). There is general consensus among climate models that temperatures will continue to rise throughout the twenty-first century and that the largest increases in the United States will likely occur in the Southwest

(Reclamation, 2011). Models also predict changes in precipitation, and while some northern latitudes may see increases in annual precipitation, decreases in precipitation are predicted for the Southwestern United States. The major river running through the Southwest, the Colorado, is already diverted by more than a dozen IBTs, supporting agricultural operations and major population centers in a region comprising mostly desert. If the Colorado River experiences a twenty percent reduction in flow due to climate change, the risk of depleting the river's entire reservoir storage may reach 50% by 2057 (Rajagopalan, 2009). Total reservoir depletion would be catastrophic for Las Vegas, which receives as much as 90% of its water from Lake Meade, a reservoir on the Colorado River.

The most recent nationwide IBT inventories were completed in 1985 and 1986, when the USGS published two self-described "preliminary" inventories of IBTs in the western and eastern conterminous United States (Petsch, 1985; Mooty and Jeffcoat, 1986). According to the USGS, only IBTs "with the most complete information" were included in the inventories. This information included conveyance name, owner, year placed in operation, state, county, 8-digit Hydrologic Unit Code (HUC8) of the point of origin of the conveyance, HUC8 of the initial delivery point of the conveyance, and the average annual diversion for Water Years 1973-1982.

The USGS has divided the continental United States into 18 water resources regions (WRRs), 205 subregions, and 2099 sub-basins, forming a nested, multi-level representation of the drainage systems of the United States. Each sub-basin within this system is assigned a unique 8-digit HUC8 code, the first four digits of which describe the WRR and subregion. In the western United States inventory, the USGS reported that approximately 50% of IBTs export to a different USGS WRR, with the largest interregional exports originating in the Lower Colorado Region (Region 15; Petsch, 1985). Region 18, comprising mostly California, exported over four million cubic meters annually between subregions, the most of any region. The USGS inventory of the eastern United States found about 28% of IBTs exporting to different regions, with the largest interregional exports originating in the Great Lakes Region (Region

04; Mooty and Jeffcoat, 1986). The eastern inventory also found that only 7 IBTs account for 93% of exports between eastern subregions.

The formation of the Bureau of Reclamation in 1903 led to a dramatic increase in the number and size of water transfer projects through much of the 20th century, particularly in the west. Although many newspaper and journal articles have been written about individual IBTs, only six scientific journal articles were found to reference these two particular inventories. This project integrates the two USGS inventories into a single geospatial database, and it uses the database in combination with climate data and hydrological modeling to evaluate and compare IBT impacts on water balances across the United States and to assess the net impacts of IBTs on streamflow in the conterminous United States.

### *1.2 Objectives and Approach*

This project is intended to assess the relative impacts of IBTs on the water balances of all affected watersheds and determine the downstream impacts on natural flows using the only available nation-wide dataset. The 1985 and 1986 inventory data were used to model and assess the relative impacts of IBTs on HUC8 water balances. The USDA Forest Service's Water Supply Stress Index model (WaSSI) was used to model runoff at the HUC8 scale, with and without IBTs (Caldwell et al, 2012). Model results were mapped to illustrate the overall impacts of IBTs in the US. Each IBT was then categorized as either favorable or unfavorable in terms of the water balance between the source and receiving HUC8. In simple terms, and for the purposes of this study, a favorable IBT diverted water from a wetter area to a dryer area, while an unfavorable IBT did the opposite. The favorability of an IBT was determined by comparing the proportion of runoff gained in the receiving HUC8 to the proportion of runoff lost in the source HUC8. Watershed area and precipitation were analyzed for the source and receiving ends of each IBT to see if either or both may influence IBT favorability. Finally, coarse estimates of impacted stream lengths were used to assess the downstream impact of IBTs.

## 2. METHODS

### *2.1 Geospatial Database*

**2.1.1 Compiling data.** Several layers of data were required to perform the analyses in this report. Paper printouts of the 1985 and 1986 IBT inventories were scanned and converted to searchable tables. Unique alpha-numeric identifiers were assigned to each IBT in the form of "xxxE" for eastern IBTs and "xxxW" for western IBTs. Transfer volume units were converted from acre-feet to millions of cubic meters ($m^3\,yr^{-1}x10^6$). The USGS Watershed Boundary Dataset (WBD) provided HUC8 polygon features. Stream network line segments were provided by the USGS National Hydrography Dataset (NHD), while NHDPlus (Horizon Systems, 2012) added a cumulative drainage area attribute to each stream segment. All analyses were performed using ArcMap 10.0 (ESRI Inc., Redlands, CA), Python 2.6.5 (Python Software Foundation, Wolfeboro Falls, NH), MatLab R2011a (Mathworks Inc., Natick, MA), and Excel2007 (Microsoft Inc., Redmond, WA).

The inventories listed 256 unique IBTs in the conterminous US, although 23 of those were missing annual diversion data, and were excluded from analysis in this project. The remaining 233 IBTs transferred water from 149 unique HUC8s to 152 unique HUC8s. The disparity in the number of source and receiving HUC8s can be explained by individual HUC8s containing multiple IBTs. Indeed, 110 of all IBT-containing HUC8s contain two or more IBTs, with one HUC8 in Colorado (11020001) receiving water from eight IBTs and exporting water through one HUC8, for a total of nine IBTs in one HUC8.

**2.1.2 Fitting IBTs to newer WBD HUC8 map***.* The USGS hydrologic units used to identify the boundaries of HUC8 sub-basins have changed since the Eastern and Western IBT inventories were published in the 1980s (Berelson, 2004). The older HUC8s were based on 1:250,000 topographic maps while the newer WBD HUC8s are based on 1:24,000 topographic maps. This update resulted in minor changes to most HUC8 boundaries and major changes to a few. Some were changed completely and given new 8-digit codes. It was necessary to update the inventoried IBTs to the newer WBD because the WaSSI model uses the newer HUC8s. Each HUC8 containing an IBT was visually inspected for significant differences between the two HUC8 datasets. When a difference was detected, and where possible, GoogleEarth and USGS coordinates were used to help determine which HUC8 contained the starting and ending point of the IBT in question (USGS, 1981). Only three of the 233 IBTs included in this analysis were updated to reflect changes in the WBD, and all were located in California.

***2.2 HUC8 routing***

In order to quantify the downstream impacts of IBTs at the HUC8 scale, it was necessary to determine flow routing between HUC8s. The USGS has delineated medium- and high-resolution networks of connected stream segments from 1:100,000 and 1:24,000 scale topographic maps. These are known collectively as the National Hydrology Dataset (NHD). In 2006, Horizon Systems Corporation (Herndon, VA) released an enhanced set of NHD data known as NHDPlus, which provides additional stream attributes designed to improve stream network routing. Watersheds, basins and sub-basins (i.e. HUC8s) are delineated by the USGS WBD.

The WBD contains no information on flow routing (connectivity or direction) between HUC8s. In order to investigate hydrologic impacts on downstream basins, a routing matrix of all connected HUC8s was created using NHD stream segments from NHDPlus with HUC8 spatial data from the WBD. Medium resolution NHD stream segments were used to determine how HUC8s were connected. First, all stream segments were overlaid on the WBD HUC8 polygons. This resulted in roughly three million stream segments overlapping 2099 HUC8s. For the purpose of HUC8 routing, only stream segments that crossed the border of a HUC8 were examined. By definition, each HUC8 should only have a single exiting stream segment, but this is not the case when combining the NHD and WBD datasets. After all border-crossing segments were extracted, only those segments with the highest cumulative drainage in each HUC8 were kept. Each of these segments was the sole exit point of the upstream HUC, and each was separated into a from-node and a to-node. The HUC8 containing the from-node became the "from" HUC8 while the to-node resided in the "to" HUC8. The results of this analysis were saved in a two-column table of from- and to-HUC8s. A multi-column HUC8 routing matrix was made from this table using Excel's Vertical Lookup function.

The multi-column routing matrix was then converted back to a two-column table, but this time with every possible combination of connected HUC8s. This resulted in 18,777 pairs of HUC8s that were hydrologically connected, whether adjacent or on opposite ends of a river network. Each HUC8 in the left column was located upstream of its paired HUC8 in the right column. This table was joined to a HUC8 spatial layer using ArcMap GIS software and Python programming language, allowing for quick selection and analysis of all upstream or downstream HUC8s from any given HUC8. These GIS tools were used to calculate historic precipitation averages as well as convert IBT diversion amounts to runoff equivalents in millimeters. The USDA Forest Service updated its WaSSI model using the same routing matrix described above.

Figures 2 and 3 demonstrate the capabilities of the downstream and upstream HUC8 selection tools when used with ArcMap. In Figure 2, the user entered "10080003" as input for the downstream HUC8 selection tool. The tool then selected all HUC8s downstream from 10080003 and a new layer was created of just the selected HUC8s. In Figure 3, the upstream HUC8 selection tool was run twice, once for the upper Colorado River Basin by using "14070006" as the input HUC8, and once for the lower Colorado River Basin using "15030107" as input. The individual HUC8 boundaries were removed from the final display to highlight the larger river basins.

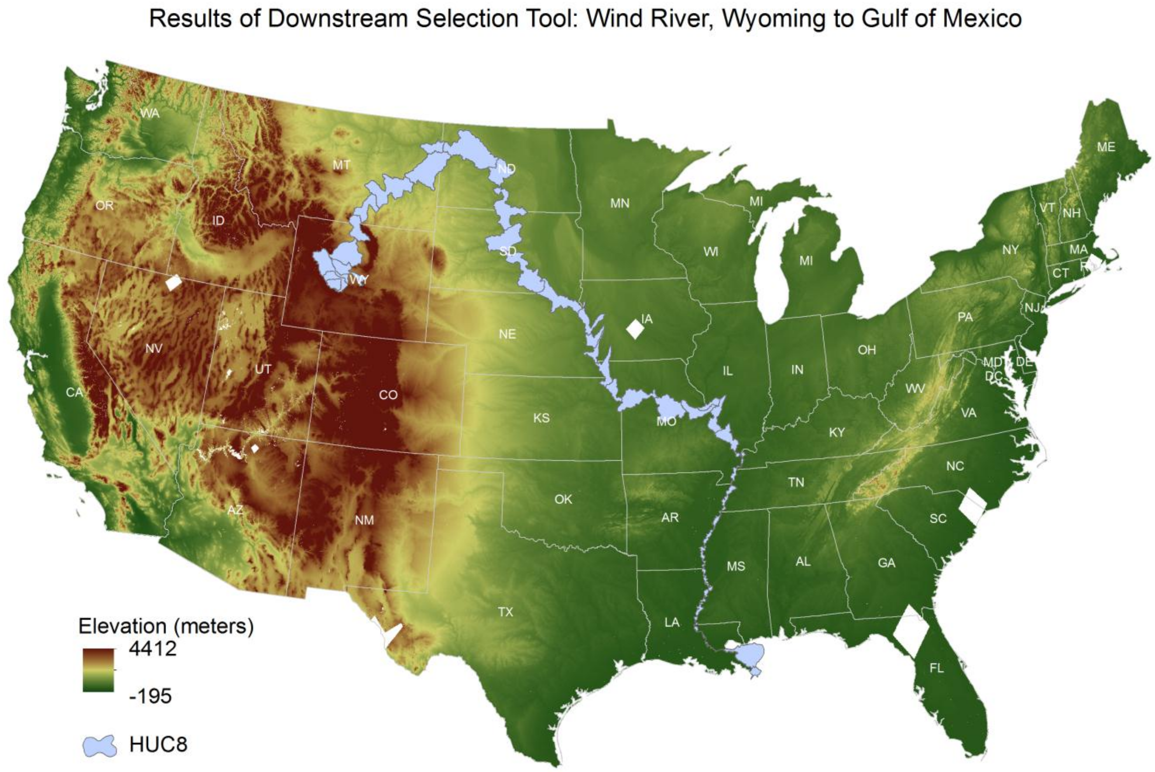


*Figure 2:* Results of Downstream Selection Tool using HUC8 "10080003" as input. Flow path stretches from Wyoming to Gulf of Mexico via 33 HUC8s, with elevations ranging from 4,200 meters to sea level.

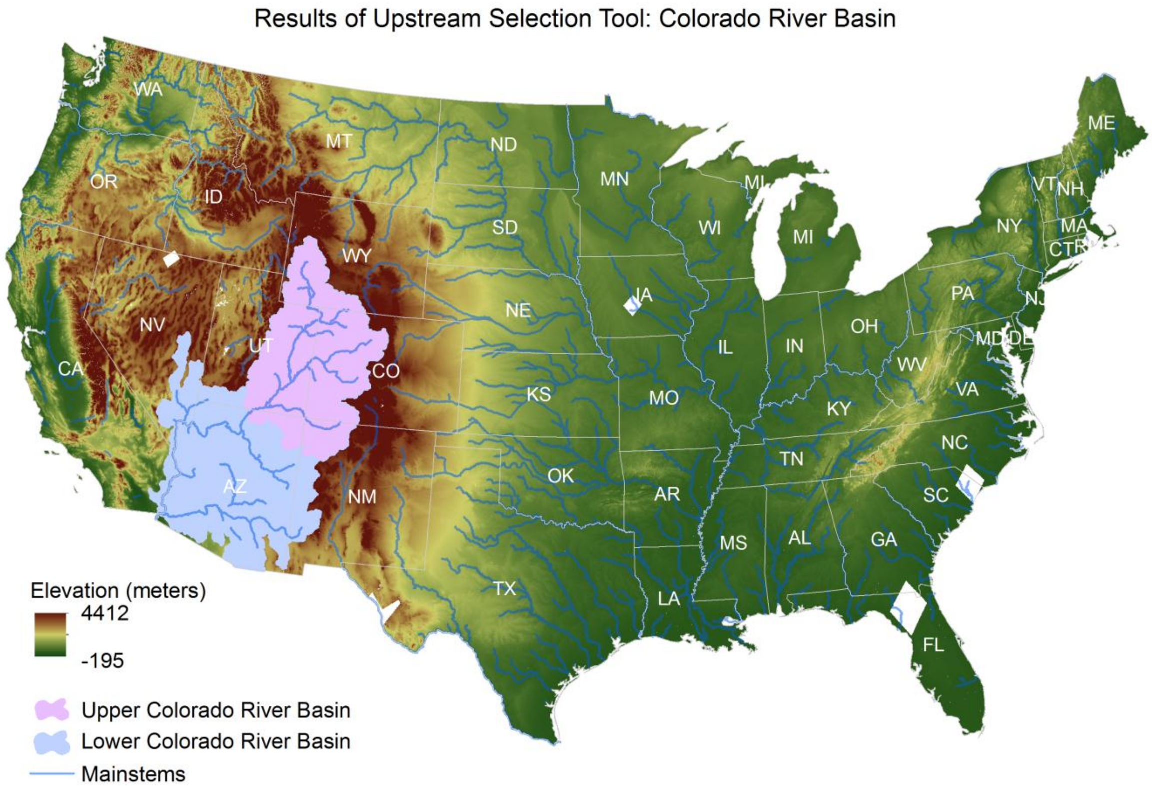


*Figure 3:* Results of Upstream Selection Tool using Colorado River HUC8 "15030107" as input for lower basin, and HUC8 "14070006" as input for upper basin.

***2.3 Assessing relative IBT impacts on watershed water balances***

**2.3.1 Comparing IBTs to modeled natural runoff.** The USDA Forest Service's WaSSI hydrologic modeling tool can be used to model HUC8 water balances under different natural and anthropogenic conditions (Caldwell et al, 2012). The WaSSI model estimates runoff generated in each HUC8 at a monthly time step. By default, WaSSI assumes natural surface water flows and ignores any anthropogenic alterations to the routing of runoff. However, users may modify WaSSI inputs or structure to consider climate change influences, land use changes, or in the case of our study, adjusted flows due to IBTs. This capability makes it an ideal tool for modeling human impacts on regional and national water balances.

For this project, the WaSSI model was used to look at the net impacts of all IBTs on all HUC8s as well as the impacts of individual IBTs on just their source and receiving HUC8s. 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 1973-1982. The model was run again for the same time period with adjusted flows due to IBTs. The two model scenarios, one with and one without IBTs, were used to determine the percentage of flow diverted by IBTs for every HUC8 containing an IBT including the fraction of flow diverted in every HUC8 located downstream from an IBT. The model results assume 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 233 additional iterations, once for each IBT. The fraction of modeled natural flow diverted by each individual IBT (β) was calculated as follows: $\beta = Flow_{IBT} / Flow_{WaSSI}$, where $Flow_{IBT}$ is the average annual IBT magnitude (1973-1982), and $Flow_{WaSSI}$ is the average annual discharge (1973-1982) at the outlet of the HUC8 containing the IBT, assuming the IBT did not exist.

To compare each IBT to precipitation (P) in the watershed upstream of where the transfer occurs, each IBT was converted to runoff equivalent in millimeters (mm) by dividing the IBT magnitude by the entire upstream drainage area (A). The routing tool described above was used to determine the upstream watershed area for each HUC8. Areal-averaged precipitation for each watershed upstream of an IBT was calculated using data from the Parameter-Elevation Regressions on Independent Slopes Model (PRISM) (PRISM Climate Group, 2004). Average annual precipitation was calculated for the entire drainage area of each IBT HUC8 for the same years reported in the IBT inventory, 1973-1982. Fraction of precipitation diverted by each IBT (α) was calculated for source and receiving HUC8s as follows: $\alpha = R_{IBT} / P$, where $R_{IBT}$ is the IBT converted to runoff units by dividing by watershed area.

**2.3.2 Classifying IBTs as hydrologically favorable or unfavorable**. A primary aim of this project was to identify imbalances among IBTs by comparing the gains in the recipient HUC8 to the losses in the source HUC8. In assessing IBT impacts on HUC8 water balances, it was determined that IBTs could be described as hydrologically favorable or unfavorable based on proportional losses and gains in source and receiving HUC8s. Hydrologic favorability was defined as follows: Each source watershed in a favorable IBT diverted a small fraction of its runoff relative to the fraction of runoff supplied to the recipient watershed, whereas the opposite was true for unfavorable IBTs. A favorable IBT has proportional gains in runoff in its receiving HUC8 that exceed the proportional losses in runoff from its source HUC8 ($\beta_R > \beta_S$), whereas an unfavorable IBT has the opposite ratio ($\beta_R < \beta_S$). There were no IBTs in which $\beta_R = \beta_S$.

The favorability of an IBT might be related to area or precipitation disparities between the two watersheds connected by the IBT. It was expected that diverting water from a small watershed to a much larger watershed would result in an unfavorable transfer, as would diverting water from a watershed with less average precipitation than the recipient watershed. To test these hypotheses, area, precipitation, and fraction of precipitation diverted by each IBT ($\alpha$) were compared for favorable and unfavorable IBTs.

### *2.4 Estimating impacts of IBTs on downstream flow conditions*

In addition to identifying the watershed 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. It was not possible to identify a mainstem for every HUC8 due to gaps in the NHD stream segment data, particularly in the Great Basin of the western United States. Headwater HUC8s were devoid of mainstems as well. Whereas each HUC8 had a single outlet, it was possible that multiple HUC8s upstream were contributing water, forming multiple inlets. Connecting these inlets to outlets often resulted in branching mainstems, creating multiple mainstems in many HUC8s.

Mainstem lengths were determined by connecting NHD stream segments from the outlet to the inlet for each HUC8 (Caldwell, 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. For example, if a HUC8 was losing 10% of its natural flow to an IBT upstream, it was determined that the average length of all the mainstems (if more than one) in that HUC8 was losing 10% of its natural flow for the purpose of this project. 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.

## 3. RESULTS

### *3.1 Geodatabase and HUC8 routing*

The geodatabase is included with the supplemental materials for this report. It contains HUC8 polygons, mainstem lines, and all IBT statistics used to create the maps and figures in this report. Also in the supplemental materials are python scripts and tools for ArcMap used for selecting upstream and downstream HUC8s and for calculating upstream areas for any HUC8.

### *3.2 Overview of IBT magnitudes*

Of the 256 unique IBTs described in the 1985 and 1986 inventories, 233 had annual water transfer data associated with them. The median magnitude of these IBTs was 1.31 million cubic meters per year ($m^3yr^{-1}x10^6$) whereas the mean was 97.67 $m^3yr^{-1}x10^6$ (Table 1). The annual transfer volume of all inventoried IBTs was 22,757 $m^3yr^{-1}x10^6$, or 1.3% of the total annual water supply of the Conterminous US, 1953-1994 (Brown, 2008).

Of the 233 IBTs with available annual flow data, four were excluded from area- and precipitation-based analyses because they transferred water into Mexico, where HUC8 data were lacking. A fifth IBT, St. Mary Canal in Montana, was excluded because both source and recipient HUC8s were divided by the US-Canada border, again limiting the data available on the non-US side. This left 228 IBTs originating in 145 unique source HUC8s, transferring water to 150 unique recipient HUC8s. There are two HUC8s associated with each IBT: the source HUC8 and the recipient HUC8. There were 51 HUC8s with more than one IBT originating in them, and 45 HUC8s receiving water from multiple IBTs. There were 37 pairs of HUC8s that were directly connected by more than one, and as many as 5, separate IBTs.

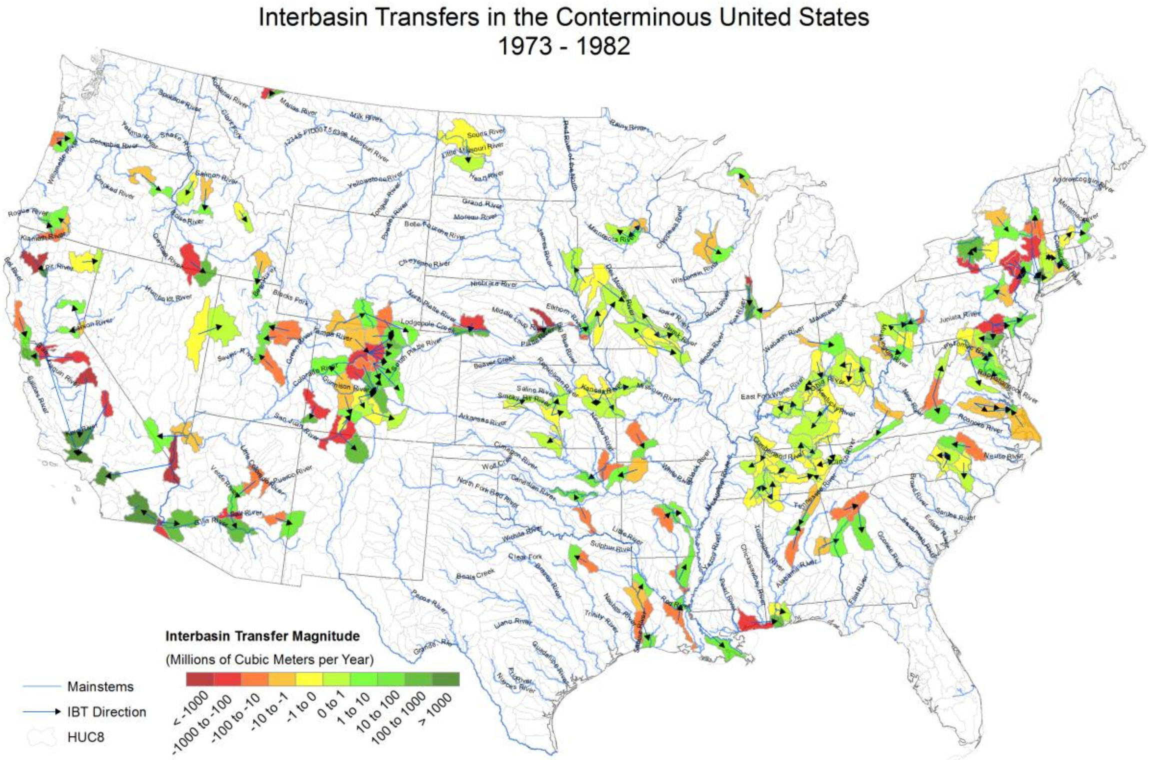


*Figure 1:* Locations and magnitudes of IBTs used for this project.

Table 1: Variable Definitions and Descriptive Statistics

| Variable | Description | N | Median | Mean | Geometric Mean |
|---|---|---|---|---|---|
| IBT Magnitude | Average annual water volume transferred by each IBT ($m^3yr^{-1}x10^6$), 1973-1982 | 233 | 1.31 | 97.67 | 1.715 |
| $A_S$ | Area of source watershed ($km^2$) | 228 | 7,634 | 102,411 | 12310 |
| $A_R$ | Area of receiving watershed ($km^2$) | 228 | 6,342 | 40,414 | 8863 |
| $Precip_S$ | Average annual precipitation in Source watershed (mm) | 228 | 1,006 | 937 | 850 |
| $Precip_R$ | Average annual precipitation in Receiving watershed (mm) | 228 | 983 | 931 | 835 |
| $\alpha_S$ | Fraction of precipitation diverted by IBT from source watershed (mm/mm) | 228 | $2.00x10^{-4}$ | $2.28x10^{-2}$ | $1.50x10^{-4}$ |
| $\alpha_R$ | Fraction of precipitation delivered by IBT to receiving watershed | 228 | $2.68x10^{-4}$ | $2.47x10^{-2}$ | $2.12x10^{-4}$ |

Table 1 Cont.

| | | | | | |
|---|---|---|---|---|---|
| | (mm/mm) | | | | |
| $\beta_S$ | Fraction of modeled natural runoff diverted by IBT from source HUC8 ($m^3yr^{-1}x10^6$/ $m^3yr^{-1}x10^6$) | 228 | $5.23x10^{-4}$ | $7.16x10^{-2}$ | $4.46x10^{-4}$ |
| $\beta_R$ | Fraction of modeled natural runoff delivered by IBT to receiving HUC8 ($m^3yr^{-1}x10^6$/ $m^3yr^{-1}x10^6$) | 228 | $6.94x10^{-4}$ | 0.7808 | $6.75x10^{-4}$ |
| Area Ratio | $A_R : A_S$ | 228 | 0.7501 | 5.6104 | 0.7200 |
| Precip Ratio | $Precip_R : Precip_S$ | 228 | 0.9878 | 1.0174 | 0.9824 |
| α Ratio | $\alpha_R : \alpha_S$ | 228 | 1.2391 | 10.9174 | 1.4139 |
| β Ratio | $\beta_R : \beta_S$ | 228 | 1.3840 | 18.1287 | 1.5157 |
| Favorable β Ratios | β Ratio of favorable IBTs | 135 | 3.3349 | 30.3584 | 5.3374 |
| Unfavorable β Ratios | β Ratios of unfavorable IBTs | 93 | 0.3262 | 0.3759 | 0.2438 |
| Favorable Area Ratios | Area Ratios of favorable IBTs | 135 | 0.3156 | 0.4936 | 0.2139 |
| Unfavorable Area Ratios | Area Ratios of unfavorable IBTs | 93 | 3.1518 | 13.0382 | 4.1915 |
| Favorable Precip Ratios | Precip Ratios of favorable IBTs | 135 | 1.0154 | 1.0544 | 1.0090 |
| Unfavorable Precip Ratios | Precip Ratios of unfavorable IBTs | 93 | 0.9599 | 0.9637 | 0.9450 |
| Favorable α Ratios | α Ratios of favorable IBTs | 135 | 3.2343 | 18.1391 | 4.6328 |
| Unfavorable α Ratios | α Ratios of unfavorable IBTs | 93 | 0.3339 | 0.4343 | 0.2525 |

The difference between the mean and median IBT magnitude suggests the majority of transfers were relatively small, and a few large transfer projects explain the comparatively large mean (Figure 4). The All American Canal in Southeastern California transferred the most water during the study period, averaging 4,155 $m^3\,yr^{-1}x10^6$. Six other IBTs exceeded 1,000 $m^3\,yr^{-1}x10^6$, and 27 exceeded 100 $m^3\,yr^{-1}x10^6$. For reference the average annual flow of the Eno River near Durham, NC is 111 $m^3\,yr^{-1}x10^6$, the Neuse River near Falls, NC is 539 $m^3\,yr^{-1}x10^6$, and the Colorado River below Laguna Dam near the Arizona-California border is 1,486 $m^3\,yr^{-1}x10^6$ (Figure 4).

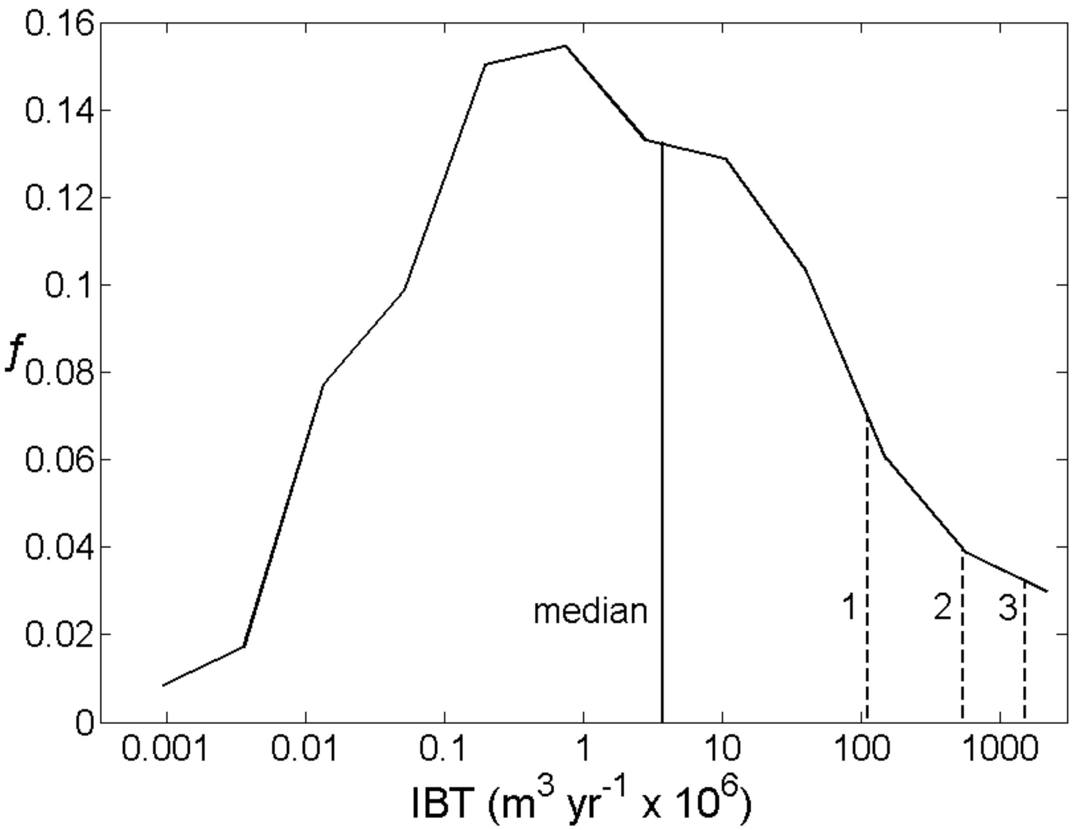


*Figure 4*: Frequency distribution (*f*) of interbasin transfer (IBT) magnitudes in the conterminous United States, 1973-1982. Median IBT=1.31 $m^3\,yr^{-1}x10^6$. Mean transfer is 97.67 $m^3\,yr^{-1}x10^6$. Total volume of water transferred annually from 1973-1982 was 22,757 $m^3\,yr^{-1}x10^6$. The average annual discharges for 3 rivers are included for comparison: Eno River near Durham, NC (1), Neuse River near Falls, NC (2), and Colorado River below Laguna Dam (3) (river discharge data provided by USGS gages 02085070, 02087183, and 09429600, respectively).

***3.3 Relationship between area, precipitation, and IBT magnitude***

The median proportional reduction in natural flow from source HUC8s was $5.23x10^{-4}$ $m^3\,yr^{-1}x10^6$ whereas the median proportional increase in flow in receiving HUC8s was $6.94x10^{-4}$ $m^3\,yr^{-1}x10^6$. Median area and precipitation in watersheds of source HUC8s were greater than those of recipient HUC8s (Table 1). Wilcoxon Rank Sum tests suggested the differences in precipitation were not statistically significant whereas area differences were significant (Table 2). Differences in area, precipitation, and fraction of precipitation were all statistically significant (Wilcoxon Rank Sum P-values of <0.001, 0.007, and <0.001, respectively) when compared between favorable and unfavorable IBTs. The Wilcoxon Rank Sum test did not reveal significant differences between $\beta_S$ and $\beta_R$, however differences were revealed by the scatter plot in Figure 6, which illustrates the imbalance between the source and receiving HUC8 for all IBTs.

Table 2: Statistical test results

| **Samples** | **Wilcoxon Rank Sum P-value** | **KS-test P-value** |
|---|---|---|
| $A_S$ vs. $A_R$ | 0.0472 | 0.0201 |
| $Precip_S$ vs. $Precip_R$ | 0.9702 | 0.2749 |
| $\beta_S$ vs. $\beta_R$ | 0.3234 | 0.3919 |
| $\alpha_S$ vs. $\alpha_R$ | 0.4144 | 0.6928 |
| Favorable Area Ratios vs. Unfavorable Area Ratios | <0.001 | <0.001 |
| Favorable Precip Ratios vs. Unfavorable Precip Ratios | 0.0074 | 0.0012 |
| Favorable α Ratios vs. Unfavorable α Ratios | <0.001 | <0.001 |

### *3.4 Diversion of natural runoff by IBTs*

All 2099 HUC8s in the NHD were analyzed to assess IBT-induced changes to natural runoff as modeled by WaSSI (Figure 5). Over 25% of all HUC8s were impacted, whether by gaining or losing runoff. Losing HUC8 areas totaled 1.07 million $km^2$ whereas gaining HUC8 areas totaled 1.04 million $km^2$. Two-thirds of impacted HUC8s gained or lost less than 1% of their natural flow. Increases of at least 5% were seen in the runoff of 52 HUC8s, whereas decreases of at least 5% were seen in 47 HUC8s. Transfers from the Colorado River were responsible for most of the >5% impacts.

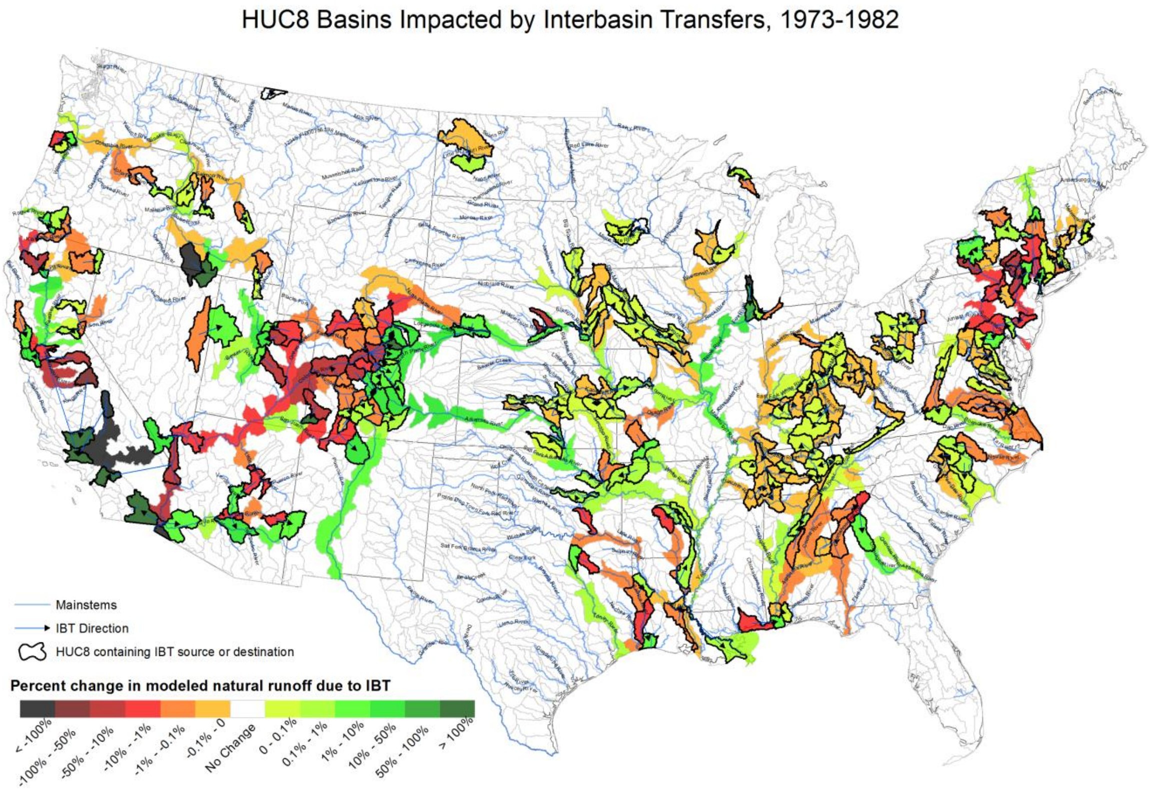


Figure 5: Net downstream impacts of all inventoried IBTs in the conterminous United States, 1973-1982. The combined impacts of all transfers are displayed as percentages of modeled natural runoff that is transferred by all IBTs. The arrows represent the direction of IBT flow between sub-basins.

### *3.5 IBT favorability*

Using $\beta_S$ and $\beta_R$, each IBT was described as favorable or unfavorable. Favorable IBTs supply a proportionally larger fraction of receiving HUC8 runoff ($\beta_R$) than the fraction of source HUC8 runoff that is diverted ($\beta_S$). Of the 228 IBTs considered in this project, 135 (approximately 60%) were characterized as favorable ($\beta_R>\beta_S$), and 93 as unfavorable ($\beta_R<\beta_S$) (Figure 6). Whereas the median $\beta_R$ and $\beta_S$ values were not significantly different (Table 2), Figure 6 shows considerable variation in β between source and receiving HUC8s.

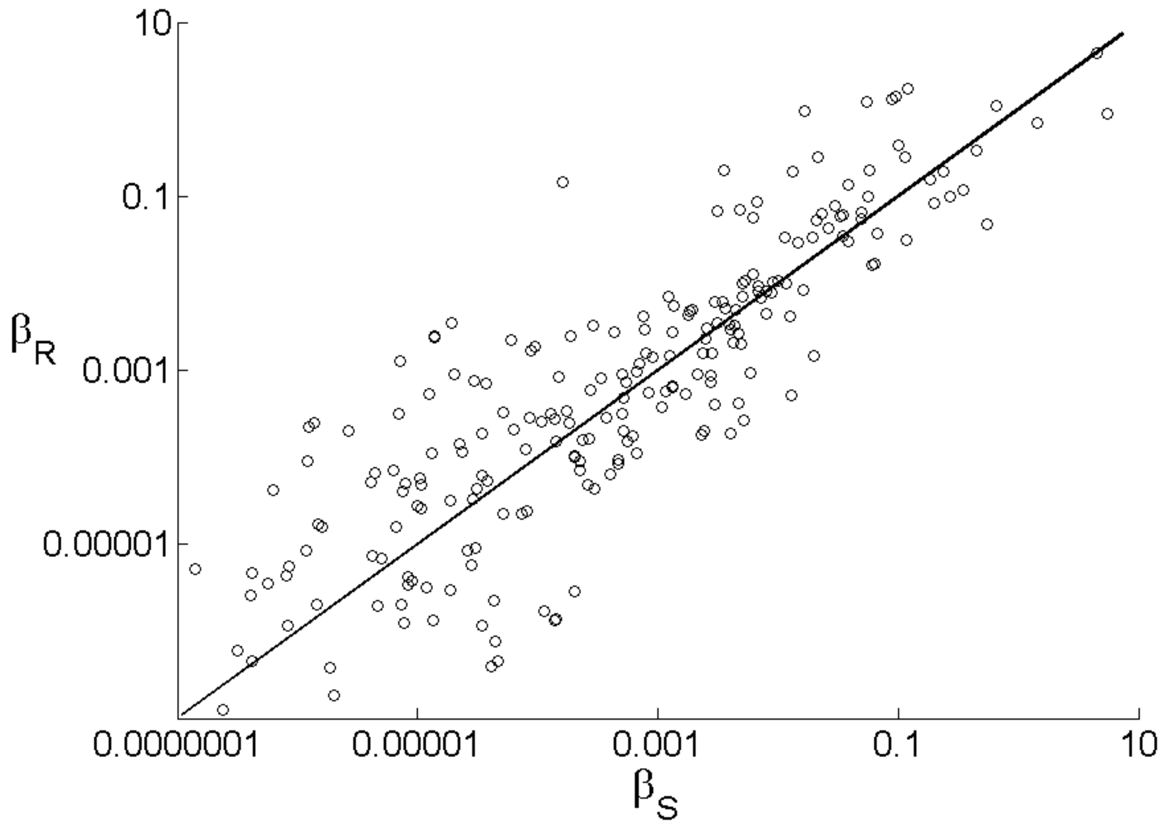


Figure 6: IBT as a fraction of natural runoff added to receiving HUC8s versus IBT as a fraction of natural runoff diverted from source HUC8s. Each circle represents a single IBT and shows that most IBTs are imbalanced (i.e. $\beta_R$<>$\beta_R$). IBTs above the 1:1 line are considered favorable because the IBT represents a larger fraction of runoff in the receiving HUC8 than in the source HUC8s. IBTs below the 1:1 line are considered unfavorable because their source HUC8s are losing proportionally more water than their receiving HUC8s are gaining.

### *3.6 Influence of area and precipitation on IBT favorability*

Watershed area and precipitation were evaluated separately as contributors to imbalances between an IBT's source and receiving watershed. Not surprisingly, it was found that the source watershed of a favorable IBT was likely to have a larger area and more precipitation than the receiving watershed. The median ratio of receiving to source watershed areas was 0.32 for favorable IBTs and 3.15 for unfavorable IBTs. The difference in this ratio between favorable and unfavorable IBTs was significant (Wilcoxon rank sum p-value <0.001, Table 2), indicating favorable IBTs tended to have proportionally larger source watershed areas than unfavorable IBTs (Figure 7).

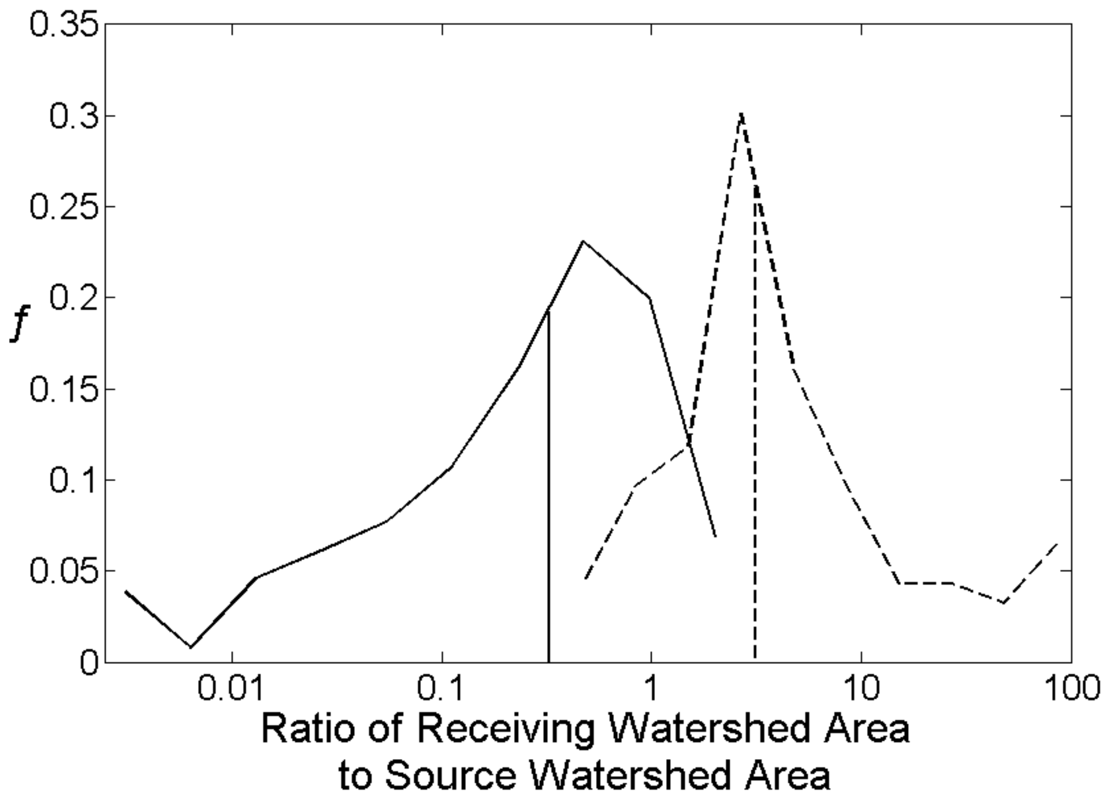


Figure 7: Frequency distribution (*f*) of ratios of receiving IBT watershed area to source IBT watershed area for IBTs considered to be favorable (solid line, median 0.316) and IBTs considered to be unfavorable (dashed line, median 3.15). The significant difference in median values (Wilcoxon rank sum p-value < 0.001) indicates favorable IBTs had

larger source watershed areas relative to receiving watershed areas than did unfavorable IBTs.

For precipitation, the median of $\alpha_R$:$\alpha_S$ was 3.23 for favorable IBTs and 0.33 for unfavorable IBTs (Wilcoxon rank sum p-value <0.0001, Table 2). This significant difference indicates that favorable IBTs tended to transfer a fraction of precipitation from the source watershed that was small relative to the fraction of precipitation that the IBT represented in the receiving watershed. Unfavorable IBTs tended to transfer a fraction of precipitation from the source watershed that was large relative to the fraction of precipitation that the IBT represented in the receiving watershed (Figure 8).

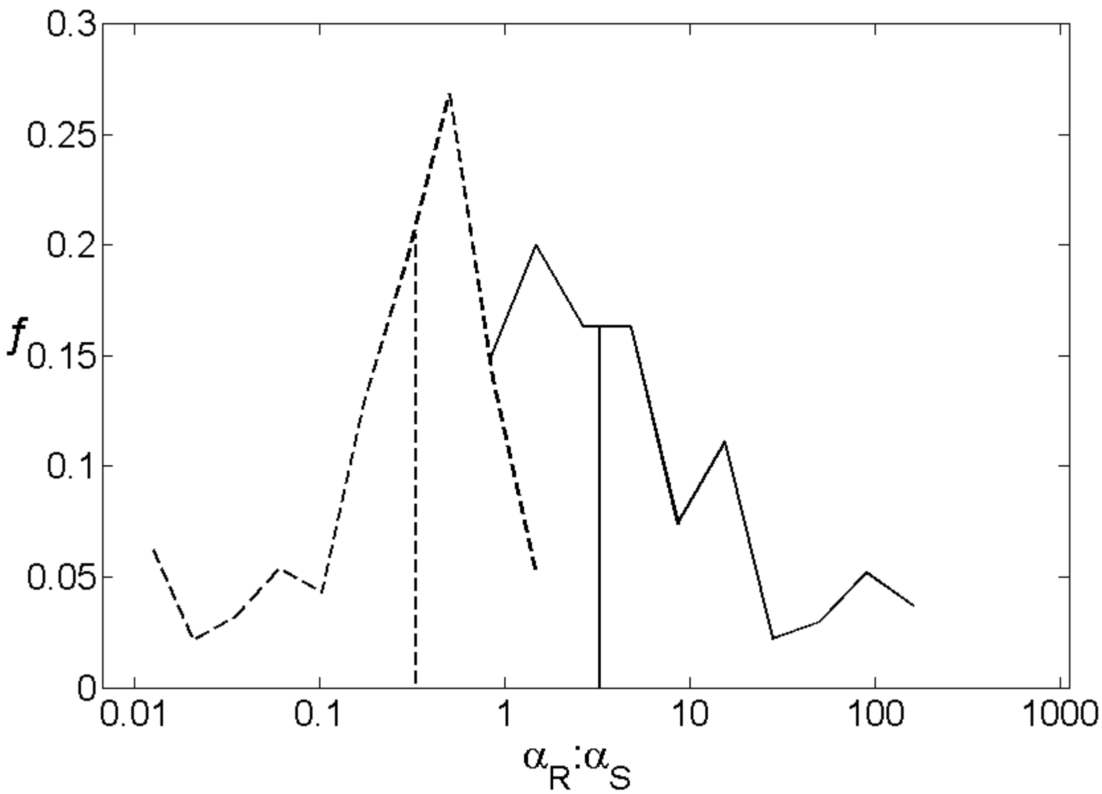


Figure 8: Frequency distribution (*f*) of $\alpha_R$:$\alpha_S$ for favorable (solid line) and unfavorable (dashed line) IBTs. Median α for favorable IBTs is 3.23 while unfavorable IBTs have a median α of 0.334. The significant difference in median values (Wilcoxon rank sum p-

value < 0.001) indicates that favorable (unfavorable) IBTs tend to transfer a small (large) fraction of precipitation away from the source watershed relative to the fraction of precipitation that the IBT represented in the receiving watershed.

### *3.7 Downstream flow impacts*

Finally, a table of downstream impacts on runoff was created (Table 3). The source and receiving HUC8s of IBTs were excluded from downstream distance calculations. Nearly 2,000 km of stream reaches gained more than 5% of their natural flow during the study period due to IBT contributions, and 270 km of stream reaches gained more than 20%. On the source, or losing, side of all IBTs, 1648 km of stream reaches experienced natural flow reductions of at least 5% due to IBT losses, 189 km were reduced by more than 20%, and 92 km were left with less than 5% of their natural flow. Approximately 233 km of the South Platte River and 37 km of the Illinois River received more than 20% of their natural flow during the 10-year study period, whereas nearly 100 km of the San Joaquin River had a 20% deficit due to IBTs.

Table 3: Distance flow is impacted downstream from IBTs on both source and receiving sides.

| **Percent gained or lost** | **Downstream Gaining (km)** | **Downstream Losing (km)** |
|---|---|---|
| >5% | 1999 | 1648 |
| >10% | 1128 | 737 |
| >15% | 519 | 232 |
| >20% | 270 | 189 |
| >25% | N/A | 92 (unnamed stream in the Great Basin) |
| … | N/A | … |
| >95% | N/A | 92 (unnamed stream in the Great Basin) |

**4. DISCUSSION AND CONCLUSIONS**

This report is an overview of where IBTs occur, how they generate imbalances in the water balances of source and receiving watersheds, and how these imbalances combine and propagate downstream to affect flow. Most IBTs were classified as favorable, diverting small fractions of natural flow from source HUC8s to provide recipient HUC8s with comparatively larger fractions of natural flow. This result is expected, and could be due to the fact that water managers plan IBTs in a way that minimizes stress on the source watershed, or it may simply be that humans living in dry areas are more likely to find water to divert in areas with more runoff. Approximately 40% of IBTs were classified as unfavorable, suggesting it is not always possible or preferable to minimize stress on the source watershed. The construction of an unfavorable IBT might be explained by excessive human demand, limited water resources nearby, or poor planning. It was also found that the source watersheds of favorable IBTs were approximately three times larger than their receiving watersheds. This area disparity, though possibly larger than expected, makes sense considering larger areas can capture more precipitation, thus improving an IBTs chances of being favorable. Favorable or not, IBTs are controversial features of the American landscape that require extensive study to fully understand their impacts.

The results of this project may have implications for downstream aquatic ecosystems and human activities, on both the losing and gaining sides of IBTs. Figure 6 illustrates the compounding effects multiple IBTs can have on a single downstream river or sub-basin. This compounding effect can be seen in the lower Colorado River (Figure 6), where already reduced flows are diverted by even more IBTs before the river flows into Mexico at a fraction of its pre-IBT flow. A slightly different form of this compounding effect can be seen east of the upper Colorado River, where more than a dozen IBTs divert water towards the Mississippi River. These IBTs increase flows in the Platte and Arkansas Rivers, which then converge with other IBTs hundreds of kilometers downstream, again compounding the impacts of multiple IBTs (Figure 6).

Potential uses of this report and the methods developed to perform these analyses include identifying stream reaches that may be at risk of having water quantity and quality issues associated with IBTs. For example, the Arkansas and Platte Rivers appear to have excess flows for hundreds of kilometers due to IBTs diverting water east from the Colorado River. Researchers might look at the possible ecological effects of sustained water surpluses in these two rivers. The report and the routing tools could also be used to predict impacts of hypothetical or proposed IBTs, or they may help water managers hoping to reduce impacts of existing water projects.

This report provides tools and lays out methods that other researchers may use to expand these preliminary findings. Land uses, such as forest and crop cover, can be compared in source and receiving basins to help better understand the imbalances identified by this paper. Flow parameters obtained from stream gages may be used to validate or improve the accuracy of the downstream impacts on surface flows. Each IBT also presents opportunities for water quality research downstream of both source and receiving HUC8s. A researcher could use the maps, mapping tools, and results of this report to hone in on a particular IBT and more closely examine specific impacts on aquatic ecosystems and flow-species relationships.

One limitation of this project was its failure to consider consumptive uses, such as irrigation, of some IBTs. All modeled IBT impacts assume water was taken directly from the surface runoff at the outlet of one HUC8 and delivered directly to the outlet of another HUC8. This limitation applies primarily to the receiving end of IBTs. Water use is often described as either consumptive or nonconsumptive, where a consumptive use might include irrigationbut definitions of these two terms can vary by state or region (Chong 2006). The model did not account for evaporation from reservoirs and open canals used for water storage and transport, or evapotranspiration (ET) from croplands if the water is used for irrigation. Groundwater recharge was ignored as well. These are all factors worth exploring further, particularly on an individual IBT basis.

Horizon Systems Corporation is currently updating its NHDPlus dataset and associated tools, calling it NHDPlusV2. The new version uses improved NHD, WBD, and elevation datasets, but is not yet available to the general public (Horizon Systems, 2012). This study and future studies could benefit from the improved data when it is released.

The IBT inventory used in this research is nearly 30 years old. If a current analysis of IBT impacts on national water balances is to be conducted, an updated IBT inventory is needed. The updated inventory should include spatial coordinates of IBTs for improved mapping and modeling accuracy. Additionally, the inventory should indicate the end use of the IBT water, as well as monthly or seasonal conveyance data to account for possible changes in flow throughout the year.

Given the life-limiting value of water, it is not surprising that controversy arises when humans in one region want to take water from humans and wildlife in another region. Even the most "favorable" IBT as described in this report is likely to be unfavorable to multiple stakeholders. Continued IBT research is necessary if the wide range of social, economic, political, and environmental issues associated with them are to be addressed.

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