Report as of FY2006 for 2006TX223B: "Impacts of Texas Interbasin Water Transfers on the Water Dependent Economy and the Environment"

Publications

Project 2006TX223B has resulted in no reported publications as of FY2006.

Report Follows

Project Report

Economic, Hydrologic and Environmental Appraisal of Texas Inter-basin Water Transfers: Model Development and Initial Appraisal

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Table of Contents

1 Introduction

Water scarcity is becoming a pervasive and persistent problem in Texas particularly in the drier regions containing cities like San Antonio, Austin, and Corpus Christi while growth causes emerging problems in Dallas, Fort Worth and Houston. A number of options are being considered including Inter-basin water transfers (IBTs) shifting water from surplus to deficit regions. Potential water transfers can have unforeseen or negative impacts on basin of origin, regional economies, and or on the environment including water quality. The Texas water Code mandates that water transfers should consider economic, environmental and water quality impacts (in section 11.085, (K), (F)) demanding projections of impacts on water quality, aquatic and riparian habitat in all affected basins. While there are 51 proposed Texas Inter-basin water transfers in 2006 Texas Water Plan, there is no comprehensive evaluation of or even evaluation methodology proposed for these transfers.

The water models available in Texas have various limitations that affect their usefulness in evaluating IBT induced economic impacts and water quality changes. Water-related models that deal with hydrologic and environmental issues commonly focus on the quantity issues such as water supply and water flow but do not have economic or water quality dimensions (Wurbs, 2003). Models with economic considerations tend to cover only restricted areas, for example, the Edwards aquifer and Nueces, Frio and Guadalupe-Blanco basin regions (Gillig et al, 2001; Watkins Jr & McKinney, 2000). Much of the research has been localized looking at only single or a couple of basins without looking at broader statewide issues.

This research is designed to build a statewide model integrating economic, hydrologic, and environment components. Such a model will be used to examine Texas water scarcity issues and socially optimal water allocation along with the effects of inter-basin water transfers.

We developed an integrated economic, hydrologic, and environment model covering 21 Texas riverbasins: Colorado, Brazos-Colorado, Brazos, Brazos-San Jacinto, Canadian, Red, Sabine, Guadalupe, San Antonio, Sulphur, Cypress, Neches, Neches-Trinity, Trinity, Trinity-San Jacinto, San Jacinto, Colorado-Lavaca, Lavaca, Lavaca-Guadalupe, San Antonio-Nueces, and Nueces.

The model is designed to yield information to support effective public water policy making for state agencies, water management authorities and regional water planning groups.

The surface water aspects of this project are summarized in this report. Future research work will be focused on combining surface and ground water by integrating the Edwards Aquifer Groundwater and River System Simulation Model (EDSIMR).

2 Modeling framework

Economic theory indicates that water should be allocated to the highest valued users in order to achieve economic efficiency. Maximizing the economic efficiency of water allocation involves maximizing the economic value gained from the use of the allocated water. The value of water is classified into (1) the direct value of water to the water user, and (2) the value that would accrue to producers and consumers that are affected by activity of water users and (3) the future value of water. The value of water and the indirect effects must be considered in the economic analysis of water (Castle, 1968). An inter-basin transfer can involve significant costs to the basin of origin along with the benefits to the receiving basin. One cost can involve the opportunity cost to the basin of origin of potentially reduced future economic growth and prosperity (Keeler, et al, 2002).

While desirable it is difficult to quantify the indirect value, and the future value of water, here the analytical and conceptual model only considers the direct use value of water under a projection of the future adjusted for the construction cost of IBTs.

(1)

$$
\begin{aligned}
&ENB = \\
&\sum_{s} \overline{prob(s)} * \left(\sum_{c} \sum_{t} \sum_{m} \int_{0}^{Qs,c,t,m} \left[P_{s,c,t,m}\left(Q_{s,c,t,m}\right) - MC_{s,c,t,m}\left(Q_{s,c,t,m}\right) \right] d\left(Q_{s,c,t,m}\right) \right) \\
&- \sum_{i} \left(\overline{FC_i} * B_i - \overline{VC_i} * \sum_{s} \left(\overline{prob(s)} * \sum_{t} \sum_{m} TQ_{s,i,t,m} \right) \right)
\end{aligned}
$$

St.

$$Q_{s,c,t,m} = \sum_{d} DQ_{s,c,t,m,d} + \sum_{d}\sum_{i} DTQ_{s,i,c,d,t,m} \tag{2}$$

$$DQ_{s,c,t,m,d} \le \overline{DQ_{c,t,m,d}} \tag{3}$$

$$\begin{aligned} &\sum_{t}\sum_{c}(DQ_{s,c,t,m,d} + \sum_{i} DTQ_{s,i,c,d,t,m}) + FLOWout_{s,d,m} + STOREafter_{s,d,m} + TOBAY_{s,d,m} \\ &\le \overline{INFLOW}_{s,d,m} + RETURN_{s,d,m} + FLOWin_{s,d,m} + STOREbefore_{s,d,m} \end{aligned} \tag{4}$$

$$TQ_{s,i,t,m} = \sum_{c}\sum_{d} DTQ_{s,i,c,d,t,m} \tag{5}$$

$$\sum_{t}\sum_{m} TQ_{s,i,t,m} \le B_i * \overline{capacity_i} \tag{6}$$

$$STOREafter_{s,d,m} \le \overline{STORAGE_d} \text{ and } STOREbefore_{s,d,m} \le \overline{STORAGE_d} \tag{7}$$

$$\sum_{s} \overline{prob(s)} * (\sum_{m}(STOREafter_{s,d,m} - STOREbefore_{s,d,m})) = 0 \tag{8}$$

Where,

s	State of nature
c	City or county
t	Type of user, or sector including municipal, industrial, agricultural, recreational and other water uses, as well as fresh water flowing into bays and estuaries
m	Month
i or j	Inter-basin water transfer project
d	River place where water is withdrawn
ENB	Expected net benefit from water uses
$\overline{prob(s)}$	Probability of a flow state of nature

$P_{s,c,t,m}$	Inverse water demand function in month M as it varies by state of nature, user type and place
$Q_{s,c,t,m}$	Quantity of water used as it also varies by state of nature, type and place
$MC_{s,c,t,m}$	Marginal cost function of supplied water as it varies by state of nature, type and place
FCi	Annualized fixed cost of a proposed inter-basin water transfer project
VCi	Annual operating cost per unit transferred for a proposed water transfer project
$TQ_{s,i,t,m}$	Amount of water transferred from an IBT and used by sector t in month m
B_i	Binary variable indicating whether an IBT in constructed or not
$DQ_{s,c,t,m,d}$	Amount of monthly water withdrawn from a diverter by sector t in place c
$DTQ_{s,i,c,d,t,m}$	Amount of water transferred from a diverter
$\overline{DQ_{c,t,m,d}}$	Maximum amount of water can be withdrawn from a diverter permitted by water authority
$\overline{INFLOW}_{s,d,m}$	Amount of water supplied by the nature at a river place
$FLOWout_{s,d,m}$	Amount of water flow out from the river place to down stream
$FLOWin_{s,d,m}$	Amount of water flow in from upstream river places to this river place

$STOREafter_{s,d,m}$	Amount of water stored at the end of a month in a reservoir
$STOREbefore_{s,d,m}$	Amount of water stored at the beginning of a month in a reservoir
$TOBAY_{s,d,m}$	Amount of water flow to bay or estuary
$RETURN_{s,d,m}$	Amount of water returned to the river place
$\overline{STORAGE_d}$	Maximum storage capacity in a reservoir
$\overline{capacity_i}$	Maximum yield of an IBT

Equation (1) is the objective function and gives the annual expected net benefit accrued from municipal, industrial, agricultural, and recreational usage as well as a minimal value for the fresh water escaping to bays and estuaries less the fixed costs of constructed IBT projects and the variable costs of the water transferred using the constructed IBTs.

The problem includes a number of constraints. Equation (2) is a water supply and demand balance linking the economic component to the hydrological component. The water demand for each city or county for different type of use $Q_{s,c,t,m}$ will be supplied from various diverters in a riverbasin $DQ_{s,c,t,m,d}$ and water transferred from other riverbasins $DTQ_{s,i,c,d,t,m}$. If d is a source diverter, $DTQ_{s,i,c,d,t,m}$ will be negative; if d is a destination diverter, $DTQ_{s,i,c,d,t,m}$ will be positive.

Equation (3) indicates that the water withdraw from a diverter for a particular type of use $DQ_{s,c,t,m,d}$ should not exceed the permitted amount $\overline{DQ_{c,t,m,d}}$. This constraint links the institutional regulation to the water supply.

Equation (4) is the instream flow balance depicting at each river place, total inflow must be in balance with total outflows by state of nature and month. The left side of the equation is the total outflows, equaling to the sum of water diverted by human activities $DQ_{s,c,t,m,d}$, water transferred in $DTQ_{s,i,c,d,t,m}$, and water flow to down stream $FLOWout_{s,d,m}$. If d is a source diverter for an

IBT, $DTQ_{s,i,c,d,t,m}$ will be negative; otherwise, $DTQ_{s,i,c,d,t,m}$ will be positive. If d is a reservoir or end river place in a riverbasin, then total inflows should also include reservoir storage at the end of the month $STOREafter_{s,d,m}$ and outflows would include retention for storage. If d is last river place on a riverbasin, outflows will include water flow out to bays and estuaries $TOBAY_{s,d,m}$. The right hand side is the total inflows at this river place, equal to the sum of water supplied by the nature $\overline{INFLOW}_{s,d,m}$, water flow from upstream $FLOWin_{s,d,m}$, and return flow $RETURN_{s,d,m}$. Again, if d is a reservoir, then total inflows should include water stored in the reservoir at the beginning of the month after discounting reservoir evaporation loss. Return flows come from upstream diverted water and once we add groundwater from groundwater diversions.

Equation (5) states the amount of water transferred from an IBT will be equal to the sum of the amount of water transferred to various destinations by this IBT.

Equation (6) states that the amount of water transferred from an IBT is restricted by the capacity. B_i is a binary variable indicator. If an IBT is built, B_i=1 and this constraint become working, and fixed cost for its construction incurs and will be considered in the objective function. If an IBT is not built, B_i=0, then no water will be transferred and fixed cost for its construction will not incur and thus not be considered in the objective function.

Equation (7) specifies that water stored at a reservoir in any time and any states of nature are limited by its storage capacity. Therefore, $STOREbefore_{s,d,m}$ and $STOREafter_{s,d,m}$ will not exceed the maximum storage capacity.

Equation (8) is a storage balance constraint for a reservoir. The states of nature-weighted sum of water stored at end of the month will be in balance of weighted sum of water stored at the beginning of the month in a reservoir.

3 Empirical model specification

The empirical TEXRIVERSIM model is a two stage stochastic programming with recourse model implemented using the General Algebraic Modeling System (GAMS). The model maximizes net statewide welfare while simultaneously considering environmental, hydrological, institutional, stochastic climate conditions and annualized IBT fixed and unit variable costs. In doing this, it chooses optimal IBTs and water allocation, instream flows, return flows, reservoir storage, bays and estuary freshwater outflows. It contains 21 riverbasins (see table 1), 46 major municipal water use cities, 25 major industrial water use counties, and all of the agricultural counties. 51 IBTs are introduced in the model: 10 river-to-river IBTs and 41 river-to-user IBTs (see table 20 in appendix).

Table 1: Riverbasins covered in the model

Basin name in GAMS	**Original basin name(s)**
Brazos	Brazos and Brazos-San Jacinto rive basins
Colorado	Colorado riverbasin and Brazos-Colorado
Canadian	Canadian riverbasin
Red	Red riverbasin
Sabine	Sabine riverbasin
Guadsan	Guadalupe-San Antonio riverbasin
Sulphur	Sulphur riverbasin
Cypress	Cypress riverbasin
Neches	Neches riverbasin
NechTrinity	Neches-trinity riverbasin
Trinity	Trinity riverbasin
TrinitySanJac	Trinity-San Jacinto riverbasin
SanJacinto	San Jacinto riverbasin
ColLavaca	Colorado-Lavaca riverbasin
Lavaca	Lavaca riverbasin
LavaGuadl	Lavaca-Guadalupe riverbasin
SanioNues	San Antonio-Nueces riverbasin
Nueces	Nueces riverbasin

The model TEXRIVERSIM maximizes expected welfare accumulated from municipal and industrial (M&I) consumers' surplus, recreational benefits and net farm income less the cost from IBTs. Based on the analysis of historical instream flows, nine states of nature ranging from very dry to very wet are defined in the model to reflect climate variability with probabilities reflective of historical frequency in a 50-year period. In turn, these probabilities serve as weights in the objective function. Therefore, the model is stochastic reflecting nine states of nature for water flows following the historical climate patterns.

Municipal water uses are divided into two classes: water in major cities where we introduce explicit demand curves and water from the small cities, which we treat as having constant net marginal benefit from using water up to a maximum quantity. Municipal water demand for major cities has constant price elasticity ε_1 while municipal water demand for small cities is infinitely price elastic but cannot exceed historical water use. Major cities' water demand is shifted up and down depending on the rainfall and climatic conditions characterizing each state of nature (See figure 1). The climate shifter is introduced as monthly average temperature (F) times the number of days without rainfall in a month divided by 1000 (W) as in Griffin and Bell (2006). The climate elasticity ε_2 is represented as the percentage change in quantity of water demand given 1 % change in climate shifter. Therefore, the major cities' water demand function is follows:

$$Q_c = \gamma_c P_c^{\varepsilon_1} W_c^{\varepsilon_2}$$

Industrial water demand is also separated into two types: 25 major industrial counties with explicit demand curve (McCarl, 1999); and small industry counties with constant marginal net water benefit using water up to a maximum amount. Municipal and industrial prices are set as the first block and last block price following Bell and Griffin (2006). Marginal cost is assumed to be 50% of the corresponding water price.

Benefits from water use for major cities or major industrial counties are measured as consumer surplus, the area below a constant elasticity demand curve and above the marginal cost curve. Benefits from water use for small cities or small industrial counties will be the constant net marginal net benefit times the amount of water used.

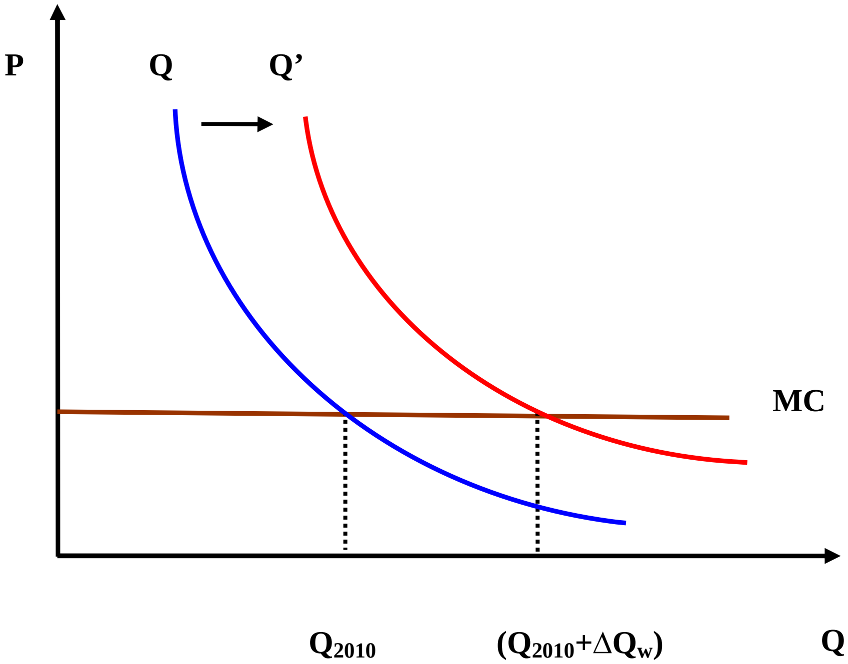

Figure 1: A major city’ water demand curve & its climate shift factor

Benefits from agricultural water use are represented using a linear programming crop mix representation. Net agricultural income from irrigated and dry land crop production is considered. Irrigated and dryland crop yields along with irrigation water requirements differ by state of nature, and are developed by using the Blaney-Criddle procedure (Doorenbos and Pruitt, 1977). The model employs a two-stage stochastic programming with recourse formulation. The choice of the crops to grow is decided early in the year at the first stage when the state of nature is unknown. At the second stage, harvest and irrigation water use can be adjusted when the amount of water available and state of nature are known. Cropland use across the crop mix patterns employed is restricted to the land available.

Recreational water use is gaining importance. The travel cost method is widely used to estimate the value of recreational water use, but this is beyond our scope. In this project, we assume recreational water withdraws have constant marginal net benefit in all riverbasins. Freshwater inflows to bays and estuaries are valuable and thus we include a term for this in the objective function. We did not find appropriate values for freshwater inflows to bays and estuaries. Currently we assign a net value of $0.01 per ac-ft to water which flows out. Higher values may well be in order.

4 Data specification

The model involves huge amount of data. The data sets used mainly involve water demand, including water prices and consumption, climate data, crop data, IBT data, hydrological data and state of nature data. Each is described below:

4.1 Water demand

Water is used by various sectors. Water demand quantities for municipal and industrial interests in 2010 are drawn from the "2006 Regional Water Plan" from the Texas Water Development Board (TWDB) website at (http://www.twdb.state.tx.us/data/popwaterdemand/2003Projections/DemandProjections.asp). Major municipal cities and industrial counties are designated as those with annual water use greater than 2000 and 3000 ac-ft respectively. This results in 46 cities and 25 major industrial counties being designated.

Municipal and industrial water prices in 2003 are drawn from a survey of over 2000 communities in Texas that was done by Bell and Griffin (2006). Municipal prices through which demand curves will be passed are the first block prices, and industrial water prices are the last block prices. We assume water prices in year 2010 are real prices same as the nominal prices in 2003. Monthly price elasticity for major cities' water demand is from the same survey by Bell and Griffin (2006) while price elasticity for industrial water demand is from Renzetti (1988).

Marginal cost including treatment and operating cost for each city or county is assumed to be 50% of the water prices.

4.2 Climate data

Major cities water demand is sensitive to the climate. A climate-driven demand shifter is defined as monthly average temperature (F) times the number of days without rainfall in a month then divided by 1000 (W) as developed in Griffin and Bell (2006). Monthly average temperature and precipitation data for identified major cities for the period 1950-2004 are collected from National

Climatic Data Center (NCDC). Climate elasticity is adopted from the survey results by Bell and Griffin (2006). Therefore, we could identify the climate effects on major cities' water demand.

4.3 Crop data

TEXRIVERSIM models agricultural water use and crop management choice, so crop data are needed in the form of crop budgets, crop mix and surface water irrigated lands in Texas.

Crop budget data including crop yield, price and cost are adapted from Texas Cooperative Extension data on the website (http://agecoext.tamu.edu/). Crop irrigation water requirements and crop dryland yield are also sensitive to the climate. Therefore, monthly average temperature and precipitation data for all agriculture counties for the period 1950-2004 are obtained from the same source of NCDC. The Blaney-Criddle formula (Doorenbos and Pruitt, 1977) is used to obtain the climate-driven crop water requirements. A dryland crop yield is assumed proportional to the irrigated crop yield depending on how much rainfall is available. For example, if rainfall available is 70% of crop irrigation water requirement, then 70% of irrigated crop yield is assigned to the dryland crop yield.

Available agriculture land is defined as acreage of irrigated land available in a county in 2003 and drawn from the NASS, which serves as an upper limit that the optimal cropland use across the crop mix patterns can not exceed.

Historical crop mix is extracted from USDA county level statistics as developed by NASS (ftp://www.nass.usda.gov/pub/nass/county/byyear/) and will provide information for agricultural land constraints with land for irrigated and dryland uses having to be a convex combination of historic crop mix following McCarl(1982), McCarl and Onal(1989, 1991) and Gillig et al (2001). 21 crops from the historical crop mix are therefore included in the model (see table 19 in Appendix)

4.4 Hydrologic network structure

TEXRIVERSIM model is an integrated economic, hydrological model. When defining the model it is necessary to introduce a network flow structure that represents water flow in the various rivers dividing each basin into a set of reaches and nodes then linking the reaches to depict water flows from upstream to downstream as well as points of diversion. This is defined as follows:

A primary control point in Water Availability Modeling (WAM) (by Texas Commission on Environmental Quality –TCEQ) and Water Rights Analysis Package (WRAP) (Wurbs) is named as a “river place” in the TEXRIVERSIM model. River place is the most important unit in this model and used to define reaches, reach members, and river flow linkages. All the calculations are made with reference to the river place.

A secondary control point in WRAP is named as a “diverter” in the TEXRIVERSIM model. A diverter is the actual place that water users divert some amount of water for particular type of use and all usages in a reach are assigned to the downstream river place.. Diverter is one of the most fundamental units in the model as well as river place, and most of hydrological data such as historical water use and permitted diversion are based on it.

The area between two adjacent river places is defined as a reach. Diverters located in that reach are considered reach members of the down stream river place. A river place can contain many reach members. The diverter-river place mapping builds a link between a diverter and down stream river place, which enables us to aggregate diverter based data into the river flow model features.

The riverbasins contain many reservoirs. A reservoir is treated as both a diverter and a river place since it is an actual water diversion point. 175 major reservoirs with a capacity more than 5000 ac-ft are covered in the model. The normal storage capacity $\overline{STORAGE_d}$ for the major reservoirs is obtained from Texas Water Development Board (http://www.twdb.state.tx.us/publications/reports/waterconditions/twc_pdf_archives/latest.pdf)

Modeling the riverbasins involves representing the rivers with a series of river places and connecting them in sequence according to the river flow. The mapping between upstream river place and its consequent down stream river place is very important in modeling water flow sequence and instream flow balance particularly to determine how $FLOWin_{s,d,m}$, $FLOWout_{s,d,m}$ and $RETURN_{s,d,m}$ enter the model.

The tuple sector-diverter mapping is directly extracted from WRAP output and represents a particular diverter and type of water use.

4.5 Hydrological data

The hydrological data including naturalized flows, historical water use, and permitted diversion mainly obtained from the input data used within the WRAP and WAM.

Naturalized stream inflows represent water inflows that would have occurred in the absence of today's water uses, water management facilities etc. The naturalized inflow is used to calculate $\overline{INFLOW}_{s,d,m}$ for the instream water flow balance constraint.

Historical water use is used to identify the level of demand by the major industrial and municipal counties and set a limit for water withdrawn for recreational or other use.

Texas Commission on Environmental Quality issues permits to water right holders and specifies the maximum amount of water that can be diverted. Permitted diversions for a diverter serve as an upper bound $\overline{DQ_{c,t,m,d}}$ that the diverter can actually withdraw before IBT transfers.

Evaporation loss is defined as the percentage of water evaporating per unit water stored for a reservoir. Reservoir evaporation takes away a part of the available supply for diversion and eventually affects the variables $STOREbefore_{s,d,m}$ and $STOREafter_{s,d,m}$.

The model reflects the difference between diversions and consumptive use where a given proportion of diverted water return flows into a river. Once water is diverted for use, some percentage of water will return to the river and add water supply for the downstream users. This is represented as $RETURN_{s,d,m}$ in the instream flow balance constraint. Water returns to different locations after certain period. Recreational use has a 100% return flow since there is no consumptive use. The return flow percentage is obtained from the EDSIMR model (Gillig, 2001) (see table 22 in Appendix). It is assumed that water diverted from one river place will return to the next downstream river place and no time delay is considered in the model.

4.6 IBT data

Inter-basin water transfer is the key component and major focus in the TEXRIVERSIM model. Inter-basin water transfer related data includes the project name, corresponding fixed, and variable cost, capacity and as well as the IBT source and destination locations. These data are drawn from the Texas Water Plan 2002, 2006 along with regional water planning group reports (http://www.twdb.state.tx.us/RWPG/main-docs/2006RWPindex.asp).

Two types of IBTs are included in the model. An IBT associated with more than one diverter is treated as a River IBT (RIBT), where transferred water is not directly dedicated to a user but rather is placed in the instream flow of the destination basin that is used by downstream diverters. An IBT where the water is dedicated to only one diverter is treated as User IBT (UIBT) in which transferred water is assumed dedicated to that diverter. The source and destination river places are mapped according to their physical places. 51 possible inter-basin water transfers (10 RIBTs and 41 UIBTs) are included in the model (see table 20 in Appendix).

4.7 State of nature data

Inter-basin water transfers will not only operate in dry years when water is highly needed but also would operate in wet years when they may not be needed and in fact will operate across the spectrum of water availability years. Consequently, for accurate modeling and IBT appraisal we need to depict the full variety of water flow possibilities and their relative frequencies of occurrence. The states of nature define the stochastic part of the model.

Nine states of nature are defined based on the WRAP input historical river flow and climate data from the years 1949 to 1998 so they depicted conditions ranging from very dry to very wet. Years with similar flow and climate condition are grouped into the nine states and their relative incidence is used to define the probability $\overline{prob(s)}$. Weighted averages of all of the data with each of the states describing temperature, precipitation, and naturalized flows are then formed.

In turn given the definitions of the nine states of nature and the associated climate condition, the stochastic element of the model is defined. Nine secondary states of nature are defined within a stochastic programming with recourse formulation with varying levels of

- naturalized inflows for each river place and month
- agricultural water use, and crop yield for each irrigated crop that is defined in the major agricultural counties, for each water use month
- agricultural crop yield for each dryland crop that is defined in the major agricultural counties
- water demand quantity through which a constant elasticity demand curve will be passed for each major municipal water demand city based on a climate shift elasticity approach developed by Griffin and Chang (1990) and later updated by Bell and Griffin (2006)
- water demand quantity for minor cities

5 Model results and discussion

5.1 Optimal water allocation without IBTs

Once TEXRIVERSIM is constructed, a baseline scenario is run through the model. The "base" model is defined as a model without IBTs being built. The consequent results are discussed in the following sections.

5.1.1 Expected net benefit

Table 2 lists the expected net benefits for each riverbasin. The expected annual net benefits accruing from Texas surface water use across all riverbasins is $8,450 billion. Municipal water benefit ("mun") is the largest component of this accounting 99.88% of the above total benefits. Agricultural water benefits ("ag") are $2.44 million, while industrial water benefit ("ind") accounts for 0.11% of total benefits and reaches a value of $9.76 billion. The water benefits from recreation ("rec"), other ("other") and the value of fresh water inflows to a bay ("TOBAY") are $99, 7.01, 0.47 million respectively. The net benefit value from municipal and industrial water use must be carefully interpreted since their benefits are measured as area below a constant elasticity demand curve and above the marginal cost curve. That measure is large as price approaches infinity then the quantity of water approaches zero yielding very large areas. However, the net benefits from agriculture, recreational, other and value of fresh water inflows to bays and estuaries have real meaning. They are the real net income either from agriculture production or from other activities. Value from fresh water flows inflows to bays and estuaries is very small due to the assumption that its marginal net value is $0.01/acft.

Trinity, San Jacinto, Guadalupe-San Antonio and Brazos are four biggest components of the net benefit, accounting for 80%. This is not surprising since municipal water use is the dominant contributor and Dallas, and Forth Worth are in the Trinity basin, while Houston is in the San Jacinto basin, and San Antonio in the Guadalupe-San Antonio riverbasin. The total benefit from Trinity-San Jacinto, San Antonio-Nueces, Colorado-Lavaca, Lavaca, Neches-trinity fiver riverbasins are less than $0.8 million, reflecting the result that little water is used for municipal purpose.

Municipal water benefit ("mun") comes from two parts: from 46 major cities ("mun-city") and from other minor cities ("mun-other"). In Texas, there are around 960 cities with a range of population spanning from 1000 to 1 million. The projected surface water demand for the 46 major cities totals 1.146 million ac-ft, accounting for 49.1% of total municipal demand projection. Therefore, ignoring the small cities is not appropriate. These small cities are assigned to have constant marginal water benefit of $280.23/ac-ft, which is the lowest price from major cities.

The results shows that benefit from the small cities are relatively small, ranging from $0.21 million in Nuces basin to $105 million in Brazos Basin. Trinity, San Jacinto, Guadalupe-San Antonio and Brazos again are four big players in the municipal water benefit from major cities, followed by Neches, Red, Colorado, Nueces, and Sabine. Meanwhile, Trinity-San Jacinto, San Antonio-Nueces, Colorado-Lavaca, Lavaca and Neches-Trinity do not contribute greatly in terms of net welfare.

Industrial water benefit ("ind") are also composed of two parts: a major industrial part arising from explicit demands by 25 major industrial counties ("ind-main") and an other industrial part arising from the other 230 counties in Texas ("ind-other"). The projected water demand for these 25 major industrial counties accounts for 55% of total industrial demand. Therefore, it is necessary to include the small industrial counties in the model. The net benefits from these major counties accounts for 96.2% of the welfare, having a value of $9.39 billion. It does make sense since the marginal benefit for the rest counties are assumed constant to be the lowest ind. price from major counties ($570/ac-ft). San Jacinto, Brazos, Guadalupe-San Antonio and Sabine are four big players in both “ind” and “ind-main” categories, and contribute for 86% and 88% respectively, while Trinity-San Jacinto, San Antonio-Nueces and Colorado-Lavaca have zero net benefits.

The agricultural water benefits for all riverbasins totals $2.44 million. The major agriculture basins are Guadalupe-San Antonio, Colorado, Brazos and Nueces with net farm income ranging from $1.22 to $0.16 million, while Canada, Cypress, Lavaca, Neches, Neches-Trinity, Sabine, San Jacinto, Sulphur, Trinity, and Trinity-San Jacinto do not have any irrigated agricultural income. In the San Antonio and Guadalupe Riverbasin, surface water resources currently supply about 12% and 52% of the water used for all purpose (WAM- Guadalupe-San Antonio). In the Colorado Riverbasin, only 25% of water is for irrigation, 66% is for municipal supplies, 8% is for industrial purposes (WAM-Colorado). In the Brazos Riverbasin, surface water resources only supply for 18% of water use for all purposes while irrigated agriculture accounts for 77% of all water used and is concentrated in the High Plains and supplied largely from the Ogallala Aquifer (WAM-Brazos). This implies that majority of irrigation water are from ground water source (which is not depicted in TEXRIVERSIM), which means to only small percentage of agriculture production are covered in the model.

Benefits from recreational, other and fresh water flows to bays and estuaries are trivial in most basins. Recreational benefit in Guadalupe-San Antonio reaches $95.44 million, indicating that recreational use is an important competitor therein.

Table 2: Expected net benefit by basin ($ million)

Riverbasin	ag	ind	ind-main	ind-other	mun	mun-city	mun-other	other	outtobay	rec	sum
Brazos	0.5	2,526	2,452	74	532,061	531,955	106	0.1	0.07	0.3	534,587
Canadian	-	63	63	-	24	-	24	-	-	-	87
ColLavaca	0.01	-	-	-	-	-	-	-	0.005	0.0	.01
Colorado	0.6	136	90	47	365,940	365,915	25	0.7	0.03	0.4	366,079
Cypress	-	145	112	33	23,084	23,068	16	-	0.02	-	23,229
Guadsan	1.2	1,333	1,330	3.6	918,595	918,559	36	5.4	0.02	95	920,031
Lavaca	-	0.2	-	0.2	-	-	-	-	-	-	0.2
Neches	-	508	506	2	453,710	453,704	6	0.0	0.06	0.0	454
NechTrinity	-	0.2	-	0.2	-	-	-	0.4	0.01	-	0.6
Nueces	0.2	0.02	-	0.0	278,786	278,786	0.2	0.1	-	-	278,787
Red	0.0	53	46	7	414,803	414,789	14	0.2	0.10	-	414,856
Sabine	-	1,249	1,212	37	108,058	108,049	9.1	-	0.06	2.8	109,310
SanioNues	0.0	-	-	-	-	-	-	-	0.006	-	0.01
SanJacinto	-	3,289	3,289	-	1,584,368	1,584,368	-	0.0	0.02	0.0	1,587,657
Sulphur	-	15	15	0.1	44,825	44,820	5	-	0.02	-	44,841
Trinity	-	440	276	163	3,716,093	3,716,002	91	0.0	0.06	-	3,716,532
TrinitySanJac	-	-	-	-	-	-	-	-	0.002	-	0.00
Total	**2.4**	**9,758**	**9,391**	**367**	**8,440,348**	**8,440,016**	**332**	**7.0**	**0.47**	**99**	**8,450,215**

Table 3: Expected water use by basin (thousand ac-ft)

Basin	**ag**	**ind**	**ind-main**	**ind-other**	**mun**	**mun-city**	**mun-other**	**other**	**outtobay**	**rec**	**sum**
Brazos	46.02	308.21	178.63	129.58	462.22	84.13	378.09	1.35	6,683.83	3.6	821.40
Canadian	0.87	7.62	7.62	-	84.65	-	84.65	0.03	199.75	-	93.17
ColLavaca	-	-	-	-	-	-	-	0.07	78.04	-	0.06
Colorado	127.47	94.35	12.55	81.81	258.12	168.21	89.91	8.77	2,661.51	4.58	493.30
Cypress	-	68.81	11.69	57.12	59.07	3.29	55.79	-	1,570.23	-	127.88
Guadsan	45.3	142.44	136.18	6.26	269.44	140.03	129.42	67.56	1,848.07	1,060.45	1,585.20
Lavaca	1.8	0.37	-	0.37	-	-	-	-	784.63	-	2.17
Neches	-	106.48	102.54	3.94	69.16	46.25	22.92	0.47	5,501.06	0.13	176.24
NechTrinity	-	0.26	-	0.26	-	-	-	4.89	1,118.00	-	5.16
Nueces	9.32	0.04	-	0.04	62.68	61.94	0.74	0.75	524.24	-	72.79
Red	3.1	17.77	5.59	12.18	141.88	92.49	49.39	2.97	9,542.54	-	165.71
Sabine	-	145.05	80.23	64.82	49.38	17.01	32.37	-	6,295.28	30.54	224.97
SanioNues	0.21	-	-	-	-	-	-	-	565.43	-	0.21
SanJacinto	-	377.99	377.99	0.01	399.61	399.61	-	0.32	1,649.17	0.15	778.07
Sulphur	-	2.81	2.7	0.1	25.22	6.49	18.73	-	2,382.21	-	28.02
Trinity	-	307.81	21.27	286.54	1,169.51	845.35	324.15	0.45	5,696.40	0.08	1,477.85
TrinitySanJac	-	-	-	-	-	-	-	-	173.19	-	0
Total	**234.1**	**1,580.00**	**936.99**	**643.01**	**3,050.95**	**1,864.79**	**1,186.15**	**87.63**	**47,273.59**	**1,099.53**	**6,052.19**

5.1.2 Expected water use by basins and sectors

Socially optimal water allocation states that water should be allocated to highest value users to achieve economic efficiency. Generally, municipal and industrial water use creates higher value than other sectors, so the water demand from these sectors should be satisfied first.

The expected water use in each riverbasin is listed in table 3. The “sum” is defined as the total water use from all sectors (excluding fresh water flows to the bay). There are total of 6.05 million ac-ft of water used across all riverbasins. Approximately 3.9% of the water (234,100 ac-ft) supplies are used in the agricultural sector, 26.1% (1580,000 ac-ft) by industry, 50.5% (3051,000 ac-ft) in municipalities, while recreational water use accounts for 18.5% (1100,000 ac-ft).

Water use from the small cities is 1186,000 ac-ft, or 38.9% of the municipal total. Meanwhile, water use from the other small industrial counties is 403,000 ac-ft, accounting for 40.7% of total industrial water use. The results verify that it is necessary to include them in the model even though they do not create high welfare; otherwise, the results will be biased. On the other hand, 47.3 million ac-ft of water escapes to bays and estuaries, approximately 8 times the actual water use by all sectors.

Guadalupe-San Antonio, Trinity, Brazos, and San Jacinto are four biggest basins with total of 4.66 million ac-ft water used by all sectors, accounting for 77% of total water use. Water use in Neches-Trinity, Lavaca, San Antonio-Nueces, Colorado-Lavaca, Trinity-San Jacinto totals less than 10,000 ac-ft.

Water distribution among sectors varies significantly across riverbasins. In Guadalupe-San Antonio, recreational water use plays an important role, reaches 1067,000 ac-ft and is equivalent to 4 times of municipal consumption, 7.5 times of industrial consumption, 23 times of irrigational water use. Note a large portion of the San Antonio use is mainly supplied from the Edwards Aquifer that is out of our current modeling scope.

In the Trinity, water use totals 1477,000 ac-ft, while 79.1% are for municipal, 20.8% are for industrial. Recreation, other and agriculture use very small amount of water.

In the Brazos, water use totals 821,000 ac-ft, where agricultural, industrial, municipal, recreational water use account for 5.6%, 37.5%, 56.3% and 0.4% respectively, indicating that water are mainly used for municipal. This is consistent with the WRAP inputs.

In the San Jacinto, total water use reaches 778,000 ac-ft, which is exclusively used for major cities (51.4%) and major industrial counties (48.6%). The results do make sense since Houston and Harris County where Houston is are in San Jacinto riverbasins.

In the Colorado, water use totals 493,000 ac-ft. Among it, 25.8% are for agricultural purpose, 19.1% for industrial use, and 52.3% for municipal purpose. Therefore, agricultural water use has relatively larger portion in Colorado than in other riverbasin.

5.1.3 Major cities water use

Table 3 displays socially optimal water allocation by riverbasin. Table 4, 5, and 6 show details of water allocation for the major cities, major industrial counties and agricultural counties respectively.

Forty-six major cities are classified based on the historical municipal surface water use data from WRAP. Cities like College Station using ground water as main source are excluded in the model. However, San Antonio is an exception. A large potential water shortage (78,467 ac-ft) is being faced by San Antonio due to Edwards Aquifer pumping limits and rapid population growth. It is likely the shortage will be supplied by surface water possibly from inter-basin water transfer. Therefore, it is important to include San Antonio in the model. The projected water demand for these 46 cities totals 1.146 million ac-ft, accounting for 49.1% of total municipal demand. Dallas, Houston, Fort Worth, Austin and San Antonio are the five largest cities, constituting 62.8% of the projected municipal water demand among the 46 cities.

The optimal water allocation (“Base”) less the projected water demand gives us the water shortage faced by each city. If the water shortage is large and no ground water source available, then an inter-basin water transfer may become an option. The results show that Houston, Austin, and Dallas water demand is largely met if water is optimally allocated. However, San Antonio, Arlington, Fort Worth, Tyler, San Angelo, and Round Rock still face large shortages especially San Antonio and Arlington. This is why entities like San Antonio Water System (supplies water for San Antonio), Tarrant Regional Water District (serves Fort Worth and surrounding communities in ten counties), North Texas Municipal Water District (supplies water to cities such as Plano, Farmersville, Forney, Garland, McKinney, Mesquite, Princeton, Rockwall, Royse City, Wylie and Richardson) and Dallas Water Utilities (supplies water to Dallas and surrounding cities) are actively participating in many proposed inter-basin water transfer projects.

Table 4: Major Municipal City Water Use (thousand ac-ft)

City	**Base***	**Pre-demand****	**Difference*****
Abilene	22.93	22.87	0.06
Allen	22.25	23.62	-1.37
Arlington	13	79.73	-66.73
Austin	150.82	153.69	-2.87
Beaumont	27.09	26.97	0.12
Bonham	2.2	2.74	-0.54
Cedar Park	3.33	10.92	-7.59
Center	1.64	1.63	0.01
Cleburne	5.7	5.75	-0.05
Coleman	1.26	1.28	-0.02
Conroe	9.34	9.33	0.01
Corpus Christi	61.94	61.83	0.11
Corsicana	0.66	5.83	-5.17
Dallas	388.56	389.34	-0.78
Denison	5.52	5.5	0.02
Denton	29.46	29.6	-0.14
Fort Worth	100.77	149.57	-48.8
Frisco	45.82	45.58	0.24
Garland	40.12	42.85	-2.73
Georgetown	2.69	8.6	-5.91
Gonzales	1.55	1.54	0.01
Graham	1.53	1.53	0

Grapevine	13.45	13.5	-0.05
Greenville	5.56	5.55	0.01
Houston	390.27	388.93	1.34
Irving	55.23	55.41	-0.18
Liberty Hill	0.14	0.45	-0.31
Mansfield	9.36	13.54	-4.18
Marlin	2.51	2.65	-0.14
Marshall	3.29	3.26	0.03
McKinney	22.54	24.67	-2.13
Nacogdoches	7.71	7.65	0.06
Paris	6.24	6.25	-0.01
Plano	64.98	72.62	-7.64
Richardson	32.71	32.46	0.25
Round Rock	5.78	19.63	-13.85
San Angelo	10.31	20.78	-10.47
San Antonio	138.48	216.07	-77.59
Snyder	2.8	2.8	0
Sweetwater	3.02	3.01	0.01
Temple	14.66	20.89	-6.23
Terrell	3.58	3.58	0
Texarkana	6.49	6.47	0.02
Tyler	11.45	25.88	-14.43
Waco	25	24.89	0.11
Weatherford	2.85	5.2	-2.35

** “Base”gives the optimal water allocation under baseline scenario;*

*** “Pre-demand” gives the projected water demand;*

**** “difference” is the gap between the “Base” and the “pre-demand”*

5.1.4 Major industrial counties’ water use

Industrial water counties with average historical surface water use greater than 3000 ac-ft are classified as major industrial counties. 25 counties fall in this category accounting for 55% of total industrial demand projection. Brazoria, Harris, Harrison and Jasper are the four largest industrial counties, using 70.8% of the water in this category.

The optimal level of water use by the major industrial counties is listed within the “base” column of Table 5. Again optimal water allocation is often less the projected water demand as in the "difference" column. This shows problems in Brazoria, Nueces, Harris, Dallas, Hutchinson, Tarrant, Harrison, Live Oak and Victoria counties. The water shortage is largest in Brazoria County with a shortage of 111,000 ac-ft. Therefore, interests within these counties may well seek alternative strategies to solve the water shortage issue including IBTs.

Table 5: Major industrial counties’ water use (thousand ac-ft)

County	**Pre-demand**	**Base**	**Difference**
Angelina	30.28	30.28	0
Bastrop	5.13	5.13	0
Bell	1.14	1.13	-0.01
Bexar	29.53	29.53	0
Bowie	2.33	2.33	0
Brazoria	264.34	153.33	-111.01
Calhoun	49.82	79.76	29.94
Dallas	37.03	11.83	-25.2
Fort Bend	9.87	9.86	-0.01
Harris	397.28	375.46	-21.82
Harrison	85.24	78.33	-6.91
Hutchinson	24.06	7.62	-16.44
Jasper	64.27	64.27	0
Lamar	5.6	5.59	-0.01
Live Oak	5.84	0	-5.84
McLennan	3.94	3.94	0
Montgomery	2.53	2.53	0
Nueces	47.98	0	-47.98
Robertson	10.39	10.37	-0.02

Rusk	1.62	3.24	1.62
Smith	4.55	7.99	3.44
Tarrant	17.69	9.44	-8.25
Titus	10.71	10.71	0
Tom Green	2.3	2.3	0
Victoria	32.67	26.89	-5.78

** The column labeled "Base" gives the optimal model base scenario water allocation*

*** The column labeled "Pre-demand" gives the level of projected water demand*

**** The column labeled "difference" gives the gap between the optimal level and the level of projected demand*

5.1.5 Agriculture water use and production

Table 6 lists agricultural water use by county under different state of nature. Table 7 and 8 list the irrigated and dryland crop acres planted. Total agriculture water use averages 220,000 ac-ft. Agriculture water use is sensitive to state of nature and water use under drier conditions is more than water use in wet years. Wharton, Medina, Tom Green, Comanche, and Robertson are the five largest irrigation water using counties, accounting for 85% of total agricultural water use and 82.3% of total irrigated land. Crop mix differs across counties. In Wharton County, 100,000 ac-ft of water is used largely for rice production (3,695 acres) and upland cotton ("CottonU" 205 acres). In Medina, pima cotton ("cottonP"), upland cotton, peanuts and grain sorghum ("Sorghum") share 39,000 ac-ft of water. In Tom Green, upland cotton is the major crop accompanied with a few acres of grain sorghum, wheat and winter wheat (Winwht). In Comanche, peanuts are the principal irrigated crop using 15,000 ac-feet of water, while in Robertson upland cotton is the dominant irrigated crop.

Total dryland acres reach 2042,000 acres, which is 201 times larger than the total irrigated land (10,100 acres). Crop dryland acres in each county are much larger than the irrigated acres. One reason is that most irrigation water is from ground water source, while it is not covered in our current surface model. Therefore, majority of land will be converted to dryland if there is not enough surface water available. It also verifies that the agriculture water creates lowest value and will be first sacrificed once there is water shortage problem in a region in a social optimal point of view.

5.1.6 Instream water flows and fresh water inflows to bays and estuaries

Table 9 shows average instream flows at a river place in a riverbasin. It can be seen that Sabine, Neches and Trinity have the largest average instream water flows above 700,000 ac-ft, while Trinity-San Jacinto have the lowest instream flow less than 30,000 ac-ft. Monthly instream flows vary by basin. In the Brazos basin, instream flow is higher in December, January, May, while lower in July, August. In Sabine, instream flows are higher from January to July, while lower from August to December. Instream flow depends on the naturalized stream flow, diversion amount, return flow, so there is no clear pattern.

Table 6: Agricultural counties' water use under different state of nature (thousand ac-ft)

County	Average	HDry	MDry	Dry	Dnormal	Normal	Wnormal	Wet	MWet	HWet
Wharton	99.76	126.06	113.12	107.78	105.91	95.22	98.51	89.96	89.00	78.63
Medina	38.86	48.12	40.35	44.63	41.59	37.23	40.55	35.43	32.74	27.94
Tom Green	18.02	20.41	20.16	19.90	19.50	16.90	18.38	16.43	16.91	15.28
Comanche	15.21	18.01	15.13	16.68	17.23	14.55	13.98	14.38	13.45	14.45
Robertson	15.00	19.79	16.69	16.76	17.22	13.91	13.67	13.35	13.92	12.21
Wilson	7.93	8.66	8.50	8.22	8.50	7.73	7.79	7.39	7.51	7.62
Zavala	7.80	7.97	7.94	8.19	8.02	7.74	8.38	7.23	7.04	7.51
Concho	6.02	6.65	6.14	6.75	6.72	5.58	6.29	5.73	5.74	5.29
Mason	2.29	2.64	2.37	2.44	2.57	2.21	2.32	2.08	1.84	2.18
Runnels	2.21	2.47	2.44	2.41	2.39	2.12	2.23	1.98	2.05	1.85
Nolan	1.27	1.41	1.30	1.43	1.42	1.18	1.33	1.21	1.22	1.12
Wilbarger	1.04	1.33	1.07	1.21	1.31	1.05	0.75	0.82	0.72	0.96
Castro	0.46	0.58	0.46	0.52	0.47	0.44	0.50	0.45	0.39	0.35
Baylor	0.42	0.52	0.47	0.50	0.46	0.39	0.46	0.34	0.40	0.31
Hale	0.41	0.43	0.39	0.45	0.47	0.39	0.45	0.39	0.38	0.30
Haskell	0.38	0.45	0.42	0.42	0.44	0.37	0.36	0.35	0.33	0.32
Roberts	0.34	0.47	0.32	0.40	0.38	0.32	0.37	0.30	0.27	0.26
Donley	0.26	0.30	0.27	0.26	0.32	0.27	0.19	0.24	0.21	0.23
Deaf Smith	0.26	0.28	0.25	0.30	0.25	0.25	0.27	0.25	0.22	0.21
Hansford	0.25	0.33	0.24	0.28	0.23	0.25	0.26	0.23	0.23	0.19
San Patricio	0.22	0.24	0.24	0.24	0.23	0.21	0.24	0.19	0.19	0.19

Randall	0.20	0.23	0.20	0.24	0.20	0.20	0.22	0.19	0.17	0.17
Carson	0.19	0.24	0.18	0.21	0.21	0.18	0.19	0.17	0.15	0.15
Fisher	0.18	0.20	0.19	0.21	0.21	0.17	0.19	0.18	0.18	0.16
Swisher	0.17	0.20	0.16	0.19	0.18	0.16	0.18	0.16	0.15	0.13
Moore	0.16	0.20	0.15	0.18	0.15	0.16	0.16	0.14	0.15	0.12
Wheeler	0.15	0.17	0.15	0.15	0.18	0.15	0.12	0.14	0.12	0.13
Dallam	0.12	0.18	0.11	0.13	0.12	0.13	0.10	0.11	0.11	0.11
Dickens	0.12	0.14	0.13	0.13	0.13	0.11	0.11	0.10	0.12	0.09
Parmer	0.12	0.14	0.12	0.13	0.11	0.11	0.12	0.12	0.10	0.09
Crosby	0.09	0.10	0.10	0.10	0.10	0.08	0.09	0.09	0.09	0.08
Motley	0.05	0.06	0.05	0.05	0.06	0.05	0.04	0.04	0.04	0.04
Cottle	0.03	0.04	0.03	0.03	0.03	0.03	0.02	0.03	0.03	0.03
Atascosa	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02
Collingsworth	0.01	0.02	0.01	0.02	0.02	0.01	0.01	0.01	0.01	0.01
Hardeman	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.00	0.00	0.00
Total	**220.01**	**269.04**	**239.87**	**241.55**	**237.34**	**209.87**	**218.88**	**200.25**	**196.20**	**178.72**

Table 7: Agricultural counties' irrigated crop acres (acre)

County	Corng	CottonP	CottonU	Peanuts	Rice	Sorghum	Soybeans	Wheat	Winwht	Sum
Wharton			204.6		3695.4					3900.0
Medina		1071.0	318.4	289.5		173.7				1852.5
Comanche				950.8						950.8
Tom Green			685.1			52.4		43.6	43.6	824.7
Robertson			770.9							770.9
Wilson				411.5						411.5
Zavala		95.0	176.7					15.8	15.8	303.4
Concho			284.4							284.4
Mason				133.4						133.4
Runnels			100.9							100.9
Wilbarger				62.4						62.4
Nolan			60.2							60.2
Baylor								24.4	24.4	48.9
Castro	14.1		5.5			2.7	0.7	12.7	12.7	48.4
Roberts								23.0	23.0	45.9
Hale	8.0		12.0			3.5		3.9	3.9	31.4
Hansford						3.2		13.2	13.2	29.6
Deaf Smith			0.5			3.5		10.5	10.5	25.0
Haskell			4.0	13.1				3.8	3.8	24.6
Carson			1.9			3.2		8.1	8.1	21.3
Donley				20.7						20.7

Moore						2.4		9.0	9.0	20.5
Randall						1.8	0.4	9.1	9.1	20.3
Dallam						0.3		9.1	9.1	18.5
Swisher	1.9		3.1			2.0		4.6	4.6	16.1
Parmer			1.1			1.3		4.9	4.9	12.3
Wheeler			6.0	4.3						10.3
San Patricio			9.0							9.0
Fisher			8.7							8.7
Dickens			3.1			0.7		1.8	1.8	7.5
Crosby			4.9	0.1		0.1				5.1
Motley				2.7						2.7
Cottle			0.4	1.2						1.6
Collingsworth			0.1	0.7		0.0		0.1	0.1	1.0
Atascosa				1.0						1.0
Hardeman			0.1					0.2	0.2	0.5

Table 8: Agricultural counties' dryland crop acres (acre)

County	**Barley**	**Corng**	**CottonU**	**Oats**	**Peanuts**	**Sorghum**	**Soybeans**	**Wheat**	**Winwht**	**Sum**
Hale		1987.0	128491.9			163122.3	33305.7	25830.8	25830.8	378568.6
Parmer	602.2	11459.3	27519.0	83.6		111163.3	3680.4	37639.9	37639.9	229787.7
Castro	368.5	21870.5	33326.5	600.8		72501.1	9733.6	32525.3	32525.3	203451.6
Crosby		247.0	85050.5			52936.0	4834.8	14963.2	14963.2	172994.9
Deaf Smith	1642.2	2758.8	3678.4	144.5		60168.7	3547.1	45717.7	45717.7	163375.0
Swisher	197.4	3477.3	19501.0			59959.6	6061.7	26643.5	26643.5	142483.9
Sherman		3454.4				34283.0	945.1	38258.8	38258.8	115200.0
Dallam		3089.1		51.5		59797.1		24271.9	24271.9	111481.5
Hansford	201.8	4237.1		84.1		28751.8	168.1	32013.7	32013.7	97470.4
Moore	685.2	9235.7		521.4		20169.7	149.0	21659.3	21659.3	74079.5
Carson	126.2	97.1				10816.8	87.4	14875.6	14875.6	40878.7
Briscoe		192.9	7293.0	19.3		11653.3	1234.8	8103.3	8103.3	36600.0
Collingsworth		53.9	11432.9	251.7		10066.7		3846.9	3846.9	29499.0
Haskell	233.4		12147.1	1449.3		4949.7		4347.9	4347.9	27475.4
Tom Green	104.9		9507.4	2644.4		11375.3		671.6	671.6	24975.3
Uvalde	84.3	2190.5	315.9	4296.8		10236.5		2338.0	2338.0	21800.0
Hutchinson	80.2	951.0				4963.1		7102.8	7102.8	20200.0
Robertson		2449.8	10301.9	565.3	458.6	5653.5				19429.1
Randall	89.0	331.0	147.9	33.1		5296.4	206.9	6237.7	6237.7	18579.7
Zavala		2438.7	1927.4	531.0		7158.8		570.3	570.3	13196.6
Gray			190.6	84.7		2361.0		5081.9	5081.9	12800.0

Medina	13.3	1322.0	95.1	1559.8	190.2	5240.5		1413.3	1413.3	11247.5
Donley			3417.6			4430.2		1265.8	1265.8	10379.3
Burleson		1454.5	5030.3	363.6		1651.5				8500.0
Frio		416.3	327.1	148.7	2721.1	3434.8		226.0	226.0	7500.0
San Patricio			1238.2	3.0		5733.8		8.0	8.0	6991.0
Wilbarger	394.4		961.7	240.4		108.1		1916.6	1916.6	5537.6
Motley			1860.5	22.2	106.7	1220.4		443.8	443.8	4097.3
Hardeman	327.1		494.4	150.0		59.0		1484.4	1484.4	3999.5
Roberts						294.5		1579.8	1579.8	3454.1
Dickens	9.2		1471.8	52.3		689.9		384.7	384.7	2992.5
Wheeler	42.4		705.6			859.4		541.1	541.1	2689.7
Mason			105.3	157.9	2157.8	245.6				2666.6
Nolan			1226.6	101.0		487.0		262.6	262.6	2339.8
Howard			1729.2	6.5		501.5		31.3	31.3	2300.0
Comanche		16.7	30.7	315.2	1567.6	163.2		27.9	27.9	2149.2
Concho	42.3		410.4	450.6		385.0		413.6	413.6	2115.6
Cottle	30.0		1186.0	66.4		253.0		281.5	281.5	2098.4
Fisher	3.5		1123.5	65.4		143.6		327.6	327.6	1991.3
Atascosa		69.4	39.2	16.6	697.4	637.1		19.6	19.6	1499.0
Baylor	25.5		144.4	93.4		73.8		457.0	457.0	1251.1
Runnels	3.7		406.5	160.5		363.4		132.4	132.4	1199.1
Wilson		58.7		3.1	127.4	203.7		97.8	97.8	588.5

Table 9: Instream flows by basins (thousand ac-ft)

	Jan	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**	**Annual**
Brazos	70.79	47.38	24.54	32.56	71.22	32.10	12.17	9.62	16.50	47.44	38.20	67.56	470.08
Canadian	0.02	0.02	0.04	0.14	0.39	10.64	10.30	1.31	0.27	0.14	6.67	0.02	29.96
Colorado	23.74	64.16	18.79	29.22	34.57	26.38	12.62	10.62	27.25	89.69	34.37	18.50	389.90
Cypress	8.68	17.12	11.45	14.07	26.37	20.07	15.52	22.60	18.22	2.08	4.22	19.77	180.19
Guadsan	16.75	15.68	14.10	18.59	26.53	30.96	13.13	10.31	15.93	22.83	13.98	13.27	212.04
Lavaca	9.42	11.08	5.99	11.82	17.38	15.65	2.66	1.54	11.15	9.71	7.06	7.28	110.76
Neches	97.74	154.16	58.05	96.46	61.56	57.90	43.46	69.01	16.65	16.74	87.52	46.36	805.61
Nueces	6.26	6.56	6.91	10.31	10.64	19.52	7.63	10.26	13.36	16.03	5.46	3.49	116.45
Red	29.06	78.10	24.63	21.74	40.15	39.93	35.57	13.08	13.97	122.83	11.07	13.73	443.86
Sabine	133.98	115.81	71.94	138.96	137.93	139.55	140.01	5.08	38.33	69.39	18.75	32.96	1042.68
SanJacinto	30.41	33.58	19.91	29.54	25.24	23.10	10.11	11.38	12.70	24.23	14.20	23.23	257.63
Sulphur	36.48	63.30	66.90	57.88	99.50	25.59	14.57	26.89	15.60	27.95	48.06	57.55	540.28
Trinity	45.70	15.60	101.11	78.48	65.11	55.71	54.69	64.70	41.01	76.84	43.29	69.44	711.67
TrinitySanJac	2.45	2.27	1.53	2.18	2.59	3.15	1.30	0.69	1.12	1.87	1.51	2.09	22.75

6 Evaluation of inter-basin water transfers

Now we turn to the IBT appraisal examining implications for source basins, destination basins as well as other basins. Three scenarios are run within the model:

- Baseline: This scenario (“base”) assumes that no IBT is built.

- Optimal IBTs: In this scenario (“Opt”), all of the 51 IBT projects are candidates so the socially optimal IBT solution will be obtained.

- Environmental Restriction “env”: In this scenario, IBTs with medium-high or high environmental impact are ruled out of solution. 15 out of 51 IBTs are so classified (Table 10), where 4 of these are River IBTs and 11 are User IBTs.

- Permitted IBT's only(“pert”): Five IBTs (table 11) are already permitted in Texas, including the Water Project LCRA/BRA Alliance User IBT projects transferring water from Lake Travis in the Colorado Riverbasin to Cities in Williamson County within the Brazos Riverbasin. In this scenario, these already permitted IBT projects are the only candidates.

Table 10: Environmentally Sensitive IBTs

IBT names in GAMS	**Option**	**Source basin**	**Destination Basin**
Marvin_SulToTrin	Opt1	Sulphur	Trinity
Marvin_SulToTrin	Opt2	Sulphur	Trinity
BoisdArc_RedToTrin	Opt1	Red	Trinity
Parkhouse_SulToTrin	Opt1	Sulphur	Trinity
Parkhouse_SulToTrin	Opt2	Sulphur	Trinity
Fastrill_NecToTrin	Opt1	Neches	Trinity
Parkhouse_SulToTrin	Opt3	Sulphur	Trinity
RalphHall_SulToTrin	Opt1	Sulphur	Trinity
Columbia_NecToTrin	Opt1	Neches	Trinity
LCRASAWS_ColToGdsn	Opt1	Colorado	Guadsan
LCRASAWS_ColToGdsn	Opt2	Colorado	Guadsan

Bayou_TriToSan	Opt1	Trinity	SanJacinto
Bedias_TriToSan	Opt1	Trinity	SanJacinto
ETWT_SabNecToTri	Opt1	Sabine	Trinity
ETWT_SabNecToTri	Opt1	Neches	Trinity
Livingston_TriToSan	Opt1	Trinity	SanJacinto

Table 11: Permitted IBTs

IBT names in GAMS	Option	Source basin	Destination Basin
Marcoshays_GdsnToCol	Opt1	Guadsan	Colorado
Marcoshays_GdsnToCol	Opt2	Guadsan	Colorado
LCRABRA_ColToBrz	Opt1	Colorado	Brazos
LCRABRA_ColToBrz	Opt2	Colorado	Brazos
LCRABRA_ColToBrz	Opt3	Colorado	Brazos

6.1 Optimal IBTs chosen

An IBT is justified if the benefit it brings is greater than the total cost. The cost may include opportunity cost or environmental impacts, while the latter is hard to quantify. Here only the construction, operation and water opportunity costs are considered in the model.

The results (table 12) show that 7 out of 51 IBTs are economically attractive under “Opt” scenario.

- Luce Bayou Channel project (Bayou_TriToSan) originates from Lake Livingston on the Trinity Riverbasin and goes to Lake Houston in the San Jacinto River to supply water to north and northwest areas of Houston in Harris County. This IBT has the second largest yield of water (maximum 540,000 ac-ft in) and the lowest per ac-ft cost ($30/ac-ft fixed cost and $9.27/ac-ft variable cost) among the 51 IBTs. As implied by table 5, Harris County faces major industrial water shortage. It is an optimal strategy if no environmental consideration bringing 540000 ac-ft water to industrial sector in Harris County.
- LCRA/BRA Alliance (LCRABRA_ColToBrz with option 1 and option 2) are aimed to transfer water from Lake Travis in Colorado basin to Williamson Counties in Brazos basin to

supply cities such as Round Rock, George Town, and Cedar Park. These supply options are sized to meet 54 percent of water shortages in William County by 2060. The construction of a new intake structure on Lake Travis and transmission pipeline to Williamson County would entail low to moderate environmental effects, leaving it as optimal strategies under all the scenarios. Option 2 will transfer water of 20928 ac-ft municipally regardless of the state of nature, while Option 1 will serve municipal water use with range of 486 ac-ft to 3476 ac-ft depending on the state of nature. If it's wet year, less water will be transferred.

- LCRA-SAWS Water Project (LCRASAWS_ColToGdsn) with option 1: Under this IBT water will be transferred from Bay City on the Lower Colorado River and sent to Bexar County of the Guadalupe Riverbasin for municipal use in San Antonio. This IBT project is very expensive (fixed cost of $1326/ac-ft and variable cost of $302.85/ac-ft). Water transferred varies by state of nature with the range from 49,700 to 83,000 ac-ft to solve the water shortage faced in San Antonio due to pumping limits of Edwards Aquifer.
- George Parkhouse Lake N (Parkhouse_SulToTrin with option 1): water originates from George Parkhouse Lake in Sulfur basin and goes to Dallas surrounding region in Trinity basin. This IBT is relatively cheap with fixed cost of $248/ac-ft, variable cost of $77.8/ac-ft and yielding maximum of 112,000 ac-ft annually. It may bring medium high environment impact if it is built, so it is an optimal strategy only under "Opt" scenario, where 25,200 water will be used industrially regardless of state of nature while 54,600 ac-ft will be transferred municipally in the heavy dry state to solve water shortage problem faced by Dallas region.
- Cypress Basin Supplies project (Pines_CypToTrin with option 3): Water flows from Lake O' the Pines in the Cypress Riverbasin to the Trinity Riverbasin where its possible owner would be Tarrant Regional Water District with supplies dedicated to Fort Worth municipality and industrially. This user IBT is relatively more expensive than most other proposed IBTs (unit cost before amortization: $641 per acre-foot and a variable cost of $242.96). It is an optimal strategy under "Opt" and "evn" scenario while not under "pert" scenario, where 6479 ac-ft is used industrially regardless of state of nature and municipal transfer ranges from 31,040 to 59,657 ac-ft with less in wet year.
- Lake Texoma with desalination project (Texoma_RedToTrin with option 3) is to transfer water from Lake Taxoma and to supply water to multiple users such as Allen, Frisco and

Richardson. This IBT is relatively cheap with fixed cost of $476/ac-ft and variable cost of $231/ac-ft while transferring water municipally of 13,800 ac-ft under both “Opt” and “env” scenario.

Table 12: IBTs chosen under different scenarios

Names in Gams	**Option**	**Desti place**	**sector**	**Opt**	**Env**	**Pert**
Bayou_TriToSan	Opt1	Houston	ind	540000		
LCRABRA_ColToBrz	Opt1	Round Rock, Cedar Park, George Town	mun	2541.851	2541.851	2541.851
LCRABRA_ColToBrz	Opt2	Round Rock, Cedar Park, George Town	mun	20928	20928	20928
LCRASAWS_ColToGdsn	Opt1	San Antonio	mun	60694.46		
Parkhouse_SulToTrin	Opt1	Dallas, Iving	ind	25185.6		
Parkhouse_SulToTrin	Opt1	Dallas, Iving	mun	3278.877		
Pines_CypToTrin	Opt3	Forth Worth	ind	6478.716	6478.716	
Pines_CypToTrin	Opt3	Forth Worth	mun	41811.07	41811.07	
Texoma_RedToTrin	Opt3	Allen, Frisco, Richardson	mun	13830.79	13830.79	

6.2 Net benefit impacts of IBTs

Table 13 shows the IBTs impacts on net benefits under the three scenarios. The costs of constructing IBTs are assumed to be incurred by the destination basin.

Seven IBTs bring expected net benefits of $2,254 million statewide under “Opt” scenario, with $1,858 million arising in industrial benefits and $846 million from municipal benefits. Meanwhile, total annual construction and operation costs of $450 million are incurred. In the destination basins the

- Brazos basin realizes municipal benefit of $479 million less a cost of $17.4 million. The gains come from two IBT projects: LCRABRA_ColToBrz with option 1 and 2.
- Guadalupe-San Antonio faces a net loss of $63.4 million even though water brings a benefit of $262 million.
- San Jacinto basin gains $1,752 million, most from water transferred to Harris County to lessen industrial water shortage.

- Trinity receives benefits of $206 million, where $91 million is from industrial and $105 million from municipalities. This basin serves as destination basin of multiple IBT projects (Parkhouse_SulToTrin, Pines_CypToTrin, and Texoma_RedToTrin).

Under the “env” scenario, four IBTs are economically optimal,

- LCRABRA_ColToBrz with option 1
- LCRABRA_ColToBrz with option 2,
- Pines_CypToTrin with option 3,
- Texoma_RedToTrin with option 3

Leading to expected municipal benefit of $583 million and industrial benefit of $9 million while incurring IBT cost of $78.8 million. The annual net gain from these four IBTs is $513 million, of which $462 million are from Brazos Basin and $51 million are from Trinity Basin.

Under “pert” scenario, only two IBTs

- LCRABRA_ColToBrz with option 1
- LCRABRA_ColToBrz with option 2

are optimal, creating benefit of $479 million exclusively municipally for Brazos while exposed to IBTs costs of $17.4 million.

The impact of IBTs on other sectors for the destination basins is negligible. As we can see, municipal and industry are two beneficiaries in terms of net benefit. Once water is transferred to a destination basin, the return flow generally increases the water availability downstream in the destination basin, which may generate some value if it is efficiently used. Guadalupe-San Antonio does realize a gain of $3,000 in agriculture, while the gain for San Jacinto $2,000 is from fresh water inflows to bays and estuaries. On the other hand, Trinity realizes a loss of $5000 in fresh water inflows to bays and estuaries.

The construction of IBTs projects has trivial impacts on the source basins and third basins under these three scenarios. Colorado, Cypress, Trinity, Sulphur, Red are source basins for the optimal IBT projects, however, the only impacts occurs in Cypress basin is $4,000 loss industrially under “Opt” scenario. As respect to third basins impacts, Lavaca experiences a loss of $1000, $3000, and $4000 in agriculture under these 3 scenarios respectively. Nueces suffers a loss of $3000 in agriculture under "opt" scenario. Sabine has a net gain of $4000 in the industry sector.

Table 13: Welfare impact by basin (million $)

Basin	**Sector**	**Base**	**Opt-Base**	**Env-Base**	**Pert-Base**
Brazos	IBTcost		-17.422	-17.422	-17.422
Brazos	mun	532060.85	478.923	478.923	478.923
Brazos	**sum**	**534587.4**	**461.5**	**461.5**	**461.5**
Cypress	ind	144.987	-0.004		
Cypress	**sum**	**23229**	**-0.004**		
Guadsan	ag	1.216	0.003		
Guadsan	IBTcost		-325.247		
Guadsan	mun	918595.018	261.864		
Guadsan	**sum**	**920030.501**	**-63.38**		
Lavaca	ag	0.006	-0.001	-0.003	-0.004
Lavaca	**sum**	**0.223**	**-0.001**	**-0.003**	**-0.004**
Nueces	ag	0.164	-0.003		
Nueces	**sum**	**278786.63**	**-0.003**		
Sabine	ind	1249.156	0.004		
Sabine	**sum**	**109310.073**	**0.004**		
SanJacinto	IBTcost		-16.178		
SanJacinto	ind	3288.917	1767.893		
SanJacinto	outtobay	0.016	0.002		
SanJacinto	**sum**	**1587657.436**	**1751.716**		
Trinity	IBTcost		-91.401	-61.399	
Trinity	ind	439.741	91.084	8.967	
Trinity	mun	3716092.555	104.811	103.903	
Trinity	outtobay	0.057	-0.005		
Trinity	**sum**	**3716532.395**	**104.489**	**51.472**	
Total	IBTcost		-450.248	-78.821	-17.422
Total	ind	9757.921	1858.976	8.967	
Total	mun	8440348.199	845.598	582.826	478.923
Total	outtobay	0.473	-0.004		
Total	**sum**	**8450214.998**	**2254.321**	**512.972**	**461.5**

6.3 Water allocation impacts of IBTs on riverbasins

Table 14 lists the water allocation impacts of IBTs on riverbasin base. Water is largely transferred from instream flow in the source basins to supply municipal or industrial purpose in the destination basins, while the reduction of instream flow leads to the reduction of fresh water inflows to bays and estuaries.

Under the “Opt” scenario, municipal and industrial water use increase by 143,000 and 572,000 ac-ft state wide, while fresh water inflows to bays and estuaries reduces by 445,000 ac-ft. The Colorado, Cypress, Sulfur and Red basins are the sources for the seven optimal IBTs. Each of these basins experiences a significant reduction in fresh water inflows to bays and estuaries. On the other side, the destination basins Brazos, Guadalupe-San Antonio, and San Jacinto incur a significant increase in either municipal or industrial use or fresh water inflows to bays and estuaries.

The Trinity serves as both a source basin for Bayou_TriToSan and destination basin for Parkhouse_SulToTrin, Pines_CypToTrin, and Texoma_RedToTrin, therefore the impacts on water allocation is mixed. Water use in Trinity for municipal and industry increases by 59,000 and 32,000 ac-ft while showing a loss of 493,000 ac-ft in fresh water flow to bay, so we can see that Bayou_TriToSan project transferring water 540,000 ac-ft to San Jacinto plays a more important role.

Under “env” scenario, municipal and industrial water use increase by 79,000 and 6,500 ac-ft state wide, while fresh water inflows to bays and estuaries is reduced by 40,000 ac-ft. Under “pert” scenario, municipal water use will increase by 23,000 ac-ft while the loss of fresh water inflows to bays and estuaries is 10,700 ac-ft.

Overall three scenario analysis implies that source of water transfer is surplus of instream flows in the source basins while beneficiary is the municipal or industry sector. The impact of IBTs on other sectors for example agricultural sector for both source basin and destination basin or third basins are trivial.

Table 14: Water use impact (thousand ac-ft)

Basin	Sector	Base	Opt-Base	Env-Base	Pert-Base
Brazos	ag	46.021	0.004	-0.001	-0.023
Brazos	mun	462.220	23.47	23.47	23.47
Brazos	outtobay	6683.833	8.413	13.553	13.786
Brazos	**sum**	**7505.233**	**31.887**	**37.021**	**37.234**
Colorado	ag	127.470	0.456	1.015	1.168
Colorado	outtobay	2661.514	-84.353	-24.303	-24.517
Colorado	**sum**	**3154.809**	**-83.897**	**-23.287**	**-23.349**
Cypress	outtobay	1570.228	-48.29	-48.29	
Cypress	**sum**	**1698.107**	**-48.29**	**-48.29**	
Guadsan	ag	45.302	0.072	-0.008	-0.008
Guadsan	mun	130.966	60.694		
Guadsan	outtobay	1848.070	33.055	0.008	0.008
Guadsan	**sum**	**3294.789**	**93.821**	**-0.001**	**-0.001**
Lavaca	ag	1.803	-0.46	-1.017	-1.155
Lavaca	outtobay	784.632	0.431	0.952	1.081
Lavaca	**sum**	**786.801**	**-0.029**	**-0.065**	**-0.074**
Neches	outtobay	5501.057	-0.051		
Neches	**sum**	**5677.301**	**-0.051**		
Nueces	ag	9.317	-0.072	0.008	0.008
Nueces	outtobay	524.243	0.067	-0.008	-0.008
Nueces	**sum**	**597.031**	**-0.005**	**0.001**	**0.001**
Red	outtobay	9542.540	-10.332	-13.793	1.998
Red	**sum**	**9708.254**	**-10.332**	**-13.79**	**2.008**
Sabine	outtobay	6295.282	0.051		
Sabine	sum	6520.255	0.051		
SanJacinto	ind	377.990	540		
SanJacinto	outtobay	1649.174	181.332		
SanJacinto	**sum**	**2427.242**	**721.332**		
Sulphur	outtobay	2382.205	-31.948	-0.144	-2.111
Sulphur	**sum**	**2410.227**	**-31.948**	**-0.144**	**-2.111**
Trinity	ind	307.811	31.664	6.479	

Trinity	mun	1169.508	58.921	55.642	
Trinity	outtobay	5696.402	-493.117	31.743	-0.91
Trinity	**sum**	**7174.247**	**-402.532**	**93.864**	**-0.91**
Total	ind	1579.996	571.664	6.479	
Total	mun	2912.467	143.085	79.112	23.47
Total	outtobay	47273.587	-444.742	-40.281	-10.672
Total	**sum**	**53187.302**	**270.008**	**45.309**	**12.797**

6.4 Water allocation impacts of IBTs on major cities

The above sections discussed the impacts of IBTs on water allocation on riverbasins and results imply that water is mainly transferred for municipal and industrial purpose. This section will discuss the detailed impacts on major cities (table 15). The next section will discuss the impacts on major industrial counties (table 16).

San Antonio, Arlington, Fort Worth, Tyler, San Angelo, Round rock, Plano, Cedar Park, Georgetown, Corsicana, Mansfield and McKinney are major cities where water allocation is less than the projected demand under the baseline model in section 4.1.3. If there is no ground water available, these cities will face a water shortage issue, but we lack sufficient information to identify cities having ground water source. Here we only list the impacts of IBTs on the major cities' water allocation. Under the "opt" scenario, total city water allocation increases by 143,000 ac-ft, where

- 61,000 ac-ft is for San Antonio via LCRASAWS_ColToGdsn,
- 39,000 ac-ft is for Fort Worth via Pines_CypToTrin,
- 23,000 ac-ft is for Round Rock, Cedar Park and George Town via LCRABRA_ColToBrz.

The water shortages in San Antonio, Fort Worth are greatly relaxed while in other cities listed in the table 14, the water shortage is eliminated.

Under the "env" scenario, LCRASAWS_ColToGdsn and Parkhouse_SulToTrin are ruled out of solution, resulting in an increase of 79,000 ac-ft in water allocation in major cities. This includes

- 39,000 ac-ft for Fort Worth via Pines_CypToTrin,
- 23,000 ac-ft for Round Rock, Cedar Park and George Town via LCRABRA_ColToBrz.

Under the "pert" scenario, only LCRABRA_ColToBrz with option 1 and option 2 are optimal, realizing an increasing of 23,000 ac-ft for Round Rock, Cedar Park and George Town.

Overall, if no restriction on IBTs is applied, the IBTs will greatly solve cities water shortage issues especially for San Antonio and the Fort Worth region. Therefore, inter-basin water transfer is one prominent option that a policy maker should take into consideration.

Table 15: Cities' water allocation (thousand ac-ft)

City	**Pre-demand**	**Base**	**Opt-Base**	**Env-Base**	**Pert-base**
Allen	23.616	22.252	1.332	1.332	
Cedar Park	10.924	3.330	6.547	6.547	6.547
Dallas	389.338	388.565	2.607		
Denton	29.599	29.460	0.199		
Fort Worth	149.572	100.769	38.555	38.555	
Garland	42.850	40.123	2.997	2.997	
George Town	8.604	2.690	5.088	5.088	5.088
Grapevine	13.496	13.451	0.093		
Irving	55.410	55.226	0.381		
Mansfield	13.537	9.358	3.256	3.256	
McKinney	24.672	22.544	2.086	2.086	
Plano	72.619	64.982	7.415	7.415	
Round Rock	19.627	5.782	11.835	11.835	11.835
San Antonio	216.073	138.480	60.694		
Total	**1069.937**	**897.012**	**143.085**	**79.111**	**23.47**

6.5 Water allocation impacts of IBTs on major industrial counties

In section 4.1.4, Brazoria, Nueces, Harris, Dallas, Hutchinson, Tarrant, Harrison, Live Oak and Victoria are counties facing major water shortage problems. Table 16 shows the optimal water allocations for major industrial counties by IBT scenario.

Water transferred through Bayou_TriToSan is exclusively used by Harris County making the water use in Harris County greater than the projected demand. This is because optimal water transfers will be where marginal benefit equals marginal cost.

Parkhouse_SulToTrin brings 25,000 ac-ft to Dallas County under “opt” scenario and is optimal under both “opt” and “env” scenarios, realizing 6,500 ac-ft of water to Tarrant County. Under “pert” scenario, no IBTs are feasible for industrial water transfer.

Table 16: Major industrial counties water allocation (thousand ac-ft)

ind counties	**Pre-demand**	**Base**	**Opt-Base**	**Env-Base**	**Pert -Base**
Dallas	37.025	11.832	25.186		
Tarrant	17.691	9.44	6.479	6.479	
Harris	397.279	375.46	540		

6.6 Instream impacts of IBTs

Table 17 shows the impacts of IBTs on instream flows. Our interests are to see how IBTs affect the instream flows for source basins, destination basins as well as the third parties. In particular, Colorado, Sulphur, Cypress, and Red basins are source basins, while Guadalupe-San Antonio, Brazos and San Jacinto are destination basins. The Trinity basin serves as both a source and destination basin.

The average instream flows in all source basins decrease under the "Opt" scenario by about,

- 0.29% in the Colorado,
- 0.19% in the Red,

- 1.29% in the Sulphur, and
- 1.28% in Cypress.

Instream flows for all destination basins increases, where stream flow increases by 1.26% in Guadalupe-San Antonio, 0.19% in Brazos, 0.61% in San Jacinto.

As both a source and destination basin, Trinity realized a net loss of 0.37% instream flow under “Opt” scenario since the effect of Bayou_TriToSan outweighs the other two IBTs. However, under “env” scenario, it becomes a sole destination, realizing a rise of 0.71% instream flows.

Instream flows in third basins may increase or decrease or do not change. For example, instream flows in Lavaca, Nueces will increase by 0.36%, 0.10%, while decrease slightly in Neches by 0.05% and have no effect in Canadian, Trinity-San Jacinto Basin.

Table 17: Annual Instream flows under scenarios

	Base (thousand ac-ft)	**Opt-base (%)**	**Env-base (%)**	**Pert-base (%)**
Brazos	470,083	0.19	0.17	0.30
Colorado	389,904	-0.29	-0.23	-0.26
Canadian	29,955			
Red	443,857	-0.19	-0.02	-0.03
Sabine	1,042,680	-0.02	-0.01	-0.02
Guadsan	212,044	1.26	0.20	0.54
Sulphur	540,280	-1.29	-0.21	0.08
Cypress	180,188	-1.28	-1.44	0.02
Neches	805,612	-0.05	-0.04	
Trinity	711,669	-0.37	0.71	-0.19
TrinitySanJac	22,753			
SanJacinto	257,627	0.61	0.58	0.31
Lavaca	110,757	0.36	0.22	0.23
Nueces	116,448	0.10	0.01	0.10

7 Conclusions

This study develops an integrated economic-hydrological model to examine proposed inter-basin water transfer projects in Texas in the face of water scarcity issues while assuming efficient water allocation. The model includes 21 Texas riverbasins explicitly covering 46 major municipal cities, 25 major industrial counties, 44 agricultural counties, 175 major reservoirs and 51 proposed inter-basin water transfer projects. 21 agricultural crops are introduced in the model for analysis of agricultural activities.

The model maximizes regional expected net benefits of water use accrued from municipal, industrial, agricultural, recreational, others, and fresh water flowing to bays against the cost incurred from IBTs construction while subject to hydrological, financial, institutional constraints. Nine states of nature are introduced to simulate the future climate thereafter influencing water demand and water availability.

If no IBT is built, there are total of 6.05 million ac-ft water used for these sectors in Texas bringing a net benefit of $8,450 billion. Among this, 3.9% of water use is for agriculture, 26.1% for industry, 50.5% for municipal sector, and 18.5% for recreation. Municipal water use plays a dominant role in total net welfare. The value of municipal and industrial net benefits must be carefully interpreted since it values areas under the demand curves, containing consumer and producer surplus, unlike Gross Regional Product (GRP), which is measured only with producer surplus.

Total agriculture water use averages 220,000 ac-ft accounting for 3.9% of total water use for all sectors. Since a large portion of irrigation water is from ground source, which is not modeled in this model, resulting that irrigated crop acres are much smaller than dry land acres. Out of 46 modeled big cities, 19 cities face different degrees of water shortage problems totaling 281,400 ac-ft in 2010. San Antonio, Arlington, Fort Worth, Tyler, San Angelo, and Round Rock have larger shortages especially San Antonio. On the industrial side Arlington, Brazoria, Nueces, Harris, Dallas, Hutchinson, Tarrant, Harrison, Live Oak and Victoria counties faces water shortage problems. Among them, water shortage is most serious in Brazoria County with a shortage of up to 111,000 ac-ft. Therefore, inter-basin water transfer strategy becomes an option to solve the water shortage issue.

To examine IBTs four scenarios are examined with the model.

- A baseline scenario without IBTs allowed;
- An optimal scenario “Opt” that allows all IBTs;
- An environmentally motivated scenario “env”, wherein IBTs with above medium high environmental impact are ruled out of the solution;
- A permitted IBT scenario “pert” that only allow the model to choose the IBTs under current permits.

We find 7 IBTs are economically attractive under “Opt” scenario. They are:

- Bayou_TriToSan,
- LCRABRA_ColToBrz with option 1 and option 2,
- LCRASAWS_ColToGdsn,
- Parkhouse_SulToTrin,
- Pines_CypToTrin, and
- Texoma_RedToTrin.

Under the “env” scenario,

- LCRABRA_ColToBrz with option 1 and option 2,
- Pines_CypToTrin, and
- Texoma_RedToTrin.

are optimal.

In the “Pert” scenario, only LCRABRA_ColToBrz with option 1 and option 2 are constructed.

We find that when an IBT is optimally chosen, the amount of water transferred remains at its maximum level and does not vary by scenario. Water is transferred from instream flows to San Antonio, Fort Worth, Round Rock, Plano, and Georgetown along with industry in Harris, Dallas, and Tarrant counties, realizing the gains of $2254, 513, 462 million respectively under the opt, env and pert scenarios.

Agriculture production activities are not meaningfully affected by the IBTs. Destination basins Brazos, San Jacinto, Trinity, and Guadalupe-San Antonio are winners while the source basins Colorado, Cypress, Red and Sulphur are essentially unaffected.

The unrestricted set of IBTs alleviates the water shortage issues especially for large cities like San Antonio and the Fort Worth region. But implementing the IBTs generally reduces source basin instream flows and fresh water inflows but increases them in destination basins.

There are some limitations in our analysis. One is that the groundwater component is not introduced in our model with our modeling and analysis based on the surface water. This will restrict comprehensive understanding on water demand, instream flows, necessities of inter-basin water transfers and their resulting social welfare changes. More accurate information on IBT should be included. Furthermore, other than recreational value, the value of instream flows is ignored in the model and the value of bay and estuary inflows is held at a very low level. Future research will focus on incorporating ground water part into the model.

However, this research examined the water scarcity issue under optimal water allocation and developed an inter-basin water transfer evaluation system that integrates the effects of the proposed water transfer on the economic, hydrologic and environment in Texas. This system yields information on economic implications for municipal, industrial and agricultural water users by basin. Such information can support effective public water policy making for state agencies, water management authorities and regional water planning groups. It can help them to devise appropriate compensation rules for origin basin and loss of instream uses.

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9 Appendix

Table 18**:** State of nature

State of nature	**Explanation**	**Years**	**Probability**
HDry	Very dry	1956, 1963, 1954	0.06
MDry	Medium dry	1964, 1951, 1988, 1978, 1955	0.10
Dry	Dry	1998, 1996, 1952, 1967, 1972, 1962, 1971	0.14
Dnormal	Dry-normal	1984, 1965, 1980, 1970	0.08
Normal	Normal	1977, 1976, 1966, 1959, 1997, 1953, 1983, 1982, 1981, 1958, 1949, 1960, 1969, 1986, 1985	0.30
Wnormal	Normal-wet	1989, 1975, 1950, 1994	0.08
Wet	Wet	1995, 1961, 1987, 1974, 1993, 1990, 1968	0.14
MWet	Medium wet	1979, 1991	0.04
HWet	Very wet	1992, 1973, 1957	0.06

Table 19: Crops covered in the model

Crop name	**Explanation (units)**
Barley	Barley All
Corng	Corn For Grain
Corns	Corn for silage (tons)
CottonP	Pima cotton (lb)
CottonU	Cotton Upland
Alfalfa2	Hay Alfalfa Dry
Hy	Hay other than Sorghum Hay (ton)
HayOth	Hay Other Dry
Ots	Grazing Oats (days)
Peanuts	Spanish Peanuts (cwt)

Rice	Rice (cwt)
PeanutsR	Runner peanuts(ton)
Sorghum	grain sorghum (cwt)
Soybeans	(bu)
Sugarbeets	Sugar beets
Sugarcane	(tons)
Sunflower	(cwt)
SunflowerO	Sunflower seed for oil use
SunflowerNo	Sunflower seed for non oil use
Wheat	Wheat All
Winwht	Winter Wheat (bu)

Source: United States Department of Agriculture (USDA/NASS), "*Crops County Data Files*"

Table 20: Data on Inter-basin water transfers in the model

Status	**IBT names**	**Option**	**Origin**	**Destination**	**Capacity**	**FC**	**VC**
RIBT	Toledo_SabToTrin	Opt1	Sabine	Sabine	50000	1.36E+08	128.896
RIBT	Toledo_SabToTrin	Opt2	Sabine	Sabine	50000	2.15E+08	143.239
RIBT	Toledo_SabToTrin	Opt3	Sabine	Sabine	50000	1.73E+08	151.44
RIBT	Marvin_SulToTrin	Opt1	Sulphur	Trinity	172800	1.55E+08	115.189
RIBT	Marvin_SulToTrin	Opt2	Sulphur	Trinity	174840	1.6E+08	97.474
UIBT	Patman_SulToTrin	Opt1	Sulphur	Trinity	100000	35284600	203.334
UIBT	Patman_SulToTrin	Opt2	Sulphur	Trinity	100000	32025600	233.414
UIBT	Patman_SulToTrin	Opt3	Sulphur	Trinity	100000	32025600	233.414
UIBT	Patman_SulToTrin	Opt4	Sulphur	Trinity	112100	42465000	110.027
UIBT	Patman_SulToTrin	Opt5	Sulphur	Trinity	180000	68226000	110.522
UIBT	Patman_SulToTrin	Opt6	Sulphur	Trinity	180000	61349000	120.483
UIBT	Patman_SulToTrin	Opt7	Sulphur	Trinity	180000	77222200	165.754
UIBT	Patman_SulToTrin	Opt8	Sulphur	Trinity	130000	1.41E+08	180.237

UIBT	Texoma_RedToTrin	Opt1	Red	Trinity	113000	15023400	55.766
UIBT	Texoma_RedToTrin	Opt2	Red	Trinity	105000	43752600	222.347
UIBT	Texoma_RedToTrin	Opt3	Red	Trinity	50000	13616200	75.796
UIBT	Texoma_RedToTrin	Opt4	Red	Trinity	105000	49935400	230.996
UIBT	Rayburn_NecToTrin	Opt1	Neches	Trinity	200000	97276800	179.086
UIBT	Rayburn_NecToTrin	Opt2	Neches	Trinity	200000	1.05E+08	211.028
UIBT	Rayburn_NecToTrin	Opt3	Neches	Trinity	200000	97276800	179.086
UIBT	BoisdArc_RedToTrin	Opt1	Red	Trinity	123000	29606800	41.823
UIBT	Fork_SabToTri	Opt1	Sabine	Trinity	119900	27066600	48.89408
UIBT	Parkhouse_SulToTrin	Opt1	Sulphur	Trinity	112000	27786800	77.823
UIBT	Parkhouse_SulToTrin	Opt2	Sulphur	Trinity	118960	26932200	69.484
UIBT	Palestine_NecToTrin	Opt1	Neches	Trinity	111460	30993600	73.662
UIBT	Palestine_NecToTrin	Opt2	Neches	Trinity	133400	37158400	75.90405
UIBT	Fastrill_NecToTrin	Opt1	Neches	Trinity	112100	42248200	79.249
UIBT	Parkhouse_SulToTrin	Opt3	Sulphur	Trinity	108480	35541600	77.059
UIBT	Pines_CypToTrin	Opt1	Cypress	Trinity	89600	25708200	201.471
UIBT	Pines_CypToTrin	Opt2	Cypress	Trinity	87900	19227000	188.771
UIBT	Pines_CypToTrin	Opt3	Cypress	Trinity	87900	35002200	242.956
UIBT	RalphHall_SulToTrin	Opt1	Sulphur	Trinity	32940	15651200	75.252
UIBT	Columbia_NecToTrin	Opt1	Neches	Trinity	35800	16544120	80.581
UIBT	Marcoshays_GdsnToCol	Opt1	Guadsan	Colorado	1680	577162.2	354.73
UIBT	Marcoshays_GdsnToCol	Opt2	Guadsan	Colorado	1302	446339.2	353.96
UIBT	LCRASAWS_ColToGdsn	Opt1	Colorado	Guadsan	75000	1.53E+08	302.847
UIBT	LCRASAWS_ColToGdsn	Opt2	Colorado	Guadsan	18000	9598600	611.133
RIBT	AlanHenry_BrzToCol	Opt1	Brazos	Colorado	16800	17946000	130.595
UIBT	LCRABRA_ColToBrz	Opt1	Colorado	Brazos	3472	1478400	338.306
UIBT	LCRABRA_ColToBrz	Opt2	Colorado	Brazos	20928	8133600	332.11
UIBT	LCRABRA_ColToBrz	Opt3	Colorado	Brazos	1800	811400	338.667
UIBT	JoePool_TrinToBrz	Opt1	Trinity	Brazos	20000	6285380	285.891
UIBT	Bayou_TriToSan	Opt1	Trinity	SanJacinto	540000	11173010	9.269
RIBT	Bedias_TriToSan	Opt1	Trinity	SanJacinto	90700	5975025	135.303
RIBT	ETWT_SabNecToTri	Opt1	Sabine	Trinity	155646	23414010	15.6285
RIBT	ETWT_SabNecToTri	Opt1	Neches	Trinity	117305		

UIBT	Livingston_TriToSan	Opt1	Trinity	SanJacinto	59000		
UIBT	Garwood_ColToNus	Opt1	Colorado	Nueces	35000	5606400	399.931
UIBT	Garwood_ColToNus	Opt2	Colorado	Nueces	35000	471833	399.931
UIBT	Garwood_ColToNus	Opt3	Colorado	Nueces	35000	3624232	399.931

Capacity: ac-ft; FC: fixed cost ($); VC: variable unit cost ($/ac-ft)

Source: Texas Water Development Board, **“***2006 Adopted Regional Water Plan***”**

Table 21: Return flow percentages by sector

Sector	**ag**	**ind**	**mun**	**rec**	**other**
Return flow percent (%)	0.0637	0.3358	0.5452	1	0.3358

Source: Gillig, McCarl, and Boadu (2001)