ENVIRONMENTALLY RELATED WATER TRADING, TRANSFERS AND ENVIRONMENTAL FLOWS: WELFARE, WATER DEMAND AND FLOWS

A Dissertation

by

MAN SEUNG HAN

Submitted to the Office of Graduate Studies of
Texas A&M University
in partial fulfillment of the requirements for the degree of

DOCTOR OF PHILOSOPHY

May 2008

Major Subject: Agricultural Economics

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Approved by:

Co-Chairs of Committee,	Bruce A. McCarl Richard T. Woodward
Committee Members,	Frederick Boadu Ronald Kaiser
Head of Department,	John P. Nichols

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ABSTRACT

Environmentally Related Water Trading, Transfers and
Environmental Flows: Welfare, Water Demand and Flows. (May 2008)

Man Seung Han, B.S., Korea University;
M.A., Yonsei University
Co-Chairs of Advisory Committee: Dr. Bruce A. McCarl
Dr. Richard T. Woodward

This dissertation reports on economic studies of Texas Interbasin Water Transfers (IBT) as a way to lessen expected water shortages, Texas minimum freshwater inflows requirements (FWIB) to protect environmental flows and the general policy setup when generators of environmental commodities might be able to sell credits in multiple markets. The Texas-based studies address economic, hydrological and environmental impacts, focusing on welfare gain, water demand, environmental flows and complementary relationship of environmental commodities.

Conduct of the two Texas studies required development of a Texas surface water model. The developed model incorporates: (a) uncertain weather patterns and supply of water; (b) river flows in most of the Texas river basins - twenty-one basins excluding only the Rio Grande; (c) demand for water by agricultural, municipal and industrial/ mining water; (d) IBT possibilities; (e) evaporation losses; and (e) return flows across the modeled basins.

In studying the interbasin water transfers, three IBT projects where chosen as economically justified relocating water largely for municipal and industrial/mining uses. These IBT projects had the effect of increasing water use and instream flows in the IBT destination basins, but decreasing those in the source basins.

In studying the freshwater inflows the study revealed that the suggested inflow constraints were met on average and that the inflow levels for two basins had to be lowered for the constraints to be feasible. This suggests that the contemplated limits are too high and that either multiple basin or flow dependent limits need to be developed. The results also showed that under the average FWIB constraints and IBT implementation, welfare loss from the FWIB constraints was greatly reduced due to the IBT projects which were simultaneously implemented.

In the study of multiple environmental commodity markets, the results indicate that generated credits should be sold in multiple markets only when market caps are set

up close to socially efficient (so called first-best) caps: this implies that marginal benefit curves are very steep. However, restricting selling into just single market achieved the same net benefits as multiple markets did when market caps were set up at levels less than the first-best caps.

DEDICATION

To my Lord and family, you are my source of strength and wisdom.

ACKNOWLEDGEMENTS

I would like to thank the co-chairs of my committee, Dr. Bruce McCarl and Dr. Richard Woodward, for their encouragement and dedication to this dissertation. They showed me how to approach economics and gave me special insights into modeling environmental and water issues. I would also like to thank the members of my committee, Dr. Frederick Boadu and Dr. Ronald Kaiser, for contributing to my understanding of water right issues and legal aspects of interbasin water transfers.

My thanks are extended to the Texas Sea Grant College Program who supported my career as a research fellow in the Water Resources Branch at the Texas Parks and Wildlife Department, where I worked on the issue of economic valuation of Texas rivers, studying environmental flows and hydrological issues over two years.

Special thanks go to my wife, Rosa, and my parents for their unending sacrifice and patience. Thanks to my children Joseph, John, Mary and Madeleine for giving me energy when I was tired. Thanks to Fr. Chung and the St. Andrew Kim Catholic Church members in Austin for giving me spiritual strength and wisdom through their prayers. We are all one in God.

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CHAPTER I

INTRODUCTION

Water is a commodity that is frequently discussed in the context of environmental trading from both a quantity and quality perspective. Water quantity trading refers to water markets and Interbasin Water Transfers (IBT) where water is conveyed from one set of users to another set of users with money exchanged (Boadu, 2004). Water quality trading refers to the markets where the rights to discharge pollutants into water bodies are traded (Kieser & Associates, 2003). These problems are interrelated such that water quantity trading affects flows and pollutant levels in source and destination water bodies. Therefore, water quality can be at issue when water quantity trading occurs.

This dissertation examines the water quantity issue in a trading context, focusing on welfare gain, water demand and environmental flows that affect water quality. Investigations will be conducted regarding

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This dissertation follows the style of *American Journal of Agricultural Economics*.

- the economic, hydrological and environmental effects of implementing IBT projects,
- the economic, hydrological and environmental effects of implementing the minimum requirements of freshwater inflows to bays and estuaries,
- the design of policy in terms of appropriate design of market incentives when an action can jointly produce more than one potentially salable environmental good.

The water quality issue will not be investigated here..

Motivation for the IBT research arises from water scarcity in western Texas coupled with relative abundance in eastern Texas. Based on this, IBT projects have been widely discussed as ways to lessen water shortage problems (TWDB, Water for Texas 2002). In considering IBT projects, state law suggests that economic impacts and water quality changes should be examined.

Another factor in such decisions involves the level of freshwater inflows to Texas estuaries. The Texas Parks and Wildlife Department (TPWD) and the Texas Water Development Board (TWDB) have jointly developed a set of standards deigned to maintain estuary health and productivity.

The work is also motivated by interrelationships among multiple environmental commodities such as instream flows, freshwater inflows and wetland health when flow levels are altered. As the number of market-based environmental protection programs grows, so does the potential for interaction among those environmental commodities. As a result, there is a rising interest in the concept of “multiple markets”, the notion that generators of environmental credits might be able to sell credits in many markets.

The objective for this research is to provide economic information for use in water policy formation addressing the scope and implications of economically justified IBT projects in Texas, the cost of Texas freshwater inflow constraints and trading scheme setup under multiple interrelated environmental markets. To conduct this research in the context of the IBT and FWIB decision making an empirical model will be setup and used. The multiple markets concern will be examined analytically and with a simple numerical model.

The dissertation is organized around four somewhat independent essays with this unifying introduction and a unifying conclusion

Chapter II presents an essay on the model structure developed for the IBT and freshwater inflow portions of this work, which quantifies the economic, hydrological and environmental impacts of surface water actions.

Chapter III presents an essay on the analysis of the value and consequences of implementing IBT projects using the model from Chapter II.

Chapter IV presents an essay on the economic and environmental effects of environmentally sustainable minimum requirements of freshwater inflows to bays and estuaries, which uses the model developed in Chapter II and extends the analysis in Chapter III.

Chapter V presents an essay on the way that one might design policy to accommodate valuable environmental commodities that are jointly produced such cases as freshwater inflows, instream flows and wet lands when they can be traded in multiple markets.

Finally, a summary and set of overall conclusions are presented in Chapter VI.

CHAPTER II

MODELING FRAMEWORK FOR THE EVALUATION OF INTERBASIN WATER TRANSFER

2.1. Introduction

This chapter presents material on development and structure of the empirical model that will be used to examine the impacts of Texas based IBT projects and freshwater inflow constraints. After a literature review of pieces relevant to this research, the chapter presents the analytical framework including material on the scope, precursors and characteristics of the model. Then, mathematical structure of the model and a description of the data sets used follows.

2.1.1. Limitations of previous models

The IBT analysis aspects of the available Texas water models developed to date do not allow one to fully evaluate the economic and environmental impacts of IBT simultaneously. Hydrologically based water models commonly deal with hydrologic and environmental issues focusing on quantity issues such as water supply and water flows but do not typically have economic dimensions (i.e. see the model by Wurbs, 2003). Models with economic considerations typically only cover restricted areas. For example, the models in WatkinsJr et al. (2000) and Gillig et al. (2001) focus on the Edwards Aquifer and the related Nueces, Frio and Guadalupe-Blanco river basins.

2.1.2. Contribution of the research

This research develops a modeling framework that integrates and permits evaluation of the economic effects as well as hydrological and environmental impacts of IBT in Texas simultaneously based on IBT cost estimates available.

We incorporated uncertain weather patterns and thus measure the expected economic net benefit of using water as they vary across dry, normal and wet seasons. Changes in agricultural production activities and resulting water use changes due to IBT are also considered.

The model considers the hydrological water balances caused by demand for and supply of water as well as evaporation losses, rainfalls and return flows at selected points across the modeled river basins. The model depicts environmental aspects of water flows, say, instream flows and freshwater inflows to bays and estuaries. These water quantity indicators reflect important factors that affect water quality. The model also has constraints that can control IBT construction in environmentally sensitive regions.

This model is believed to be the first try to introduce environmental flow factors such as freshwater inflows in an economic and hydrological model.

As for the covered regions and sectors, the model includes major agricultural, municipal, industrial and mining uses plus a miscellaneous other water use. This is covered in cities and counties over the vast Texas river basins except for the Rio Grande basins where it borders Mexico.

The model will provide information that may allow state water agencies to analyze IBT proposals and to do analyses in support of statewide long run water management strategies. This is especially needed since state law requires agencies to weigh the 50 year impacts of any suggested IBT.

2.2. Analytical Framework

This research will depict water availability and use in 21 Texas river basins in its scope: 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, Nueces. The Nueces-Rio Grande and Rio Grande river basins are excluded as of now.

The optimal set of IBT projects is determined on the basis of maximizing the annualized expected net benefit of using agricultural, municipal, industrial and mining water plus assigned value of freshwater inflows with sets of constraints on agricultural land and water use, total water use by source and sector, demand curve convexity, freshwater inflows, hydrological water flows balance, and reservoir / IBT capacity, etc.

2.2.1. Scope of the model

Table II-1 shows 18 river basins in the model which covers 21 of the 23 Texas river basins defined by the Texas Water Development Board (TWDB, 2006a) (omitting Nueces-Rio Grande and Rio Grande, Figure II-1). Some basins are grouped together following practices in the Water Availability Model (WAM) and the underlying program Water Rights Analysis Package (WRAP) developed by R.A. Wurbs (Wurbs, 2003).

The model contains 35 big municipal water use cities, 40 major industrial and mining water use counties, 62 major agricultural water use counties with 21 agricultural crops and 175 major reservoirs based on 660 monthly naturalized river flows data. The details of data are discussed in section 2.4. Details on Model Empirical Specification. The model is developed using General Algebraic Modeling System (GAMS).

Table II-1. River Basins Covered in the Model

Basin name in the model	Original basin name(s)
Brazos	Brazos and Brazos-San Jacinto river basin
Colorado	Colorado and Brazos-Colorado river basin
Canadian	Canadian river basin
Red	Red river basin
Sabine	Sabine river basin
Guadsan	Guadalupe and San Antonio river basin
Sulphur	Sulphur river basin
Cypress	Cypress river basin
Neches	Neches river basin
NechTrinity	Neches-Trinity river basin
Trinity	Trinity river basin
TrinitySanJac	Trinity-San Jacinto river basin
SanJacinto	San Jacinto river basin
ColLavaca	Colorado-Lavaca river basin
Lavaca	Lavaca river basin
LavaGuadl	Lavaca-Guadalupe river basin
SanioNues	San Antonio-Nueces river basin
Nueces	Nueces river basin

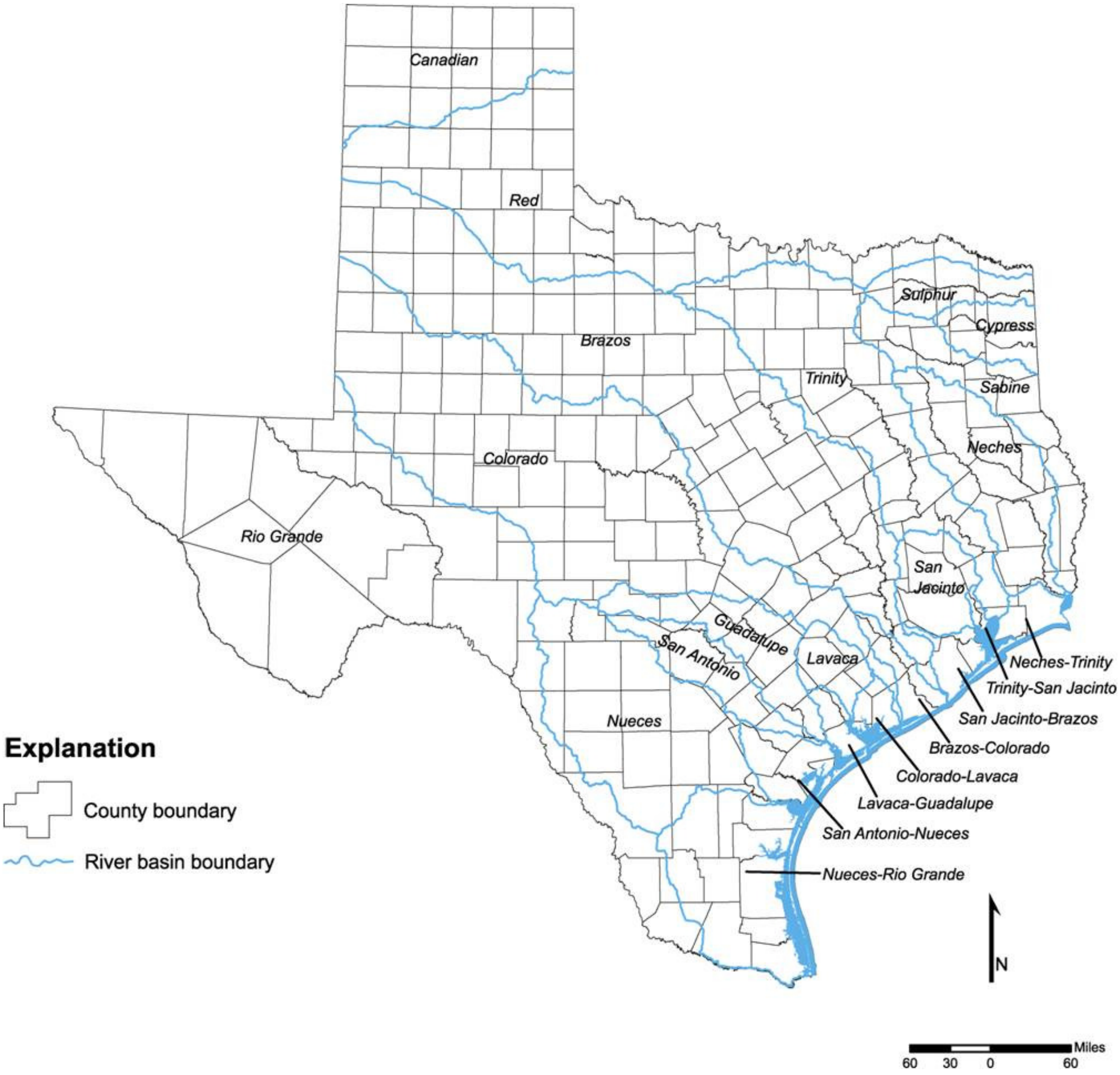


Figure II-1. 23 river basins in Texas

2.2.2. Precursors to the model

This research will be built upon three models.

- First, the data that specified the Water Rights Analysis Package (WRAP) model used in the Senate Bill 1 planning process (Wurbs, 2005) will be used to provide the hydrologic data components such as naturalized flows. The WRAP model was developed by Wurbs which is used in the Texas regional water investigation process.

- Second, the contribution of modeling by Gillig et al (2000) on Edwards Aquifer Groundwater and River System Simulation Model (EDSIMR) that maximizes expected net benefits of groundwater and surface water uses in the Edwards Aquifer region by municipal, industrial and agricultural sectors. The objective function, expected net benefit, is affected by the stochastic climate-related state of nature and climate probability distribution.

- Last of all, even though it is not directly dealt with in this research, the model herein is developed keeping in mind its potential link with a water quality simulation which can be utilized in the Soil and Water Assessment Tool (SWAT). SWAT simulates the effects of management such as water transfer and water use changes on water, sediment and agricultural chemical yields in large complex and un-gauged watersheds.

2.2.3. Characteristics of the model: TEXRIVERSIM

TEXRIVERSIM is a stochastic model that uses the data representative of rainfall and temperature conditions, with nine climate states of nature present in the model. TEXRIVERSIM is a two stage stochastic programming model with recourse. In the first stage the crop mix and IBT construction decisions are made independent of the state of nature. Subsequently in the second stage, water availability and yields are realized by the state of nature and adjustments are allowed in management with IBT transfers. The model depicts potential construction of 45 IBT projects: 8 IBT projects that move water from river-to-river IBT and 37 IBT projects that move water from a river to a specifically designated user. Water transfer volume by IBT is determined in the second stage given the state of nature (water availability) information but use requires that IBT-related construction occur in the first stage.

TEXRIVERSIM integrates three factors: (1) economic water use modeling in the form of: fixed-price agricultural production linear programming model that chooses dry land and irrigated crop acres; explicit downward sloping nonagricultural water use curves for municipal, industrial and mining uses; fixed price water demand curves for a number of small users up to a maximum quantity. (2) environmental and hydrological factors: stochastic climate effects, evaporation, instream flows, return flows and freshwater inflows to bays and estuaries. (3) IBT factors including fixed and variable costs, locations for IBT facility development projects and their maximum capacity to deliver water.

2.3. Description of the Model: TEXRIVERSIM

2.3.1. Objective function

The model maximizes an objective function that represents the annualized expected net benefit (ENB) of water use by the nonagricultural and agricultural sectors plus a value for freshwater inflows to bays and estuaries less the costs of IBT construction and operation. Conceptually it is as follows.

Maximize Annual ENB[1] =

- Fixed costs of IBT construction

+ Probability × [Net Benefits from city and county water use

+ Net Benefits for crop from agricultural water use

---

[1] The summation notation is needed to add all of net benefits and values of freshwater inflows, but this is just conceptual.

- Variable costs of IBT operation

+ Value of freshwater inflows to bays and estuaries]

Probability represents the statewide frequency of the state of nature. Nonagricultural city and county water use, other nonagricultural and freshwater inflows, and agricultural water use depend on the state of nature. Fixed and variable IBT costs are assumed to be independent of the state of nature but the volume of water transferred does depend on the state of nature.

IBT related costs

Water delivery costs consist of variable and fixed components. The fixed cost component gives the annualized cost if an IBT is built (*ribtfixed cost*, *uibtfixed cost* in the objective function below)[2]. The integer variables (RIBTCON and UIBTCON) indicate whether or not an IBT is constructed. The variable cost component depends on the amount of water used and includes: (1) withdrawal costs for nonagricultural and agricultural water (*nonagcost, agwatercost* in the objective function) and (2) variable cost for operating water transfers (*ribtcost, uibtcost*).

---

[2] The notation in the objective function is explained in the context here and other notations used in constraints are summarized in APPENDIX A.

The IBT-related facility construction variables are not dependent on the state of nature and are thus contained in the first stage of the model and their fixed costs are amortized over the project time span. Two types of IBTs are included in the model: User IBT (USERIBT) and River IBT (RIVERIBT). USERIBT is a “river-to-user” IBT that transfers water from a river to a particular diverter like a large city. Therefore, water from USERIBT is dedicated to a diverter. RIVERIBT is a “river-to-river” IBT that is transferred to a control point for use by diverters along that river. Water from RIVERIBT is added into the water flows of the destination river basin before it is diverted or used in any way.

Municipal, industrial & mining water use benefits

Benefits from using water in the nonagricultural sector are determined by the areas under the nonagricultural demand curves with constant elasticity based on the estimates by Bell and Griffin (2005) (*MUNSTEP* for municipal water use, *INDSTEP* for industrial and mining water use). These are included in the model as follows.

First, the demand curve is illustrated in Figure II-2. This demand curve is constructed using the point expansion method based on the observed water price-quantity point. We use the water quantity projected (Q_{PRO}) by each regional groups and

TWDB based on year 2010. The water price (P_{PRO}) is year 2003 marginal price and annual price increase in year 2010 is not assumed.

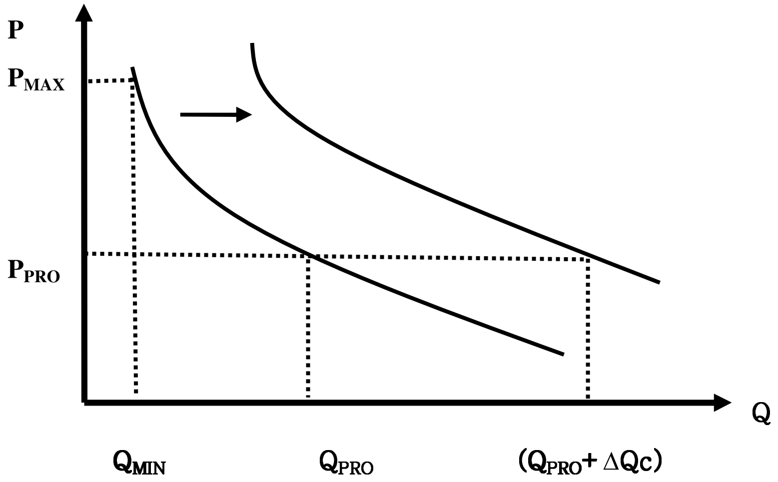


Figure II-2. Water demand curve and climate-driven shift

Second, we note that the upper left side of the curve approaches infinity in price yielding a very large area. This is undesirable because we really do not know about the choke price of water which is the maximum willingness to pay for a unit of water. Consequently, the curves are truncated at 2/10th the level of observed consumption levels (Q_{MIN}). The demand curve can generate a large objective function value especially when the demand curve is inelastic as the curve is asymptotic to the axis. Also optimal water uses are expected to occur somewhere close to the observed level of water use and its future projection (Q_{PRO}). The objective function value must be carefully interpreted since it values areas under the demand curves, unlike, for example, Gross Regional Product (GRP) which is measured with a market price times quantity as its gross benefit.

Third, a climate-driven demand shifting factor is introduced into the municipal demand curves to reflect the effect of climate on water demand. Figure II-2 shows a case where the effect of the climate-driven demand shifting factor (ΔQc) induces demand to increase, shifting the demand curve to the right. The shifting factor was developed by Griffin and Chang (1990) and more recently by Bell and Griffin (2005). It is defined in our analysis as the number of monthly days without rainfall multiplied by monthly average temperature (F) then divided by 1000 (Cvalue). The shift differs by the state of nature and is defined in the objective function as:

$$\text{Climate-driven municipal demand shifting factor} = \left(1+\varepsilon_{dm}^{c}\frac{\Delta\hat{c}_{d,y,m}}{\hat{c}_{d,y,m}}\right)^{-\frac{1}{\varepsilon_{dm}^{p}}}$$

where $\varepsilon_{\mathrm{dm}}^{\mathrm{p}} = \text{price elasticity}, \varepsilon_{\mathrm{dm}}^{\mathrm{c}} = \text{climate elasticity},$

$\Delta\hat{c}_{\mathrm{d,y,m}} = \hat{c}_{\mathrm{d,y,m}} - \bar{c}_{\mathrm{d}}$, $\hat{c}_{\mathrm{d,y,m}} = \text{Cvalue}$, $\bar{c}_{\mathrm{d}} = \text{average Cvalue}$

The exponent term $\left(= -1/\varepsilon_{dm}^{p}\right)$ in this shifting factor causes large shifts when the price elasticity (ε_{dm}^{p}) is inelastic. Municipal price elasticities range from -0.159 ~ -0.359, and industrial price elasticity is -0.540 in our model. The corresponding municipal exponent term falls on between 6.289 and 2.786. Price elasticity is defined as the % change in quantity given a % change in price and climate elasticity as the % change in quantity given a % change in climate.

Fourth, this nonlinear benefit function is approximated in stepwise form using a separable programming which is a form of the first order Taylor series expansion (McCarl, FASOMGHG Modeling Framework, 2006). We use 52 demand steps that span observed water quantities used.

Agricultural water use benefits

Agricultural demand is developed using regional linear programming models defined by county drawing water from particular river basins subdivided into reaches. Agricultural users pursue irrigated and/or dryland crop production. Modeling of crop substitution and irrigation choice is permitted.

Benefits from using water in the agricultural sector (*AGWATERUSE*) are represented by the net agricultural income derived from irrigated and dry land crop production (*yield*, *CROPACRES*). In that model climate shifts are incorporated by the state of nature. In particular, crop yields, irrigation water requirements, and water availability shift by state of nature. The cost of drawing water for agriculture

(*AGWATERUSE*) for the twelve agricultural regions in Texas was obtained from Texas Cooperative Extension.

Value of freshwater inflows to bays and estuaries

Freshwater inflows to bays and estuaries have value and thus we include a term for this in the objective function. To our best knowledge, it is the first try to introduce an environmental freshwater inflows factor in an economic and hydrological model.

The variable ESCAPETOBAY catches aggregated annual flows out to bays and estuaries in every river basin, depending on the state of nature, weighted by an observed probability of that state of nature. We could not find appropriate values for freshwater inflows to major Texas bays and estuaries, although the values from some basin might be extended in some basin (Han, 2007). The values of freshwater inflows are not subject to a market and obtained from non-market valuation methodology. Also, it is another issue to apply the numbers unilaterally into the model although we may find them because many different methodologies and assumptions were adopted for each of the non-market valuation. Currently we assigned a net value of $1 per acre foot to the freshwater inflows.

Algebraic depiction of the objective function

Now let us present the equations algebraically. In representing and depicting the model algebra we will use the actual GAMS commands. Some simplifications are made for readability, for example, eliminating tuples used to improve model speed. Variables are typed in capital letters and parameters in small letters. Each equation is followed by controlled sets in parenthesis and two dots, indicating an equation name. For example, the equation name AGLAND(countytouse)**..** is controlled by or a function of the set countytouse. For a definition of all symbols, see APPENDIX A.

Mathematically[3], the objective function can be written as follows[4].

Maximize ENB =

$$
\begin{aligned}
& prob_{d,y} * \left(\sum_{d}\sum_{y}\sum_{m} \int_{\hat{q}_{dm}/k}^{q_{dm}} p_{d,m}(q_{d,m}) d(q_{d,m}) - \sum_{d}\sum_{y}\sum_{m} \left(\mathrm{nonagcost}_{\mathrm{d,m}} * \mathrm{NONAGWATERUSE}_{\mathrm{d,y,m}} \right) \right) \\
& + prob_{d,y} * \left(\begin{array}{l} \sum_{d}\sum_{is}\sum_{c}\sum_{y} \left(yield_{d,is,c,y} * price_{d,is,c,y} - \mathrm{var}\cos t_{d,is,c,y} * CROPACRES_{d,is,c,y} \right)) \\ - \sum_{d}\sum_{R}\sum_{RP}\sum_{y}\sum_{m} \left(agwater\cos t_{d,R} * AGWATERUSE_{d,R,RP,y,m} \right) \end{array} \right) \\
& + ESCAPETOBAY \\
& - \sum_{RIBT} \left(ribtfixed\cos t_{RIBT} * RIBTCON_{RIBT} \right) - \sum_{UIBT} \left(uibtfixed\cos t_{UIBT} * UIBTCON_{UIBT} \right) \\
& - \sum_{RIBT}\sum_{y}\sum_{m} \left(ribt\cos t_{RIBT} * RIVERIBT_{RIBT,y,m} \right) - \sum_{UIBT}\sum_{y}\sum_{m} \left(uibt\cos t_{UIBT} * USERIBT_{UIBT,y,m} \right)
\end{aligned}
$$

---

[3] This model is just conceptual. The actual mathematical and computational models are more complex because of technical tools to speed up the model.

[4] Parameters and variables that are not defined will be defined in the relevant constraint sections.

where for municipal water use,

$$\sum_{d}\sum_{y}\sum_{m}\int_{\hat{q}_{dm}/k}^{q_{dm}} p_{d,m}(q_{d,m})d(q_{d,m})$$

$$=\sum_{d}\sum_{y}\sum_{m}\sum_{s}\frac{\varepsilon_{dm}^{p}}{1+\varepsilon_{dm}^{p}}\left(1+\varepsilon_{dm}^{c}\frac{\Delta\hat{c}_{d,y,m}}{\hat{c}_{d,y,m}}\right)^{-\frac{1}{\varepsilon_{dm}^{p}}}\hat{p}_{d,m}\hat{q}_{d,m}\left(qinc_{s}^{1+\frac{1}{\varepsilon_{dm}^{p}}}-qinc_{1}^{1+\frac{1}{\varepsilon_{dm}^{p}}}\right)\left(MUNSTEP_{d,y,m,s}\right)$$

and for industrial and mining water use,

$$\sum_{d}\sum_{y}\sum_{m}\int_{\hat{q}_{dm}/k}^{q_{dm}} p_{d,m}(q_{d,m})d(q_{d,m})$$

$$=\sum_{d}\sum_{y}\sum_{m}\sum_{s}\frac{\varepsilon_{dm}^{p}}{1+\varepsilon_{dm}^{p}}\hat{p}_{d,m}\hat{q}_{d,m}\left(qinc_{s}^{1+\frac{1}{\varepsilon_{dm}^{p}}}-qinc_{1}^{1+\frac{1}{\varepsilon_{dm}^{p}}}\right)\left(INDSTEP_{d,y,m,s}\right)$$

where d = diverter : CITY, COUNTY; y = state of nature, m = month, s = steps,

prob = probability of y, is = irrigation status, c = crop, R = river, RP = river place

RIBT & UIBT = RIBT & UIBT projects, $\varepsilon^{\mathrm{p}}_{\mathrm{dm}}$ = price elasticity, $\varepsilon^{\mathrm{c}}_{\mathrm{dm}}$ = climate elasticity,

$\hat{\mathrm{p}}_{\mathrm{d,m}}$ & $\hat{\mathrm{q}}_{\mathrm{d,m}}$ = base water price & quantity, k = truncation factor of demand curve

$\mathrm{qinc}_{\mathrm{s}}$ = proportion of water use for each step (= 0.1 ~ 4.0)

$\Delta\hat{\mathrm{c}}_{\mathrm{d,y,m}} = \hat{\mathrm{c}}_{\mathrm{d,y,m}} - \overline{\mathrm{c}}_{\mathrm{d}}$ where $\hat{\mathrm{c}}$ = Cvalue, $\overline{\mathrm{c}}$ = average Cvalue

2.3.2. Land and water demand constraints for agricultural sector

We impose three constraints on the agricultural sector: available land, crop mix balance, and irrigated water use balance.

Planting acres of land is absolutely constrained by land endowment. The available agricultural land constraint sets the limit of the land supply.

The crop mix balance equation by crop constrains harvested acres by crop to a historical mix of observed crop land which reflects rotation considerations and other factors following arguments in McCarl (1982) and Onal and McCarl (1989, 1991).

The water use balance equation constrains irrigated water use to the amount available from diversions by location after the state of nature is known.

Available agricultural land constraint

The crop land use across the crop mix patterns employed cannot exceed the land available in current irrigated use (availagland). In this equation, the optimal proportions (CROPMIX) of crop mix are decided. At the first stage, farmers are assumed to decide on crop acres by a convex combination of historically observed crop mix patterns (mixdata) because they do not know about the weather pattern which would happen that year. This is controlled on a county basis (countytouse) across all irrigation possibilities (irrigstatus) and crop mix possibilities (availmixdata). The “activemix” denotes a multidimensional set controlled by countytouse, irrigational possibilities, and crop, which has a historical mix data. The multidimensional set is called a tuple hereinafter. The “countytouse” is a subset of a county to denote that the county actually uses acreages for agricultural production.

```
AGLAND(countytouse)..

sum((irrigstatus,availmixdata), CROPMIX(countytouse,irrigstatus,availmixdata)

          *sum(activemix(countytouse,irrigstatus,crop),

          mixdata(countytouse,irrigstatus,crop,availmixdata  ≤  availagland(countytouse);
```

We allow for conversion of agricultural irrigated land to dry land but not the other way around due to the unlikelihood of expansions in agricultural surface water use in Texas. Then, the land being irrigated currently remains irrigated or goes dry.

Crop mix balance by crop

The crop mix constraint balances harvested acreage by crop and irrigation status (irrigated or dry land) against the acreage allowed by the crop mix possibilities. The constraint is defined for each state of nature and crop on an irrigated / dry crop land use basis.

The harvest variable CROPACRES is dependent on the realized state of nature and is thus in the second model stage. This is reflected in the CROPBALANCE equation once the state-independent CROPMIX variable is determined by the historically observed crop mix patterns at the first stage when the state of nature is unknown. That is why harvested crop acres are restricted by the past crop mix patterns in the equation.

```
CROPBALANCE(countytouse,irrigstatus,crop,state)..
CROPACRES(countytouse,irrigstatus,crop,state)
        *cropdata(countytouse,irrigstatus,crop,"land","all","annual")
        ≤  sum(availmixdata, CROPMIX(countytouse,irrigstatus,availmixdata)
        *mixdata(countytouse,irrigstatus,crop,availmixdata));
```

Agricultural irrigated water use balance

Agricultural irrigated water use (AGWATERUSE) is assumed to be linearly proportionate to crop acres. AGWATERUSE is determined by the state-of- nature dependent rate and the second stage production/harvest variable (CROPACRES) which is restricted by the first stage variable CROPMIX. The tuple isagther2 is a county in any control point of a river basin where agricultural farmers are engaged in their production activities.

```
AGWATERUSEBAL(countytouse,state,month)..

sum(activemix(countytouse,"irrigated",crop),

          CROPACRES(countytouse,"irrigated",crop,state)

          *cropdata(countytouse,"irrigated",crop,"water",state,month))

          = sum(isagther2(countytouse,riverbasins,riverplace),

          AGWATERUSE(countytouse,riverbasins,riverplace,state,month));
```

2.3.3. Total water demand and competing demand constraints

Water is usually demanded by many competing users. We categorized this competition of water uses as two types. One is demand by source, and the other by sector.

Demand by source is comprised of two sources: existing source basins (DIVERSIONQ) and new source basins (USER IBT). The variable DIVERTERUSE designates total water diverted by a river location for each sector in a given state of nature and month.

Demand by sector represents water demand among competing users by user class. The user classes modeled are agriculture including domestic and livestock users; municipal users; industrial and mining users; recreational and power electric users; and an aggregate of all other users. The model contains constraints for all user types (called sectors) and that constraint balances total diversions of a sector with the sectoral water use variable.

Total water for a user constraint

In the model, users are defined by county and for a diverter in a county. Water can be diverted from multiple reaches in a river basin or from multiple basins within a limit constrained by maximum historical diversion. Water can also be transferred in via a user IBT.

DIVERTERUSE is the model variable which gives water diverted in a river location for each sector, controlled also by each state of nature and month. It consists of two sources of demand: one source from water which flows from existing source basin, the other from IBTs outside the existing source basin.

The variable DIVERSIONQ captures diverting water from the existing source basins. What the variable DIVERSIONQ is summed up in terms of river basins and county represents that water in a control point may come from multiple river reaches.

The other source of water is USER IBT which is river-to-user. The USER IBT water flows from a source basin to a destination basin for the purpose of satisfying specific water users directly by drawing the water without the transferred water being added to flows levels. Therefore, this water comes from outside that existing river basins based on an IBT contract. Water from River IBT flows river-to-river so that the transferred water is not directly drawn by diverters but added to flows levels. River IBT water is then regarded water from an existing source regardless of its original source, and its diversion is captured by the variable DIVERSIONQ.

UInterBasinTran is a tuple that simply specifies each available USER IBT. It connects a river-to-user IBT project (interbasintranrivertouser) according to its suggested IBT scenarios defined by TWDB and regional planning groups (InterBasinTranOpt) from a source basin and place to a destination basin and place. The USER IBT is also controlled by the state of nature in a given month (USERINTBBASINTRANsce). Water from USER IBT could be originated from different source river basins. That is why USER IBT by sector is summed up by the tuple UInterBasinTran.

The summation of USER IBT in terms of sector must equal the total USER IBT of all sectors as is shown in the UIBTBALANCE equation below.

```
QUANTITYDIVERSION(riverplace,sector,state,month)..
sum(mappingall7(riverplace,sector),DIVERTERUSE(riverplace,sector,state,month))
          =sum((riverbasins,county),DIVERSIONQ(riverbasins,riverplace,county,sector,state,month))
          +sum(UInterBasinTran(interbasintranrivertouser,InterBasinTranOpt,sourcebasin,
          sourceplace,destbasin,riverplace),
          USERINTBBASINTRANsce(interbasintranrivertouser,InterBasinTranOpt,
          sourcebasin,sourceplace,destbasin,riverplace,sector,state,month));
UIBTBALANCE(UInterBasinTran(interbasintranrivertouser,InterBasinTranOpt,s
ourcebasin,sourceplace,destbasin,destplace),state,month)..
           sum(sector1,
           USERINTBBASINTRANsce(interbasintranrivertouser,InterBasinTranOpt,sourcebasin,
          sourceplace,destbasin,destplace,sector1,state,month))
          = USERINTBBASINTRAN(interbasintranrivertouser,InterBasinTranOpt,sourcebasin,
          sourceplace,destbasin,destplace,state,month) ;
```

Diversion identity: demand by sector

Water is diverted by five major classes of water users (sectors) through the variable DIVERTERUSE: agricultural including domestic and livestock, municipal, industrial and mining, recreational and electric power, and other. Nonagricultural water uses (nonag) include municipal, industrial and mining, recreational and electric power, any other uses.

Municipal water use consists of major and minor city water use. Major city use is represented by the stepwise climate-driven demand. Minor city use is represented by the constant price demand up to the observed quantity.

Industrial water use is defined for counties with major industrial use which is represented with the stepwise demand. Minor industrial use is represented by the fixed price demand.

Water uses for recreation and electric power and other uses are specified as fixed price so that it may not exceed the projected water use for that type as its upper bound. Annual water use from local basins in the equation DIVERSIONQMAX is limited by a permitted amount of diversion (upperdiversionQ) designated in each river place that is also called a control point[5], county, and sector of a river.

---

[5] The river place (or riverplace) will be used in chapter II as an element of a model variable just for the notational purpose of the model. It will be replaced with more

Municipal water use

The MUNDIVERSIONID identity equation balances DIVERTERUSE for the municipal water use ("mun") with the major city stepwise water use (MUNDIVERTERUSEs) and minor fixed price water use (MUNDIVERTERUSE).

The convex stepwise variable (MUNDIVERTERUSEs) is used in the model and gives the *proportion* ($qinc_s$) of water use at a step relative to the projected water use $(\hat{q}_{d,m})$ which the water demand curve passes through as is illustrated in Figure II-3. The municitymand2 in the CITYDIVERSIONID equation represents the climate shifting factor that increases or decreases water demand depending on the climate conditions by the state of nature (y or state), and is defined as:

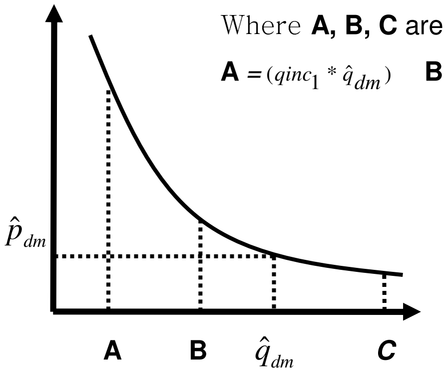
$$\text{municitymand2} = \hat{q}_{dm}\left(1+\varepsilon^{c}_{dm}\frac{\Delta\hat{c}_{d,y,m}}{\hat{c}_{d,y,m}}\right)$$

where $\hat{q}_{dm}$ = Projected water demand point of a diverter (d) in any month (m)

$\varepsilon^{c}_{dm} = climate\ elasticity,\ \Delta\hat{c}_{d,y,m} = \hat{c}_{d,y,m} - \bar{c}_d,\ \hat{c} = Cvalue,\ \bar{c} = average\ Cvalue$

---

formal term, control point, from chapter III on, though the river place will be still used when it refers to an element of any model variable.



Where **A, B, C** are examples of stepwise demand points

A $= (qinc_1 * \hat{q}_{dm})$ **B & C** $= (qinc_s * \hat{q}_{dm})$

Figure II-3. Stepwise demand points along demand curve

```
MUNDIVERSIONID(riverplace,state,month,“mun”)..

DIVERTERUSE(riverplace,”mun”,state,month)

          = sum(mappingcity(riverplace,city),

          COLLECTCITY(city,riverplace,state,month));

CITYDIVERSIONID(city,state,month)..

sum(steps,qinc(steps)*muncitydemand2(city,state,month)

          *MUNDIVERTERUSEs(city,state,month,steps))+

          MUNDIVERTERUSE(city,state,month)

          - sum(mappingcity(riverplace,city),

          COLLECTCITY(city,riverplace,state,month)) = 0;
```

Industrial water use

The INDDIVERSIONID identity equation balances the DIVERTERUSE for industrial and mining water use (“ind”) with the county water use variable for major industrial counties where we have the stepwise water use (INDMINDIVERTERUSEs) and minor counties where we have the fixed price demand (INDMINDIVERTERUSE) up to the observed quantity. Industrial and mining demand is not assumed to fluctuate according to the state of nature.

```
INDDIVERSIONID(riverplace,state,month,“ind”)..
DIVERTERUSE(riverplace,”ind”,state,month)
    = sum(indminmapping(riverplace,county),
    COLLECTINDUSTRY(county,riverplace,state,month));
INDCOUNTYDIVERSION(county,state,month)..
sum(steps, qinc(steps)*IndMinDemanddata(County,month,"quantity")
     *INDMINDIVERTERUSEs(county,state,month,steps))
    +INDMINDIVERTERUSE(county,state, month)
    -sum(indminmapping(riverplace,county),
```

```
        COLLECTINDUSTRY(county,riverplace,state,month)) = 0;
```

Agricultural water use

The AGDIVERSIONID equation balances the DIVERTERUSE for agricultural, domestic and livestock water use (“ag”) with the agricultural water use variable (AGWATERUSE).

```
AGDIVERSIONID(riverplace,state,month,“ag”)..
DIVERTERUSE(riverplace,”ag”,state,month)
        = sum(isagther2(countytouse,riverbasins,riverplace),
        AGWATERUSE(countytouse,riverbasins,riverplace,state,month));
```

Recreational and other water uses

The two constraints limit maximum water use for recreational (“rec”) and other (“other”) water use observed in a control point. Recreational water use is assumed to be non-consumptive.

RECDIVERSIONIDENTITY(riverplace,state,month,“rec”)..

DIVERTERUSE(riverplace,”rec”,state,month)

≤ *newwateruse* (riverplace,”rec”,state,month);

OTHERDIVERSIONIDENTITY(riverplace,state,month,“other”)..

DIVERTERUSE(riverplace,”other”,state,month)

≤ *newwateruse* (riverplace,”other”,state,month);

Limitation of water use

Monthly fixed price city and county water uses are assumed to not exceed the monthly water demand (CityDemanddata, IndMinDemanddata). Monthly water demand is computed by projected 2010 water demand for each city or county multiplied by the fractional monthly share for the actual annual water use.

The annual amount of water from existing source basins (DIVERSIONQ) is limited by a permitted diversion from the Texas Commission on Environmental Quality (TCEQ, 2007). The parameter, upperdiversionQ, stands for the annual permitted diversion by TCEQ, which is controlled by river basin, river place, county and sector, the data of which are from the WRAP and WAM reports.

MUNDIVERTERUSELIMIT(city,state,month)..

MUNDIVERTERUSE(city,state,month)

≤ CityDemanddata(city,month,"quantity");

INDCOUNTYDIVERSIONMAX(county,state,month)..

INDMINDIVERTERUSE(county,state, month)

≤ IndMinDemanddata(County,month,"quantity");

DIVERSIONQMAX(mappingall6(riverbasins,riverplace,county,sector),state)..

sum(month, DIVERSIONQ(riverbasins,riverplace,county,sector,state,month))

≤ upperdiversionQ(riverbasins,riverplace,county,sector);

2.3.4. Demand curve convexity constraints

When we estimate the demand curve based on the separable programming, convexity constraints were imposed on the stepwise demand function representations of the major cities and industrial counties. We assumed that water demand would be discontinuous step demand even in a municipal use because each city or county or regional water district as a water use entity in the model would hold its water to distribute to its final users. These convex stepwise variables (MUNDIVERTERUSEs, INDMINDIVERTERUSEs) represent the amount of the predetermined *proportion* (qinc(steps)) of water use steps as defined relative to the projected use. This assumption implies that water use is rationally expected and realized within the 52 steps we set, ranging from 20% (0.2) to 300% (4.0) times the projected use. This is imposed by the constraints for municipal, and industrial and mining sectors as follows.

MUNDIVERSIONCONVEX(city,state,month)..

sum(steps, MUNDIVERTERUSEs(CITY,state,month,steps)) ≤ 1;

INDDIVERSIONCONVEX(county,state,month)..

sum(steps, INDMINDIVERTERUSEs(county,state,month,steps)) ≤ 1;

2.3.5. Overall water flow constraints

Flow balance constraints depict the flows of water in the river along with freshwater inflows to bays and estuaries. At each control point, total inflows must be balanced with total outflows by the state of nature and month.

Water flow balance: demand and supply

Inflows and outflows of water less adjustments for use and transfers are controlled by river basin, river place, state of nature and month. Thus a demand and supply balance is specified at a river place (*RP*) within a river basin (*R*) in a given state and time period. It balances use with supply. The basic forms of demand are flow out, diversion for agricultural and non agricultural use, storage until the next period (for reservoirs only), IBT transfer out and water flow out to bays and estuaries. The basic sources of supply are flow in, storage holdover (for reservoirs only), new inflows/precipitation, and IBT transfer in and return flows.

Demand terms

- User IBT flow-out: Diversion of water by an *USER IBT* is an export of water to be used up in another location and diminishes water in this basin.

  [=USERINTBBASINTRAN(interbasintranrivertouser,InterBasinTranOpt, riverbasins, riverplace,destbasin,destplace,state,month)]

- River IBT flow-out: Diversion of water by an *RIVER IBT* is an export of water to add to water flow in another location and diminishes water in this basin. [=RIVERINTBBASINTRAN(interbasintranrivertoriver,InterBasinTranOpt,river basins,riverplace,destbasin,destplace,state,month)]

- Storage carry out: Demand in the form of water retained in storage to the next month diminishes the water that can flow out or be used in this month. This is only defined for regions with reservoirs

  [=STOREWITH(riverbasins,riverplace,state,month)]

- Flow out: Water flows out to downstream nodes.

  [=FLOW(riverbasins,riverplace,downriver,state,month)]

- Diversion: Water is diverted by the agricultural and nonagricultural sectors.

  [=DIVERSIONQ(riverbasins,riverplace,county,conssector,state,month)]

- Water out: Water at the last node of a river flows out to bays and estuaries. [=OUTTOBAY(riverbasins,riverplace,state,month)]

Supply terms

- River IBT flow-in: Water transferred to this place by a RIVER IBT from another basin constitutes a supply of water here.

  [=RIVERINTBBASINTRAN(interbasintranrivertoriver,InterBasinTranOpt,

  sourcebasin,sourceplace,riverbasins,riverplace,state,month)]

- Storage carry in: Water supply can come from water that was stored during the previous month and carried into this month considering evaporation loss (evaporationloss). The storage variable is only defined where there are reservoirs and is limited by capacity.

[=STOREADD(riverbasins,riverplace,state,month)]

- Flow in: Water supply arises from inflows from upstream nodes on a river. [=FLOW(riverbasins,upriver,riverplace,state,month)]
- Naturalized flows: Naturalized flows from precipitation constitute a source of supply. [=Inflow(riverbasins,riverplace,state,month)]
- Return flows: Return flows from diverted water are another source of water supply. Return flows can also come from groundwater depending on a geographical situation but this is treated in naturalized flows. A constant percentage of upstream diversions is used. [=RFpercent(conssector)]. The term conssector stands for the consumptive sector.

FLOWBALANCE(riverbasins,riverplace,state,month)..

sum(mappingall6(riverbasins,riverplace,county,conssector),

DIVERSIONQ(riverbasins,riverplace,county,conssector,state,month))

+sum(RInterBasinTran(interbasintranrivertoriver,InterBasinTranOpt,riverbasins,riverplace,

destbasin,destplace),RIVERINTBBASINTRAN(interbasintranrivertoriver,

InterBasinTranOpt,riverbasins,riverplace,destbasin,destplace,state,month))

+sum(UInterBasinTran(interbasintranrivertouser,InterBasinTranOpt,riverbasins,

```
riverplace,destbasin,destplace),
USERINTBBASINTRAN(interbasintranrivertouser,InterBasinTranOpt,riverbasins,
riverplace,destbasin,destplace,state,month))
+sum(mriverflowlink(riverbasins,riverplace,downriver)$(not sameas(downriver,'out')),
FLOW(riverbasins,riverplace,downriver,state,month))
+OUTTOBAY(riverbasins,riverplace,state,month)
+sum(Reservoir(riverbasins,riverplace),
-STOREADD(riverbasins,riverplace,state,month)
*(1-evaporationloss(riverbasins,riverplace,state,month))
+STOREWITH(riverbasins,riverplace,state,month))
≤
sum(RInterBasinTran(interbasintranrivertoriver,InterBasinTranOpt,sourcebasin,
 sourceplace,riverbasins,riverplace),
 RIVERINTBBASINTRAN(interbasintranrivertoriver,InterBasinTranOpt,
 sourcebasin,sourceplace,riverbasins,riverplace,state,month))
+ Inflow(riverbasins,riverplace,state,month)
+sum((conssector,mriverflowlink(riverbasins,upriver,riverplace)),
```

```
RFpercent(conssector)*DIVERTERUSE(upriver,conssector,state,month))
+sum(mriverflowlink(riverbasins,upriver,riverplace),
FLOW(riverbasins,upriver,riverplace,state,month));
```

Nonconsumptive recreational sector

The demand and supply balance for non-consumptive water use for recreational and electric power ("recreation" hereinafter) must be specially dealt with because recreational water is not used up unlike other consumptive water uses.

We limited the recreational water use from existing source basins (DIVERSIONQ) not to exceed maximum flows of recreational water which is defined as average flows in the basin as defined in the following.

Maximum flows of recreational water for a river basin, river place, state, and month = [Instream Flow out + Instream Flow in + Reservoir Flow out + Reservoir Flow in + Freshwater inflows to bays & estuaries + Naturalized flows increase (=inflow)] /2

Unlike other consumptive water uses being defined by demand (Flow out) and supply (Flow in) *at* each specific river place, recreational water use must be defined *near* a river place or at two river reaches which mean the area between three river places, i.e., up and down the river place. That is why the maximum flows of recreational water is averaged out by the flow outs plus the flow ins divided by two.

Interbasin water transfers for users (USER IBT) are not considered because they are dedicated to a specific user.

NONCONSUSEMAX(riverbasins,riverplace,state,month)..

```
sum(mappingall6(riverbasins,riverplace,county,nonconssector),
        DIVERSIONQ(riverbasins,riverplace,county,nonconssector,state,month))
        ≤  [sum(riverflowlink(riverbasins,riverplace,downriver),
        FLOW(riverbasins,riverplace,downriver,state,month))
        +sum(riverflowlink(riverbasins,upriver,riverplace),
        FLOW(riverbasins,upriver,riverplace,state,month))
        +sum(Reservoir(riverbasins,riverplace),STOREADD
        (riverbasins,riverplace,state,month)
        +STOREWITH (riverbasins,riverplace,state,month))
        +OUTTOBAY(riverbasins,riverplace,state,month)
        +inflow(riverbasins,riverplace,state,month) ]/2;
```

2.3.6. Freshwater inflows: flows out to bays and estuaries

The variable OUTTOBAY is the amount of water that escapes to a bay or an estuary after instream water reaches a final river place or control point of any river basin in any month, depending on the state of nature.

Then, ESCAPETOBAY is defined as the annually expected amount of water which flows out to all bays and estuaries. It is computed by multiplying the variable OUTTOBAY times the corresponding probability of each state of nature.

The escaped water to bays and estuaries can be constrained to be greater than a non-negative constant for the purpose of supplying environmental freshwater inflows which could be set by state agencies. This issue will be investigated in chapter IV.

```
FLOWOUTTOBAY..
ESCAPETOBAY
        =sum((onriver(riverbasins,riverplace),state,month),prob(state)
          *OUTTOBAY(riverbasins,riverplace,state,month));
```

2.3.7. Capacity constraints

Monthly reservoir capacity

Storage capacity of any reservoir in a river basin and river place is limited. The variable STOREADD is the water stock as supply stored from the previous month. STOREWITH is the water stock retained in a reservoir until the next month. Storage variables in a river place of a river basin and in any month and any state of nature are limited by a reservoir capacity. The reservoir capacity does not depend on the state of nature.

Storage variables explain a net water storage level of a reservoir for each month, i.e., difference between the water level in an ending month and the one in a beginning month. We forced an overall balance of water storage between withdrawals and additions to be met through the balance equation probabilistically weighted according to the state of nature. The storage variables are subject to capacity of a reservoir.

STOREcapacity1(reservoir(riverbasins,riverplace),state,month)..

STOREADD(riverbasins,riverplace,state,month)

≤ reservoircapacity(riverbasins,riverplace,month);

STOREcapacity2(reservoir(riverbasins,riverplace),state,month)..

STOREWITH(riverbasins,riverplace,state,month)

$\leq$ reservoircapacity(riverbasins,riverplace,month);

STOREBALANCE(riverbasins,riverplace)..

sum(state,prob(state)* sum(month,-STOREADD(riverbasins,riverplace,state,month)

+STOREWITH(riverbasins,riverplace,state,month))) = 0;

Annual RIBT and UIBT capacity

The amount of water transferred by IBT is limited to the capacity at which it is constructed. The IBT construction variables (RIVERINTBBASINTRANConstruction, USERINTBBASINTRANConstruction) are binary choice variables. If an IBT is built, then the IBT construction variable have a value of 1 and the capacity constraint for the IBT allows use up to the annual capacity for water transferred (InterBasinTranCapacity). Transferred water uses are given by the variables RIVERINTBBASINTRAN and USERINTBBASINTRAN. Fixed costs for IBT projects appear in the objective function.

RIVERINTBBASINTRANConstraint(RInterBasinTran(interbasintranrivertoriver, InterBasinTranOpt,sourcebasin,sourceplace,destbasin,destplace),state)..

sum(month, RIVERINTBBASINTRAN(interbasintranrivertoriver,InterBasinTranOpt,

sourcebasin,sourceplace, destbasin,destplace,state,month))

≤

InterBasinTranCapacity(interbasintranrivertoriver,InterBasinTranOpt,

sourcebasin,sourceplace,destbasin,destplace)

*RIVERINTBBASINTRANConstruction(interbasintranrivertoriver,InterBasinTranOpt);

USERINTBBASINTRANConstraint(UInterBasinTran(interbasintranrivertouser, InterBasinTranOpt,sourcebasin,sourceplace,destbasin,destplace),state)..

sum(month, USERINTBBASINTRAN(interbasintranrivertouser,InterBasinTranOpt,

sourcebasin,sourceplace,destbasin,destplace,state,month))

≤InterBasinTranCapacity(interbasintranrivertouser,InterBasinTranOpt,

sourcebasin,sourceplace,destbasin,destplace)

*USERINTBBASINTRANConstruction(interbasintranrivertouser,InterBasinTranOpt);

2.3.8. Configuration constraint

This constraint limits the total number of IBTs ($= n$) that will be considered by a decision maker exogenously. A state agency can face a budget limitation for various IBT projects across Texas so that it may want to choose the projects which are economically efficient depending on its budget constraint. Thus, the RIVER IBT and USER IBT construction variables that have values of zero or one are summed up in terms of all IBT projects, say, IBT(interbasintranrivertoriver, InterBasinTranOpt) in the constraint.

But any specific number of IBTs is actually not found by the regulatory state agency, TWDB, so that we included all IBTs proposed as long as there are relevant cost data available. An arbitrary number (=100) was used for the number n, considering that there are total 99 proposed IBTs in the 2002 Texas water plan. This constraint is not binding and redundant in this model. However, this constraint could be important by any regional planning group in a region especially when it has some financial restriction or any other reason such as environmental concerns. The constraint has the form:

IBTConfigurationConstraint..

sum(IBT(interbasintranrivertoriver,InterBasinTranOpt), RIVERINTBBASINTRANConstruction(interbasintranrivertoriver,

InterBasinTranOpt)) + sum(IBT(interbasintranrivertouser,InterBasinTranOpt),

USERINTBBASINTRANConstruction(interbasintranrivertouser,

InterBasinTranOpt)) $\leq$ n

2.4. Details on Model Empirical Specification

The above objective function and constraints involve data for parameters corresponding to all variables. Data needed for them are grouped into five sections: hydrological data, crop data, IBT cost data, water demand data and state of nature data.

2.4.1. Hydrological data

The hydrological data including naturalized flows, historical water use, permitted diversion and reservoirs and associated tuples are mainly obtained from WRAP and WAM (Water Availability Modeling) reports for each river basin from the Texas Commission on Environmental Quality (TCEQ) and TNRCC (2001a, 2001b).

River location (River place)

A primary control point in the WAM and WRAP reports is named as a “river place” or “river location” in the TEXRIVERSIM model. River location is one of the most important units in this model and all the calculations are made with reference to the river location. It is also used to define reaches, reach members, and river flow linking. To specify the location of a particular river place to a river basin, a river basin extension is added to the original primary control point ID. For example, in A10000col, A10000 is the primary control point ID from WAM and “col” is the basin extension since A10000 is located in the Colorado and Brazos-Colorado river basin.

Diverters

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. A secondary control point ID in WRAP is not unique across all river basins, so a diverter is coded as the original secondary control point ID followed by a river basin extension. For example: the diverter A10010_col in TEXRIVERSIM indicates that A10010 is a secondary control point ID from WRAP and “col” is the basin extension for the Colorado river basin. All of the diverters spread across the twenty one river basins.

Diverter is one of the most fundamental units in the model as well as river location, and most of hydrological data such as historical water use and permitted diversion are based on it.

Reaches and river flow linking

TEXRIVERSIM divides rivers into reaches. The area between two river locations is defined as a reach. Diverters located in that reach are considered reach members of the down stream river location. A river location contains many reach members.

A tuple builds a link between a diverter and down stream river location, which enables us to aggregate data at a river location. For example, when diverters A10010_col, A10020_col and A10030_col are reach members of a river location A10000col, historical water use for these three diverters can be summed up and assigned to A10000_col.

Modeling the river basins involves representing the rivers with a series of river locations and connecting them in sequence according to the river flows. The set “riverflowlinking” includes the river flow linking for all the modeled river basins. This tuple is critical to provide the link between river locations in a river basin, which allows us to mode water flow sequence and supply-demand balance at a particular point.

Sometimes, water can flow from more than one upstream river locations to one down stream river location.

WRAP output 1CPT can provide the actual water flow sequence for diverters and river locations in a particular river basin. For example, a WRAP output 1CPT may give a result as following:

$A10010\_col \rightarrow A10020\_col \rightarrow A10030\_col \rightarrow A10000col \rightarrow A20010\_col \rightarrow$
$A20030\_col \rightarrow A20000col \rightarrow A30050\_col \rightarrow A30000col,$ and
$A40000col \rightarrow A20020\_col \rightarrow A20040\_col \rightarrow A20000col$

We know that A10000col, A20000col, A30000col and A40000col are river locations and the rest are diverters in the Colorado River basin. Therefore, A10010_col, A10020_col, A10030_col are classified as reach members of the river location A10000col. A20010_col, A20020_col, A20030_col and A20040_col are reach members of A20000col. However, there is no reach member for A40000col.

In one estuary, waters flow from A10000col to A20000col then to A30000col, and in the other estuary water flows from A40000col to A20000col. Therefore, the river flow linking in the model will be A10000col.A20000col, A20000col.A30000col and A40000col.A20000col, where the river location before the dot is the upstream river location while the river location after the dot is the downstream river location.

Sector-diverter mapping

In the WAM reports and WRAP output, water usage is classified into eight sectors: agricultural, industrial, mining, municipal, recreational, power, domestic and livestock, and other (Table II-2). It is critical to separate water usage into different sectors because they have different values and costs. Municipal and industrial water usually have higher value than agriculture water.

However, the percentage of return flows data is not available for mining, domestic and livestock, and other, we made the following assumptions: mining is assumed to have the same percentage of return flows as industry, so these two sectors, mining and industry, are aggregated into “ind”; it is reasonable to assume power and recreation sectors have 100% of return flows since they are not actually used up, so they are grouped into “rec”; domestic and livestock is regrouped into “ag”. Therefore, the final sectors in the model have five categories: agricultural, industrial and mining, municipal, recreational, and other sector. The detailed description of the sectors is shown in the table. Sets or data relating to sectors are also regrouped based on these five categories.

Table II-2. Sectors of Water Use Classified in the Model

Sector in GAMS	Classified water use
ag	agricultural, domestic and livestock water use
ind	Industrial and mining water use
rec	recreational, hydro power water use
mun	municipal water use
other	other type of water use

The tuple sector-diverter mapping was directly extracted from the WRAP output. It represents what specific diverters supply water for a particular type of use. For example, a tuple may be shown as this: F30130_col.mun, F30130_col.ag, F30130_col.ind, and F30140_col.ag. This indicates that the diverter F30130_col supplies water for municipal, agricultural and industrial and mining type of use, while only agricultural water users are diverting water from F30140_col.

County-diverter-mapping

The tuple county-diverter mapping provides a link between each diverter and its physical county location. It can be used to aggregate water use in a county by summing up water use for each diverter in that county.

This tuple was generated by combining the WAM and WRAP output. The WRAP output can provide information about water right and diverter, while WAM contains information for water right and county. Therefore, we can connect the diverter and the county together if they have the same water right.

The above tuples including reaches, river flow linking, sector-diverter mapping, county-diverter-mapping are used to generate some tuples like mappingall6, isagthere, and indminmapping used in the constraints. The tuple isagthere ties an agricultural county and its location basin together. River basin, river place, county and sector are linked together in mappingall6. In Indminmapping tuple, a major industrial county is linked with its river basin.

Naturalized flows and inflows

Naturalized stream flows represent water stock that would have occurred in the absence of water users, water management facilities and practices. Naturalized flows are generated by WRAP. The data set consists of the monthly naturalized flows data for each river location from 1934 to 1989 or from 1940 to 1998 which depend on the availability of WRAP input for each river basin. The naturalized flows data are used to calculate the net inflows for that reach which is needed for the water flow balance constraint.

Net inflow is one source of water supply. If there is no upstream river location connected to a river location, then naturalized flows at this river location will be treated as net inflows at that river location. If there is more than one upstream river locations connected to a river location, then the net flow at this river location will be the summation of naturalized flows from all of its upstream river locations minus its own naturalized flow at the location. For example, if the river flow linking is A10000_col.A20000_col, A20000_col.A30000_col and A40000_col.A20000_col, naturalized flows at A10000_col and A40000_col will be considered net inflows at A10000_col and A40000_col respectively since no upstream river location exists. By adding the naturalized flows at river locations A10000_col and A40000_col then subtracting the naturalized flow from A20000_col, we can get the net inflows at A20000_col.

Water use

The WRAP data are also used to generate the monthly historical water use for each diverter. The year range for water use generated is different across each river basin.

A diverter is usually associated with more than one type of water use (sector). The WRAP output provides total water use but do not split the total use by sector. But, when we try to identify the major industrial and municipal counties and set a limit for water that can be diverted for recreational or other use, we require the water use by sector. In such cases, the permitted diversion from the WAM reports is used to obtain the split ratios. For example A10000_col is associated with agricultural and industrial usage and WRAP provides that the actual water use at A10000_col is 2000 ac-ft. Then, we go to the WAM report and find out that at A10000_col the total permitted diversion is 10,000 ac-ft of which 6,000 ac-ft was permitted for agriculture and 4,000 ac-ft for industrial use. So, 6/10 is permitted for agriculture and 4/10 for industrial use. Then, we assign that (6/10*2000) as actual agricultural usage and (4/10*2000) as industrial usage at A10000_col.

Permitted diversion

TCEQ issues permits to water right holders and specifies the maximum amount of water that can be diverted. Permitted diversions in each river basin are imposed to a diverter and use type (sector). These permitted diversions serve as an upper bound that diverters can actually divert.

The WAM report contains the information on water rights, control points and the permitted diversions by sector. The WRAP output also generates the permitted diversions. Most of the time we used permitted diversion as listed by the WRAP output. However, in the Lavaca and Sulfur river basins the permitted diversions are extracted from the WAM report. The reason is that in the WRAP output no major municipal diverters supply water to the major cities like Corpus Christi in the Sulfur River basin and Texacana in the Lavaca River basin, but a few diverters are available to supply water to these cities in the WAM report. This treatment also applies to the type-of-diverter mapping and county-diverter mapping.

In another case of the San Jacinto River basin, the permitted diversions for most diverters are from WRAP while the data are from the WAM report for some diverters. This is also because of the inconsistency between two outputs. The permitted industrial diversion for Harris county (The city of Houston is located in this county) from the WAM report is very close to the actual industrial water demand while the WRAP output shows that the permitted industrial diversion for Harris county is 100 times smaller than its actual industrial demand.

Reservoirs

Each river basin contains reservoirs. 175 major reservoirs each with capacity more than 5000 ac-ft are covered in the model. A reservoir is treated as both a diverter and a river location. For example, A30060 stands for reservoir Lake J.B. Thomas in the Colorado riverbasin, the corresponding river location and diverter will be A30060col and

A30060_col. The reservoir ID will be shown in the data sets called “riverflowlinking", "naturalized flow", "wateruse" and so on.

The model has monthly storage capacity constraints for the major reservoirs, and the monthly storage capacity is obtained from the Texas Water Development Board (TWDB, 2005) and the following web site: http://www.twdb.state.tx.us/publications/reports/waterconditions/twc_pdf_archives/.

Evaporation data

Evaporation of water from the reservoirs takes away a part of the available supply for diversion. Hence, this information is included in the model. The monthly evaporation and storage data for the identified major reservoirs are from WRAP.

The evaporation loss is computed as a percentage of water evaporated as water stored for each reservoir. The evaporation loss falling out of the range 0 to 1 is adjusted or eliminated.

Return flow assumptions

Once water is diverted for use, some percentage of water will return back to the river after certain period of time. Some sectors such as recreation and electric power have high return flows since there is no consumptive use. The return flow rate is obtained from the EDSIMR model whose values are tabulated in Table II-3. It is assumed that the return flow rate depends only on the sector and water diverted from one river location will return to the next river location to simplify the model process. No time delay is considered in the model.

Table II-3. Return Flow Percentages by Sector

Sector	ag	ind	mun	rec	other
Return flow percent (%)	6.37	33.58	54.52	100	33.58

Notes: ag/ind/mun/rec/denote agricultural/industrial & mining/municipal/recreational sector, respectively.

2.4.2. Crop data

Crop mix data

TEXRIVERSIM intensively models the agricultural water use and crop management choice, so crop data are needed for the objective function as well as for the agricultural land and water demand constraints. Crop data consists of crop mix data, crop budget data and irrigated land available in Texas. Crop mix data contain the harvested acres for each crop through different management (irrigated or dry land choice) for each county from 1970 to 2003. 21 crops covered in the model are listed in Table II-4.

Table II-4. Crops Covered in the Model

Crops	Description (units)
Barley	Barley all
Corng	Corn for grain
Corns	Corn for silage (tons)
CottonP	Pima cotton (lb)
CottonU	Cotton upland
Alfalfa2	Hay Alfalfa dry
Hay	Hay other than Sorghum hay (ton)
HayOth	Hay other dry
Oats	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)

The data are from USDA county level statistics as developed by NASS (United States Department of Agriculture, 2004).

Crop mix data serve as coefficients for the variable CROPMIX in agricultural land constraints and crop mix balance constraints, which provide the possible crop mix strategies.

Crop budgets

Crop budget data contains crop yield, price, cost and water needed for each crop. Crop yield, price and cost estimated are collected from Texas Cooperative Extension data on the website (http://agecoext.tamu.edu/).

There are 12 agricultural districts in Texas and the crop budgets are generally prepared for these 12 districts by crop based on irrigation status. It is assumed that the price, operating cost, water price and irrigated yield for a crop in counties within a district are the same. Water needed for each crop is obtained through Blaney-Criddle formula (National Engineering Handbook, chapter 2).

Following the same procedure in EDSIMR model, the dry land yield for a crop is assumed to be proportional to irrigated yield based on how much percentage of precipitation against the water requirements for the crop is available. Yield units vary based on each crop.

Available agricultural land

Available agricultural land is defined as acreage of irrigated land available in Texas, which was from NASS and saved as a parameter “availagland.” It serves as an upper limit of the optimal crop land use.

2.4.3. IBT cost estimates and IBT projects

Interbasin water transfer is the key component and major focus in the TEXRIVERSIM model. IBT related data include the project name and corresponding fixed and variable cost, capacity as well as the source location and destination location, which were extracted from Texas Water Plan 2002, 2006 and regional water planning group reports (http://www.twdb.state.tx.us/RWPG/main-docs/2006RWPindex.asp).

Actually 99 IBT projects appear in the 2002 Texas Water Plan, but some IBT information was not available. Finally, 45 proposed IBT projects are introduced in the model as follows in Table II-5 briefly with those project titles, IBT type, source and destination basins, fixed and variable costs.

The costs information is obtained from 2006 Regional Water Plans by each of regional water planning groups. Costs are based on the second quarter 2002 dollars but some cost data such as material costs are adjusted to account for price increases in the 2006 Regional Water Plans. The fixed costs (FC) consist of total annualized capital costs amortized for 30 years with 6% interest rate plus 20% of annual operation and management (O&M) costs. The regional groups permitted a 20% allowance for construction contingencies for all O&M calculations. The variable costs (VC) are comprised of: raw water costs plus electricity costs plus 80% of O&M costs divided by the acre-foot of maximum annual IBT water available.

Two types of IBTs are included in the model. An IBT associated with more than one water diverter is treated as 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 which is used by any downstream diverter.

An IBT where the water is dedicated to only one diverter is treated as User IBT (UIBT) in which transferred water is assumed to be dedicated only to that diverter. The source and destination river locations are mapped according to their physical places. The model contains 8 River IBTs and 37 User IBTs.

Table II-5. IBT Projects Covered in the Model

45 IBT projects	Type	Source	Destination	FC ($)	VC ($)
AlanHenry_BrzToCol	RIBT	Brazos	Colorado	17,946,000	130.60
Bedias_TriToSan		Trinity	San Jacinto	5,975,025	135.30
ETWT_SabNecToTri		Sabine	Trinity	23,414,010	15.63
Marvin_SulToTrin		Sulphur	Trinity	155,343,800	115.19
Marvin_SulToTrin		Sulphur	Trinity	160,141,600	97.47
Toledo_SabToTrin		Sabine	Trinity	136,065,600	128.90
Toledo_SabToTrin		Sabine	Trinity	215,079,800	143.24
Toledo_SabToTrin		Sabine	Trinity	173,213,000	151.44
Luce Bayou_TriToSan	UIBT	Trinity	San Jacinto	11,173,010	9.27
BoisdArc_RedToTrin		Red	Trinity	29,606,800	41.82
Columbia_NecToTrin		Neches	Trinity	16,544,120	80.58
Fastrill_NecToTrin		Neches	Trinity	42,248,200	79.25
Garwood_ColToNus		Colorado	Nueces	5,606,400	399.93
Garwood_ColToNus		Colorado	Nueces	471,833	399.93
Garwood_ColToNus		Colorado	Nueces	3,624,232	399.93
JoePool_TrinToBrz		Trinity	Brazos	6,285,380	285.89
LCRABRA_ColToBrz		Colorado	Brazos	1,478,400	338.31
LCRABRA_ColToBrz		Colorado	Brazos	8,133,600	332.11
LCRABRA_ColToBrz		Colorado	Brazos	811,400	338.67
LCRASAWS_ColToGdsn		Colorado	Guadsan	153,433,000	302.85
LCRASAWS_ColToGdsn		Colorado	Guadsan	9,598,600	611.13
Livingston_TriToSan		Trinity	San Jacinto	15,810,857	226.11
Palestine_NecToTrin		Neches	Trinity	30,993,600	73.66
Parkhouse_SulToTrin		Sulphur	Trinity	27,786,800	77.82
Parkhouse_SulToTrin		Sulphur	Trinity	26,932,200	69.48
Parkhouse_SulToTrin		Sulphur	Trinity	35,541,600	77.06
Patman_SulToTrin		Sulphur	Trinity	35,284,600	203.33
Patman_SulToTrin		Sulphur	Trinity	42,465,000	110.03
Patman_SulToTrin		Sulphur	Trinity	68,226,000	110.52

Table II-5. Continued

45 IBT projects	Type	Source	Destination	FC ($)	VC ($)
Patman_SulToTrin		Sulphur	Trinity	141,128,600	180.24
Patman_SulToTrin		Sulphur	Trinity	32,025,600	233.41
Patman_SulToTrin		Sulphur	Trinity	61,349,000	120.48
Patman_SulToTrin		Sulphur	Trinity	77,222,200	165.75
Patman_SulToTrin		Sulphur	Trinity	32,025,600	233.41
Pines_CypToTrin		Cypress	Trinity	25,708,200	201.47
Pines_CypToTrin		Cypress	Trinity	35,002,200	242.96
Pines_CypToTrin		Cypress	Trinity	19,227,000	188.77
RalphHall_SulToTrin		Sulphur	Trinity	15,651,200	75.25
Rayburn_NecToTrin		Neches	Trinity	97,276,800	179.09
Rayburn_NecToTrin		Neches	Trinity	105,459,400	211.03
Rayburn_NecToTrin		Neches	Trinity	97,276,800	179.09
Texoma_RedToTrin		Red	Trinity	15,023,400	55.77
Texoma_RedToTrin		Red	Trinity	43,752,600	222.35
Texoma_RedToTrin		Red	Trinity	13,616,200	75.80
Texoma_RedToTrin		Red	Trinity	49,935,400	231.00

Notes: IBT/FC/VC denote Interbasin Water transfers/fixed costs/variable costs. And RIBT/UIBT stand for River IBT/User IBT.

Some IBTs have the same source place and more than one destination place. In these cases, the same IBT ID is adopted but options are used to differentiate them. For example, Patman_SulToTrin transfers water from the same source to eight different destination places with different capacity and cost structure. They are treated as options.

In some cases, water are transferred from the same source place but shared by different locations along the pipeline. For example, in Marvin_SulToTrin, three destination places, B2410Atri, B2456Atri and B3809Atri, share the transferred water, so do the costs. In this case, only one IBT ID and one option are used to represent this project. Some IBTs are composed by two parts with different source basins but the same destination basin. For example, in ETWT_SabNecToTri, water is transferred from both the Sabine and Neches River basins to the Trinity River basin. In this case, only one IBT ID is used to refer to this project.

A riverplace of exporting and importing IBT water is critical. The assignment of IBT in this model is limited because of limited information available from each regional river authority and TWDB. However, we believe we used as much as information available we could. As for a reservoir or city, its corresponding riverplace can be exactly identified by the reservoir ID or city-mapping tuple. When it is a county or a place, one riverplace in that county is chosen.

2.4.4. Water demand data

The projected water use for the cities and industrial counties that were represented as water diverters was drawn from the “2006 Regional Water Plan” from the Texas Water Development Board (TWDB, 2006b) which is found at its website.

(http://www.twdb.state.tx.us/data/popwaterdemand/2003Projections/DemandProjections.asp)

Based on those data, 35 major cities were included in the model. The classification of major cities is based on the year 2010 projected total water use for city and their actual 2003 prices. These cities were chosen based on the criteria that they have annual water use greater than 2000 acre feet or water prices over $1000/acre feet or water values (price*quantity) over $300,000.

Dallas, Houston, Fort Worth, and San Antonio are the four largest water demanding cities based on quantity. These four cities constitute 71.4% of the projected 35 city total water use and 65.1% of the total water value ($601 million/ $923 million).

A large potential water shortage is being faced by San Antonio due to Edwards Aquifer developments and it is assumed that part of the shortage may be supplied by transferred surface water. Woodson and Blanco have the smallest levels of demand but their water prices are among those highest with their prices over $2,000/acre foot (twice as much as the arithmetic average price of $1,049/acre foot). San Antonio and Austin are the two cities which have the cheapest water prices (below $290/acre foot).

Forty major industrial water counties are also included. They have their water use greater than 3,000 acre feet from surface water or water prices higher than $1,000/acre foot or water values over $1 million. Brazoria, Harris and Harrison counties are the three largest industrial water demanding counties. These three counties account for 64.9% of projected 40 county total industrial water use and 66.2% of the total water value ($713 million/$1,078 million).

Washington and Freestone counties are among those with highest prices but have small water use. Victoria and Robertson counties have the cheapest water prices (about $570/acre foot).

Municipal water prices for major cities and industrial and mining water prices for major counties are year 2003 prices that can be obtained from the survey over 2,000 communities in Texas by Bell and Griffin (2005).

We introduced the so called marginal price concept in our model, rather than using average price concept which has been used in other analyses so far. That is to say, municipal prices are the first block prices, and industrial and mining water prices are the last block prices, being based upon the best fit of data which are available from cities or counties.

Variable costs such as treatment and operating costs for each city or county are assumed to be 50% of the water prices which are based on the block pricing system.

There was no way to identity the proportion of the variable cost in the water price.

Municipal price elasticities vary across months. But industrial and mining elasticity and climate elasticity are assumed to be the same across months (-0.540, 0.630122 respectively) by Gillig et al (2000), and Bell and Griffin (2005).

The municipal monthly share used to split the annual water use projection is obtained from the Griffin and Chang's study (1990) on historical water use. The industrial monthly share was extracted from WAM reports for each river basin. It is assumed that each county or city has the same monthly share.

Table II-6 summarizes the information on municipal water price and quantity, and Table II-7 on industrial price and quantity.

Table II-6. Major Cities' Water Use in 2010 and Price in 2003

City	Quantity (acre feet)	Price ($/acre foot)	Price*Quantity (dollar)
Abilene	22,891	566.98	12,978,739
Austin	154,173	280.23	43,203,900
Beaumont	27,040	1,841.06	49,782,262
Blanco	303	2,052.86	622,017
Bonham	2,735	977.55	2,673,599
Center	1,633	1,189.36	1,942,225

Table II-6. Continued

City	Quantity (acre feet)	Price ($/acre foot)	Price*Quantity (dollar)
Coleman	1,285	1,189.36	1,528,328
Corpus Christi	61,953	765.75	47,440,510
Dallas	389,548	420.35	163,746,502
Denison	5,489	1,303.41	7,154,417
Denton	29,561	847.21	25,044,375
Fort Worth	149,596	772.27	115,528,503
Gonzales	1,545	700.58	1,082,396
Graham	1,528	1,867.13	2,852,975
Greenville	5,555	1,687.91	9,376,340
Houston	389,082	668.00	259,906,776
Longview	10,671	628.89	6,710,885
Marlin	2,660	977.55	2,600,283
Marshall	3,257	1,163.29	3,788,836
Nacogdoches	7,625	870.02	6,633,903
Paris	6,252	1,437.00	8,984,124
San Angelo	20,800	329.11	6,845,488
San Antonio	216,946	688.20	62,068,251
Stamford	645	928.68	598,999
Sweetwater	3,013	1,723.75	5,193,659
Teague	536	1,202.39	644,481
Temple	21,033	876.54	18,436,266
Terrell	3,575	847.21	3,028,776
Texarkana	6,472	1,163.29	7,528,813
Thorndale	193	1,075.31	207,535
Tyler	25,886	736.42	19,062,968
Waco	24,876	788.56	19,616,219
Weatherford	5,209	1,045.98	5,448,510
Wichita	346	892.83	308,919
Woodson	283	2,606.81	737,727
Average	45,834	1,048.85	48,073,138
City Total	1,604,195		923,308,503

Table II-7. Major Industrial Counties' Water Use in 2010 and Price in 2003

County	Quantity (acre feet)	Price ($/acre foot)	Price*Quantity (dollar)
Angelina	30,284	1,111.20	33,651,581
Bastrop	5,125	1,156.80	5,928,600
Bell	1,135	896.10	1,017,074
Bexar	29,533	896.10	26,464,521
Bowie	2,329	801.60	1,866,926
Brazoria	264,343	1,208.90	319,564,253
Calhoun	49,816	1,221.90	60,870,170
Coke	488	1,166.50	569,252
Dallas	37,025	1,000.40	37,039,810
Fannin	85	1,195.90	101,652
Fayette	247	752.70	185,917
Fort Bend	9,873	694.10	6,852,849
Freestone	116	1,309.90	151,948
Harris	397,279	703.80	279,604,960
Harrison	85,244	1,336.00	113,885,984
Henderson	401	1,029.70	412,910
Hill	185	1,107.90	204,962
Hood	187	1,098.10	205,345
Hutchinson	24,057	671.30	16,149,464
Jasper	64,271	615.90	39,584,509
Lamar	5,596	1,332.70	7,457,789
Live Oak	5,840	586.50	3,425,160
Marion	176	977.60	172,058
McLennan	3,942	1,160.00	4,572,720
Montgomery	2,525	619.10	1,563,228
Newton	710	1,059.00	751,890
Nueces	47,982	863.50	41,432,457
Palo Pinto	31	1,169.80	36,264
Polk	648	1,446.80	937,526
Robertson	10,385	570.20	5,921,527
Rusk	1,622	964.50	1,564,419
Smith	4,552	964.50	4,390,404
Somervell	310	1,098.10	340,411

Table II-7. Continued

County	Quantity (acre feet)	Price ($/acre foot)	Price*Quantity (dollar)
Tarrant	17,691	1,274.10	22,540,103
Titus	10,710	1,433.70	15,354,927
Tom Green	2,299	1,166.50	2,681,784
Victoria	32,670	570.20	18,628,434
Washington	599	1,365.30	817,815
Wilson	243	713.60	173,405
Wood	420	1,189.40	499,548
Average	28,774	1,012.50	29,133,957
Total	1,150,974		1,077,574,554

Table II-8. Municipal Monthly Elasticity

Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
-0.168	-0.164	-0.209	-0.268	-0.291	-0.335	-0.327	-0.359	-0.313	-0.2	-0.206	-0.159

Table II-8 shows municipal price elasticities. Municipal water demand depends on temperature and precipitation. If the temperature is high and/or the precipitation is low, then one would expect higher demand for water. Thus, fluctuation in temperature and precipitation is accommodated in the objective function by including the Griffin and Bell climate-driven demand shifting factor. It has the form:

$$\text{Climate-driven municipal demand shifting factor} = \left(1+\varepsilon_{dm}^{c}\frac{\Delta\hat{c}_{d,y,m}}{\hat{c}_{d,y,m}}\right)^{-\frac{1}{\varepsilon_{dm}^{p}}}$$

where $\varepsilon^{p}_{dm} = \text{price elasticity}, \varepsilon^{c}_{dm} = \text{climate elasticity},$

$\Delta\hat{c}_{d,y,m} = \hat{c}_{d,y,m} - \overline{c}_{d}$, $\hat{c}_{d,y,m} = \text{Cvalue}$, $\overline{c}_{d} = \text{average Cvalue}$

Cvalue ($\hat{c}$) is the composite climate index used to shift the municipal demand curves according to the formula. It is the number of days in a month with precipitation less than or equal to 0 inches as frequency of precipitation multiplied by the temperature and divided by 1000. Under this formulation when the Cvalue in a particular month is higher than the average Cvalue, the demand curve will shift to the right side.

To specify this shifter, monthly average temperature and precipitation data for identified major cities for the period 1950-2004 were collected from National Climatic Data Center (NCDC). The units for temperature and precipitation are degree Fahrenheit and inch respectively. For certain major cities some of the needed data are missing for a subset of the years or months. For example, precipitation data in Paris were missing from 1958 to 1961, so data from the nearest city Denton are used to fill the period from 1958 to 1961. In case the data for one month are missing, the average value from the same months in the previous and the next year is used. There are also some climate data that are not available for certain cities. For example there are no monthly temperature data for the whole period in Sweetwater and Terrell, so that the monthly temperatures from the closest weather station, Abilene in the case of Sweetwater and Kaufman for Terrell, are used.

2.4.5. State of nature

Climate not only affects water demand, but also influences water supply. Nine states of nature are considered in the model based on the historical river flows and climate data for 50 years from 1949 to 1998 (Table II-9). To develop these data the inflow between control points from 21 river basins are summed up by year and sorted from low to high. Years with similar inflows were then grouped into one state. All of the yearly data such as water use, temperature, precipitation, crop data, naturalized flows, and evaporation are aggregated according to the state of nature classification. For example, the evaporation loss percentages in year 1956, 1963 and 1954 are averaged and assigned to the very dry state (HDry).

The state of nature constitutes the stochastic part of the model. Future event such as water demand, temperature and precipitation are subject to uncertainty and we assume that the future event will have the same probability distribution as the past event. The state of nature allows us to analyze how dry or wet conditions affect water use, net benefit and the need for IBT. Incorporating the state of nature into the model is an important contribution.

Table II-9. State of Nature (SON)

SON	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

2.5. Conclusion

This chapter developed a modeling framework that integrates and evaluates the economic, hydrological and environmental effects of Interbasin Water Transfers (IBT) in Texas. It depicts water use in 21 Texas river basins covering 35 big municipal water use cities, 40 major industrial and mining counties, 62 agricultural counties, and 175 major reservoirs. It is based on monthly naturalized river flows data for 55 years, numerous control points and related data sets. Twenty-one agricultural crops are introduced for the analysis of agricultural activities after IBT projects.

The model maximizes the objective function that represents the annualized expected net benefit of water uses by the nonagricultural and agricultural sectors and the assigned freshwater inflows value. The constraints consist of agricultural land and water use, total water use by source and sector, demand curve convexity, freshwater inflows, hydrological water flows balance, reservoir and IBT capacity, etc.

The model is a two stage stochastic programming with recourse. In the first stage, the crop mix and IBT construction are decided independent of the state of nature. Subsequently in the second stage, water availability and yields are realized by the state of nature, and adjustments are allowed in management.

CHAPTER III

ECONOMIC AND ENVIRONMENTAL EVALUATION OF INTERBASIN WATER TRANSFERS IN TEXAS

State law or policy guidance suggests that the state must weigh the economic impacts and water quality changes when considering a possible IBT project as well as a number of other requirements (Texas Water Code 11.085, (K), (F)). From economic viewpoint, IBT is meaningful when total benefits arising with the IBT in place exceed its total costs, that is to say, net benefits are greater than zero. Net benefits are affected by: changes in economic activities in the source basin and the destination basin; hydrological and environmental implications such as alterations in recreational uses and fish and wildlife habitat effects.

This chapter reports the results of the simulated model developed in Chapter III to evaluate economic, hydrological and environmental impacts of IBT projects which also affect water quality changes.

3.1. Model Experimentation

Once TEXRIVERSIM was constructed, three scenarios were run through the model. First, a baseline scenario was run without IBT projects. Second, an IBT scenario without any restriction on the construction of Interbasin Water Transfers (IBT) was run with all 45 IBT projects included in the model.

Third, an environmental restriction scenario was run. This scenario eliminates IBT projects that are of medium-high or high environmental concerns, as categorized by each regional planning group and the Texas Water Development Board (TWDB). Twelve projects out of 45 IBT projects were so classified. These twelve eliminated IBT projects are listed as follows in Table III-1.

3.1.1. Assumptions for simulation

It is critical to connect the appropriate IBT delivery point in the source basin and IBT diversion point in the destination basin. However, our data from TWDB and regional water planning groups do not specify the exact diversion and delivery points based on the WAM/WRAP-specific control points. Moreover, most water users from IBT projects are designated as regional water districts (e.g. Tarrant Regional Water

District is designated as a possible owner), instead of specific final users.

Therefore, we connected the IBT diversion and delivery points to the control points closest to any city or county where an IBT project is planned. When there are more control points which belong to the city or county of an IBT project, we treated them as different IBT projects, accommodating all of them.

Table III-1. Environmentally Sensitive Interbasin Water Transfers (IBT)

Project (IBT project in model)	Region	Source basin	Destination basin	IBT Type
Marvin Nichols Reservoir (Marvin_SulToTrin)	C	Sulphur	Trinity	1 River IBT
George Parkhouse Lake (Parkhouse_SulToTrin)	C	Sulphur	Trinity	3 User IBTs
Lake Ralph Hall (RalphHall_SulToTrin)	C	Sulphur	Trinity	1 User IBT
Lower Bois d'Are Creek (BoisdArc_RedToTrin)	C	Red	Trinity	1 User IBT
Lake Columbia (Columbia_NecToTrin)	C	Neches	Trinity	1 User IBT
Lake Fastrill (Fastrill_NecToTrin)	C	Neches	Trinity	1 User IBT
Lake Livingston (Livingston_TriToSan)	H	Trinity	San Jacinto	1 User IBT
Bedias Reservoir (Bedias_TriToSan)	H	Trinity	San Jacinto	1 River IBT
East Texas Water Transfer (ETWT_SabNecToTri)	H	Sabine	Trinity	1 River IBT
LCRA-SAWS (LCRASAWS_ColToGdsn)	L	Colorado	Guadalupe-San Antonio	1 User IBT

The second assumption is that San Antonio will be a destination despite the fact that it does not currently use much surface water. It is assumed that annually 50% of the projected municipal water use in San Antonio would come from the groundwater (108,473 acre feet), after considering the Edward Aquifer pumping limit and reflecting the possibility of reducing dependency on the groundwater. Houston and Harris County are also assumed to depend on the groundwater, say, 35% of the projected water uses (136,179 and 139,048 acre feet respectively). The groundwater portions are given as parameters in the model.

Lastly, it is assumed that the annually expected total water use of city and county is given by the projected annual water use of city and county. It will be unrealistic that water use could increase way beyond the projected water use just because IBT water is available as much as it can be and it contributes to increasing net benefit.

3.2. Simulation Results

The two scenarios allowing IBT projects did not show differences in the IBT projects chosen, the expected (*average*) values of net benefits and water uses in each sector. The constraints not to build those environmentally-sensitive IBT projects are not binding to the objective function on average. The opportunity costs of the non-optimal

IBT projects are provided.

Two sub-scenarios will be analyzed: with-IBT scenario under the environmental restriction and without-IBT scenario as a baseline scenario. The results will be reported based on the annualized expected values[6] weighted by the probabilities of the states of nature if there is no specific term in tables or texts to differentiate them from monthly or each state-of-nature based values.

3.2.1. Definition of water demand and water use

Water demand is a schedule of water uses. Water use is a specific point among the schedule or on a water demand curve that represents the schedule. In our model, a municipal water demand shifts due to the climate-driven water demand shifting factor, moving every level of water uses on a water demand curve. The term water use will be used in most numerical analysis section because a specific point of water use on a demand curve will be analyzed.

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[6] Costs are based on the second quarter 2002 dollars but some cost data such as material costs are adjusted to account for price increases in the 2006 Regional Water Plans. Total annualized capital costs that consist of the IBT fixed costs are amortized for 30 years with 6% interest rate.

3.2.2. Optimal IBTs, IBT gain (cost) and water right issues

Optimal IBTs chosen and IBT gain

Three User IBT projects were selected for construction, which supply water to three big cities such as Houston in Region H (Luce Bayou Channel project), Fort Worth in Region C (Cypress Basin Supplies project) and San Antonio in Region L (LCRA-SAWS Water Project).

Luce Bayou Channel Project (LB IBT) in Region H: This User IBT originates from Lake Livingston in the Trinity River basin and sends water to Lake Houston in the San Jacinto River basin to supply water to north and northwest areas of Houston in Harris County. The IBT water is dedicated to the industrial and mining sector.

This IBT has the second largest capacity volume of water transferred of all the 45 modeled IBTs (maximum 540,000 acre feet in year 2020), being smaller than only the Marvin Nichols Reservoir IBT projects (maximum 612,300 acre feet). It also has the least variable cost per acre foot among the suggested IBT projects (variable cost $9.27 per acre-foot).

The second largest volume of transferred water and the least IBT variable cost contribute to the total net benefit gain. Annually, 169,260 acre-foot of water is transferred on average.

LCRA-SAWS Water Project (LS IBT) by Region L: Water is transferred from Bay City on the Lower Colorado River and is sent to the City of San Antonio of Bexar County on the Guadalupe River basin. Although this IBT project looks very expensive when we look at the cost side (variable cost: $302.85 per acre-foot, fixed cost: $153 million), apparently its expected net benefit justifies the project. Annually, 98,574 acre-foot of water is transferred on average.

Cypress Basin Supplies Project (CB IBT) in Region C: This runs from Lake O' the Pines in the Cypress River basin to the Trinity River basin where its possible[7] owner would be Tarrant Regional Water District with supplies dedicated to the Fort Worth municipality. This user IBT costs $188.77 per acre-foot for its variable costs and $19 million for fixed costs. Annual average water transferred is 39,469 acre feet out of 87,900 acre feet of the maximum IBT water available.

Regarding the LS and CB IBT project, San Antonio and Forth Worth are two cities where the climate-driven water demand shifting factor coefficients are the first and

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[7] 2005 water plan of the Region C has it that Tarrant Regional Water District is a "possible" owner.

second largest (12.43 and 12.26) among major cities in the model as was and will be discussed in detail. This means that per-acre-foot of water use will most contribute to increasing the total benefit from water transferred to these two cities among others, via the shifting factor coefficients especially in dry years. Two cities increased the total net benefit by 77 million dollars (San Antonio $61 million, Forth Worth $16 million).

Each of the three IBT projects (LB IBT, LS IBT and CB IBT) realizes the average IBT gains of $750, $616 and $397 per an acre-foot of annual IBT water transferred, respectively. These are all summarized in Table III-2.

Table III-2. Summary of Optimal Interbasin Water Transfers Chosen

Project (Region)	Source - Destination (big city)	IBT var. cost ($ / af)	IBT fixed cost ($1000)	Annual IBT transferred (af)	Max. IBT (af/ year)	IBT gains ($ million)
LB IBT (H)	Trinity - San Jancinto (Houston)	9.27	11,173	169,260	540,000	126.98
LS IBT (L)	Colorado – Guadalupe (San Antonio)	302.85	153,433	98,574	150,000	60.70
CB IBT (C)	Cypress – Trinity (Fort Worth)	188.77	19,227	39,469	87,900	15.68

Notes: LB/LS/CB denote Luce Bayou/ Lower Colorado - San Antonio/Cypress Basin.

IBT opportunity costs for non-optimal IBT projects

Table III-3 summarizes the IBT opportunity costs for 32 IBT projects which are not chosen in an optimal state, so called non-optimal IBT projects. The opportunity cost of the non-optimal IBT project is derived from the total net benefit loss that accrues by the change of the objective function values when one of the non-optimal IBT projects is forcibly constrained to be constructed without any other environmentally sensitive IBT constraints.

An objective of this analysis is to show how much each of the non-optimal IBT projects costs if it were chosen and constructed for any reason. Irrespective of any one of the constraints of these non-optimal IBT projects, three optimal IBT projects (LB, LS, CB IBT) have been chosen consistently along with the non-optimal one that must be forcibly constrained.

Table III-3 shows that IBT projects in Region C are very costly in terms of the IBT opportunity cost as in Toledo Bend Reservoir and Marvin Nichols Reservoir projects. However, Garwood projects in Region N (Coastal Bend) and LCRA-BRA projects in Region G starting from the Colorado River basin are among those cheapest.

Table III-3. IBT Opportunity Costs for Non-optimal IBTs (unit: million dollars)

Three Optimal IBTs	NB*(=A)	IBT costs	Non-optimal IBTs (cont)	NB*(=B)	IBT costs
LB, LS, CB IBT	200,722.88	0.00	Pines_CypToTrin_Opt1	200,697.17	-25.71
Non-optimal IBTs (30)	NB*(=B)	(B-A)	Pines_CypToTrin_Opt2	200,687.87	-35.01
AlanHenry_BrzToCol_Opt1	200,704.93	-17.95	Rayburn_NecToTrin_Opt1	200,625.60	-97.28
Marvin_SulToTrin_Opt1	200,567.53	-155.35	Rayburn_NecToTrin_Opt2	200,617.42	-105.46
Toledo_SabToTrin_Opt1	200,586.81	-136.07	Rayburn_NecToTrin_Opt3	200,625.60	-97.28
Toledo_SabToTrin_Opt2	200,507.80	-215.08	Texoma_RedToTrin_Opt1	200,707.85	-15.03
Toledo_SabToTrin_Opt3	200,549.66	-173.22	Texoma_RedToTrin_Opt2	200,679.12	-43.76
Garwood_ColToNus_Opt1	200,717.27	-5.61	Texoma_RedToTrin_Opt3	200,709.26	-13.62
Garwood_ColToNus_Opt2	200,722.40	-0.48	Texoma_RedToTrin_Opt4	200,672.94	-49.94
Garwood_ColToNus_Opt3	200,719.25	-3.63	Environmentally sensitive IBTs (12)		
JoePool_TrinToBrz_Opt1	200,716.59	-6.29	Bedias_TriToSan_Opt1	200,716.90	-5.98
LCRABRA_ColToBrz_Opt1	200,721.40	-1.48	ETWT_SabNecToTri_Opt1	200,699.46	-23.42
LCRABRA_ColToBrz_Opt2	200,714.74	-8.14	Marvin_SulToTrin_Opt2	200,562.73	-160.15
LCRABRA_ColToBrz_Opt3	200,722.06	-0.82	BoisdArc_RedToTrin_Opt1	200,693.27	-29.61
Palestine_NecToTrin_Opt1	200,691.88	-31.00	Columbia_NecToTrin_Opt1	200,706.33	-16.55
Patman_SulToTrin_Opt1	200,687.59	-35.29	Fastrill_NecToTrin_Opt1	200,680.63	-42.25
Patman_SulToTrin_Opt2	200,680.41	-42.47	LCRASAWS_ColToGdsn_Opt2	200,713.28	-9.60
Patman_SulToTrin_Opt3	200,654.65	-68.23	Livingston_TriToSan_Opt1	200,707.07	-15.81
Patman_SulToTrin_Opt4	200,581.75	-141.13	Parkhouse_SulToTrin_Opt1	200,695.09	-27.79
Patman_SulToTrin_Opt5	200,690.85	-32.03	Parkhouse_SulToTrin_Opt2	200,695.94	-26.94
Patman_SulToTrin_Opt6	200,661.53	-61.35	Parkhouse_SulToTrin_Opt3	200,687.33	-35.55
Patman_SulToTrin_Opt7	200,645.65	-77.23	RalphHall_SulToTrin_Opt1	200,707.23	-15.65
Patman_SulToTrin_Opt8	200,690.85	-32.03			

Notes: NB and IBT denotes the Net Benefit and Interbasin Water Transfers.

Water right issues and IBT markets

Anybody who wants to use surface water in Texas must get permission from the Texas Commission on Environmental Quality (TCEQ) unless the water uses are such exempt uses as domestic and livestock use, wildlife management, emergency use and other specified uses (TCEQ, May 2007). For instance, when the domestic and livestock sector in the agricultural sector uses water to water range livestock, meet household need or irrigate a yard or home garden, water use permit is not required.

It is also absolutely needed to get permission to use IBT water from another river basin. According to Senate Bill 1, the right of the IBT water from one to another basin is regarded a junior water right to permits in the destination basin regardless of its source basin priority date of the permit on the source water. Therefore, the junior right holder must be aware of domestic and livestock sector users and senior right holders especially downstream of that junior right holder in a basin. This absolutely constrains effective IBT water right trading in the market.

We assumed in this analysis that the junior water right status of IBT water is not considered. In other words, we just looked at the pure economic and environmental aspect of IBT projects rather than its institutional aspect.

3.2.3. Gains from IBTs: Net benefit changes

The gain from IBT construction is the difference between the expected (average) annual net benefit with IBT projects *and* without them. The terminology IBT gain will be used to mean the expected annual gain from IBT projects if it is not noted otherwise. The IBT gain from three optimal IBT projects reaches $203 million (Table III-4).

The industrial and mining sectoral IBT gain ($127 million) comes from LB IBT (169,260 acre feet from Trinity to San Jacinto) whereas the municipal sectoral IBT gain ($76 million) is achieved due to LS IBT ($61 million for 98,574 acre feet from Colorado to Guadsan) and CB IBT ($16 million for 39,469 acre feet from Cypress to Trinity).

The net benefit value must be carefully interpreted since its benefit is measured with an area under a water demand curve. The value is different from, for example, Gross Regional Product (GRP) which is measured with a market price times quantity as its benefit. The net benefit value consists of a producer surplus and consumer surplus whereas GRP only measures the producer surplus.

Table III-4. Net Benefits on Annual Average (unit: million dollars)

Sector	without IBT	with IBT	IBT gain	% change
ag	4.16	4.16	0.00	0.00
ind	3,149.23	3,276.21	126.98	4.03
city	197,318.46	197,394.84	76.38	0.04
FWI	47.83	47.66	-0.18	-0.37
Total	200,519.69	200,722.88	203.19	0.10

Notes: FWI/IBT denote freshwater inflows/Interbasin Water Transfers. ag/ind/city/FWI denote agricultural/industrial & mining/municipal/freshwater inflow sector.

We also introduced a climate-driven water demand shifting factor to the municipal water demand curve which will increase or decrease the scale of net benefit. The climate-driven water demand shifting factors range from 9.9 to 16.3 depending on a city and state of nature (Table III-5).

Table III-5. Climate-driven Municipal Demand Shifting Factor Coefficient (annual)

SON	Austin	Corpus Christi	Dallas	Forth Worth	Houston	San Antonio
HDry	16.32	14.93	15.05	14.95	15.65	16.09
MDry	13.63	12.52	13.22	12.92	12.61	13.88
Dry	13.71	13.79	13.30	13.43	14.00	15.31
Dnormal	12.30	12.08	13.45	13.37	12.90	12.59
Normal	10.95	10.76	11.96	11.91	11.39	11.06
Wnormal	12.59	13.63	12.38	12.50	12.19	11.53
Wet	11.74	11.58	10.40	10.89	11.09	11.93
MWet	9.94	10.33	10.72	10.93	10.03	10.64
HWet	10.21	11.01	10.23	9.82	10.88	9.92
Average	12.19	12.06	12.24	12.26	12.19	12.43

Notes: SON denotes states of nature from heavily dry (HDry) to heavily wet (HWet).

This means that the municipal water use contributes to the total net benefit annually 10 to 16 times as much as the industrial water use which does not have the shifting factor contributes to the net benefit per a unit of water use. Some cities such as Beaumont and Center record 18.4 and 18 respectively in a very dry season (HDry). The shifting factor coefficients are especially high in dry seasons (HDry, MDry, Dry) which are greater than 13 in major cities. The average coefficient is greatest in the City of San Antonio. Forth Worth, Dallas and Houston are next in order of the magnitude of the coefficient.

There is no change in the agricultural sectoral IBT gain because IBT water is not dedicated to agricultural purpose and the sector did not change its planting and harvesting decisions from irrigated lands to dry lands, overall. The optimal crop acres for all irrigated crops do not change after IBT is implemented. Along the six river basins where there are agricultural activities, post-IBT net benefits do not change. The agricultural production activity in the Guadsan River basin contributes to 51.2% of the whole agricultural sector net benefit (Table III-6).

The industrial and mining sectoral IBT gain accounts for 62.5% of the total IBT gain. The gain comes from the industrial and mining purpose User IBT, Luce Bayou Channel Project, from the Trinity to the San Jacinto River basin. The San Jacinto River basin where Houston and Harris County will consume the IBT water contributes to the net gain, and net benefits of other river basins do not change. The Brazos, Guadsan, Sabine and San Jacinto River basins are major players in the industrial/mining sector.

Four river basins account for about 84% of the industrial/mining sectoral net benefit.

Municipal water users account for 37.5% of the total IBT gain from the IBT construction. The contribution of the municipal IBT water destination basin San Antonio is greater than that of Forth Worth, reflecting the magnitude of the IBT water transferred (98,574 vs. 39,469 acre feet) and the climate-driven water demand shifting factor coefficients (12.43 vs. 12.26 on average). Note that Houston municipality does not contribute to the municipal IBT gain since Luce Bayou IBT is just for the industrial and mining purpose.

The four cities, San Antonio, Fort Worth, Dallas and Houston, explain 68.3% of the city total net benefits before and after IBT. The municipal contribution to the IBT gain was especially high in dry years (HDry, MDry, Dry), pushing up the demand curve due to the climate-driven demand shifting factor.

Freshwater inflows to bays and estuaries (FWI) decrease by 0.18 million acre feet as a result of IBT construction. It will be inevitable that transferring water for use results in reducing freshwater inflows and/or water flows in the source basins. Note that the FWI value in the objective function is assigned $1.

Table III-6. Net Benefits by Sector and River Basins (unit: million dollars)

Sector	River	City/County	without IBT	with IBT	IBT gain	% change
City	Guadsan	San Antonio	29,954.41	30,015.11	60.70	0.20
	Trinity	Forth Worth	22,640.88	22,656.56	15.68	0.07
	Trinity	Dallas	32,147.09	32,147.09	0.00	0.00
	San Jacinto	Houston	50,098.05	50,098.05	0.00	0.00
	Four cities		134,840.44	134,916.82	76.38	0.06
	City total		197,318.46	197,394.84	76.38	0.04
Ind	Brazos		921.44	921.44	0.00	0.00
	Colorado		45.67	45.67	0.00	0.00
	Canadian		23.80	23.80	0.00	0.00
	Red		27.78	27.78	0.00	0.00
	Sabine		496.07	496.07	0.00	0.00
	Guadsan		540.51	540.51	0.00	0.00
	Cypress		45.82	45.82	0.00	0.00
	Neches		243.74	243.74	0.00	0.00
	Trinity		114.49	114.49	0.00	0.00
	San Jacinto	Harris County	689.90	816.89	126.98	18.41
	Ind total		3,149.23	3,276.21	126.98	4.03
Ag	Brazos		0.49	0.49	0.00	0.00
	Colorado		0.59	0.59	0.00	-0.02
	Canadian		0.02	0.02	0.00	0.00
	Red		0.05	0.05	0.00	0.00
	Guadsan		2.13	2.13	0.00	0.00
	Nueces		0.89	0.89	0.00	0.00
	Ag total		4.16	4.16	0.00	0.00
FWI	Total		47.83	47.66	-0.18	-0.37
Total			200,519.69	200,722.88	203.19	0.10

Notes: FWI/IBT denote freshwater inflows/Interbasin Water Transfers.

3.2.4. Effects on agricultural production

We allowed for conversion of agricultural irrigated lands to dry lands but not the other way around. This is to reflect relatively high opportunity cost of agricultural water use with respect to the productivity of irrigated lands. It could be more economical to cease irrigation and get compensated for the forgone agricultural water use by selling the diversion right. Thus, the land being irrigated currently remains irrigated or goes dry. This constraint would work when water for IBT is very limited and IBT water markets are well developed enough to buy or sell water rights without institutional barriers.

The harvested crop acres for all irrigated crops do not decrease in the with-IBT scenario. The resulting net benefits without- and with-IBT scenarios remain the same. This is because IBT water is not dedicated to agricultural purpose at all and agricultural water use is not limited in the model as is commonly observed in the real world even though its opportunity cost is so high. Actually in reality, when the domestic and livestock sector in the agricultural industry uses water to feed livestock, meet household need, or irrigate a yard or home garden, water use permit is not required (TCEQ, May 2007). Agricultural water use does not change in each state of nature as is seen in the section of Effects on water use.

However, if we take a look at individual river basins and counties, there are minor changes in the crop acres (Table III-7). Four counties that grow winter wheat in the Canadian River basin adjusted their crop acres inside the basin, nullifying the net effect of net benefit changes in the basin. In the Brazos River basin, Fisher County adjusted acres for cotton upland and winter wheat, and this crop acre changes in Brazos are exactly compensated by changes of Nolan County in the same basin.

Table III-7. Changes of Crop Acres (unit: acre)

River	County	Crop	without IBT	with IBT	change
Canadian	Roberts	winter wheat	14.90	18.21	3.31
	Hansford	winter wheat	29.38	28.42	-0.95
	Hutchinson	winter wheat	31.81	28.50	-3.31
	Dallam	winter wheat	20.86	21.82	0.95
	Canadian total		96.95	96.95	0.00
Brazos	Fisher	cotton upland	1.10	1.00	-0.11
	Fisher	winter wheat	12.01	12.67	0.65
	Nolan	cotton upland	0.64	0.75	0.11
	Nolan	winter wheat	78.39	77.73	-0.65
	Brazos total		92.14	92.14	0.00
Whole basins / all crops			12,825.11	12,825.11	0.00

Notes: IBT denotes Interbasin Water Transfers.

Therefore, any change for water use and net benefit would not arise in a basin as long as the agricultural soil and watering conditions are assumed to be the same for the same crops inside a basin. Changes of crop acres in these two basins do not affect the agricultural IBT gain and no other basins change in terms of agricultural net benefits.

3.2.5. Quantity of transferred IBT water

In total, 307,303 acre-feet of water are transferred via three optimal IBT projects and explain the changes of water use in the whole basins (Table III-8).

Overall, peak time for water transfer via the IBT projects is during the summer season from May through August, transferring 44.6% of annual IBT water.

In the Luce Bayou Channel Project (LB IBT) which runs from the Trinity to the San Jacinto River basin for the industrial and mining sector, the model shows that 31.3% (169,260 acre feet) of the IBT water is transferred on average out of the annual maximum 540,000 acre-foot of the IBT water. Water is transferred most in March through May and July through September.

In case of the LCRA-SAWS Water Project (LS IBT) from the Lower Colorado to the Guadalupe River basin, 65.7% (98,574 acre feet) of the IBT surface water is transferred out of the annual maximum capacity of 150,000 acre feet. The IBT water into San Antonio and Bexar County of the Guadalupe River basin is mainly transferred from May through September, and rather evenly or stably distributed among months than the other IBT projects, LB and CB IBT. This is probably due to the fact that the region is a resort area so that water should be needed stably in each month for the municipal use of this rapidly growing travel-oriented place.

The Cypress Basin Supplies Project (CB IBT) from the Cypress to the Trinity River basin transfers 44.9% (39,469 acre feet) of water out of annual maximum capacity of 87,900 acre feet. The IBT water transferred is highly variable across the states of nature and months.

Table III-8. Average Monthly IBT Water Transferred (unit: acre feet)

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
LB IBT	7,164	7,600	17,766	15,245	16,273	10,556	25,457	23,739	15,580	10,237	10,448	9,195	169,260
LS IBT	7,604	6,054	6,858	7,982	8,581	9,024	12,037	11,222	8,970	6,947	6,391	6,905	98,574
CB IBT	1,445	4,042	3,841	2,593	2,526	809	5,769	10,947	4,375	891	330	1,901	39,469
Total	16,212	17,695	28,466	25,820	27,379	20,390	43,263	45,908	28,925	18,075	17,169	18,001	307,303

Note: IBT denotes Interbasin Water Transfers. LB/LS/CB denote Luce Bayou/ Lower Colorado - San Antonio/Cypress Basin

3.2.6. Effects on water use

Water use by sector and state of nature

Water use changes are largest in the dry seasons (HDry, MDry, Dry and Dnormal) as is expected (Table III-9).

Overall, agricultural water use does not change in the with-IBT scenario because crop acres were not altered from irrigated to dry lands. Agricultural water use explains just a small portion of total water use (9-10%). Agricultural demand is not restricted in the model so that agricultural users are allowed to use water as much as they want regardless of the IBT projects. And all River and User IBT projects suggested by each regional group and TWDB are designed to supply municipal and industrial/mining water, not agricultural water as are the cases of three optimal IBT projects. Minor crop acre changes in the Brazos and Canadian river basins were exactly offset inside each basin so that there were no net effects as were already discussed.

Industrial water use increases by 169,260 acre feet on average due to the Luce Bayou IBT. Municipal water use accounts for more than half of the total water use. The other two IBTs (LCRA-SAWS Water Project and Cypress Basin Supplies Project) increase municipal water use by 138,101 acre feet on average.

Table III-9. Aggregate Water Use by Sector and State of Nature (unit: acre feet)

without IBT										
SON	**HDry**	**MDry**	Dry	Dnormal	Normal	Wnormal	Wet	MWet	HWet	average
ag	248,497	243,818	247,188	235,018	281,652	231,834	276,532	228,319	265,192	259,501
ind	791,740	789,661	789,321	793,185	789,006	794,082	789,830	794,375	793,449	790,617
city	1,541,632	1,463,900	1,461,714	1,459,787	1,410,681	1,441,855	1,391,044	1,352,855	1,365,887	1,429,677
total	2,581,869	2,497,378	2,498,224	2,487,990	2,481,339	2,467,771	2,457,407	2,375,549	2,424,528	2,479,794

Table III-9. Continued

with IBT										
ag	248,497	243,818	247,188	235,018	281,652	231,834	276,532	228,319	265,192	259,501
ind	962,830	961,504	959,466	958,333	959,098	958,530	958,266	964,877	963,342	959,877
mun	1,719,769	1,612,965	1,615,238	1,606,634	1,543,642	1,553,243	1,526,587	1,474,028	1,476,595	1,567,778
total	2,931,096	2,818,287	2,821,893	2,799,986	2,784,392	2,743,607	2,761,385	2,667,225	2,705,130	2,787,155
changes in water use due to IBT (with-without IBT)										
ag	0	0	0	0	0	0	0	0	0	0
ind	171,089	171,843	170,145	165,148	170,092	164,448	168,436	170,503	169,893	169,260
city	178,137	149,065	153,524	146,848	132,961	111,388	135,543	121,174	110,709	138,101
total	349,227	320,909	323,669	311,996	303,053	275,836	303,979	291,677	280,602	307,361

Notes: IBT/SON denotes Interbasin Water Transfers/climate states of nature from heavily dry (HDry) to heavily wet (HWet). ag/ind/city stand for agricultural/industrial & mining/municipal sector respectively.

Water use in the river basins

Water use increases in the Brazos, Colorado, Guadsan, Trinity and San Jacinto River basins, while it decreases in the Lavaca River basin if the changes less than ±0.1% are ignored (Table III-10). Water use in the Guadsan and San Jacinto River basin increases clearly as the amount of IBT water is imported to these destination basins. Water use in the destination basin Trinity also increases as water is imported into the Fort Worth municipality from the Cypress River basin. Water use in the IBT source basin Cypress does not change.

Table III-10. Water Use by Major Rivers (unit: acre feet)

River	without IBT	with IBT	changes	% change
Brazos	380,866	389,210	8,344	2.19
Colorado (S)	294,159	295,489	1,329	0.45
Canadian	9,015	9,015	0	0.00
Red	23,327	23,329	2	0.01
Sabine	98,349	98,362	14	0.01
Guadsan (D)	195,223	293,855	98,632	50.52
Sulphur	8,794	8,792	-2	-0.02
Cypress (S)	15,496	15,496	0	0.00
Neches	150,080	149,989	-91	-0.06
Trinity (S, D)	169,578	209,125	39,546	23.32
SanJacinto (D)	253,016	413,971	160,955	63.61
Lavaca	64,994	63,626	-1,368	-2.10
SanioNues	232	232	0	0.00
Nueces	35,557	35,557	0	0.00
Total	1,698,687	2,006,048	307,361	18.09

Notes: IBT/S/D denote Interbasin Water Transfers/IBT Source/Destination basins.

It is very interesting to find out that there are offsetting forces of water uses between some river basins as Table III-11 shows: industrial and mining water use between the Neches and Trinity River basin; municipal water use between the Sabine and Neches River basin; agricultural water use between the Colorado and Lavaca River basin; municipal water use between the Brazos, Colorado and San Jacinto River basin. The basin-wide net effect of water uses just reverts back to water use changes in the three destination basins, Guadsan, Trinity and San Jacinto after all those water uses are offset with each other.

The offsetting forces of water uses in Neches-Trinity and Sabine-Neches have small magnitudes. However, it would be very characteristic to see that the IBT source basin Colorado increases its agricultural water use and the IBT-neutral basin Lavaca, where IBT water is not exported or imported, decreases the exactly same amount of its agricultural water use. Net increase of municipal water uses in Brazos *and* Colorado exactly matches decrease in San Jacinto. We have already seen that agricultural crop acres did not go through any major change that affects the basin-wide water use and net benefits.

Agricultural and municipal water uses are offset in the neighboring basins of Colorado, Lavaca, Brazos and San Jacinto. Agricultural water users in Colorado County and Wharton County have three water sources to draw their water over the Colorado and Lavaca River basin. After IBT, these two counties switch water from Lavaca (GS1000, WGS800) to Colorado (K20000).

Table III-11. Water Use Changes by Sector and River (unit: acre feet)

		Brazos	Colo-rado	Sabine	Guad-san	Neches	Trinity	San Jacinto	Lavaca
ag	without IBT	40,293	114,560	0	55,302	0	0	0	7,286
	with IBT	40,293	115,928	0	55,302	0	0	0	5,918
	Changes	0	1,368	0	0	0	0	0	-1,368
ind	without IBT	180,130	13,531	81,776	130,633	102,679	23,464	91,496	0
	with IBT	180,130	13,531	81,776	130,633	102,602	23,542	260,756	0
	Changes	0	0	0	0	-77	77	169,260	0
city	without IBT	160,443	166,068	16,572	9,288	47,401	146,114	161,520	57,708
	with IBT	168,787	166,029	16,586	107,920	47,387	185,583	153,215	57,708
	Changes	8,344	-39	14	98,632	-14	39,469	-8,305	0
total	without IBT	380,866	294,159	98,349	195,223	150,080	169,578	253,016	64,994
	with IBT	389,210	295,489	98,362	293,855	149,989	209,125	413,971	63,626
	Changes	8,344	1,329	14	98,632	-91	39,546	160,955	-1,368

Notes: IBT denotes Interbasin Water transfers. ag/ind/city denote agricultural/industrial & mining/municipal sector respectively.

This is a unique nature of water use pattern in the area. The part of the reasons would be that the agricultural users of these counties are located in the neighborhood of the control point (K10000) of the Lower Colorado River basin where the IBT water starts to go out of the basin.

Municipal water users also substitute water between the Brazos, Colorado and San Jacinto River basin. Table III-12 shows this relationship.

Table III-12. Water Use Changes in Some Basins (unit: acre feet)

Sector	County	River basin	Control point	without IBT	with IBT	Changes
ag	Colorado	Colorado	K20000	46,326	31,621	-14,706
	Wharton	Colorado	K20000	38,262	54,335	16,074
		Sub-total		84,588	85,956	1,368
	Colorado	Lavaca	GS1000	74	68	-6
	Wharton	Lavaca	GS1000	3,159	2,233	-926
	Colorado	Lavaca	WGS800	831	856	25
	Wharton	Lavaca	WGS800	3,221	2,760	-461
		Sub-total		7,286	5,918	-1,368
city	Fort Bend	Brazos	BRRO72	91,383	99,688	8,305
		Sub-total		91,383	99,688	8,305
	Montgomery	San Jacinto	A4963A	26,853	21,008	-5,845
	Harris	San Jacinto	A4964A	134,667	132,208	-2,460
		Sub-total		161,520	153,215	-8,305

Notes: IBT denotes Interbasin Water transfers. ag/city denote agricultural/municipal sector respectively.

It seems that there is a correlation of water use pattern in some geographical boundaries: one is Colorado-Lavaca- Brazos-San Jacinto that has a strong relationship based on water use changes; the other is Sabine-Neches-Trinity that has rather a weak relationship.

The IBT-neutral Lavaca and Brazos River basins are adjacent river basins which are located inside the IBT exporting and importing basins: exporting Colorado and importing Guadsan in the south-western side, net exporting Trinity and importing San

Jacinto up in the north-eastern side. Lavaca is especially located in the down side near Gulf coast where more complex water routes are interacting. This geographical aspect could affect the water use pattern.

Water use by major cities

Water from User IBT projects goes to Fort Worth in the Trinity River basin and San Antonio in the Guadsan River basin (Table III-13). Imported water in the San Jacinto River basin is dedicated to the industrial and mining sector of Houston and Harris County. In the case of San Antonio, municipal water use is comprised of groundwater (108,473 acre feet) and surface water (106,073 acre feet), including IBT water. Increases in municipal water use of San Antonio and Fort Worth are accounted for by their imported IBT water. Houston and Dallas municipalities are not affected.

Table III-13. Water Use by Major Cities (unit: acre feet)

	Dallas	Forth Worth	Houston	San Antonio	City total
without IBT	389,548	110,127	252,903	7,441	1,429,677
with IBT	389,548	149,596	252,903	106,073	1,567,778
changes	0	39,469	0	98,632	138,101

Notes: Groundwater uses in San Antonio (=108,473 acre feet) and Houston (=136,179 acre feet) are not included. IBT denotes Interbasin Water Transfers.

Flows to bays and estuaries

The model variable ESCAPETOBAY is total freshwater inflows to all bays and estuaries (FWI). Such flows are desirable as they keep the bays environmentally healthy, recreationally enjoyable and productive in marine resources according to the definition of freshwater inflows (Loeffler, 2006).

The FWI value is assigned $1 per an acre foot in our model. The FWI values are not subject to a market, thus not easily obtained. Furthermore, it is another issue to apply the values unilaterally into the model although we may find them because many different methodologies and assumptions are adopted for each of the non-market valuation (Han, 2007). It will be a future research task to develop a model to obtain and incorporate those values in this model. But it is believed to be the first try to introduce an environmental freshwater inflows factor in an economic and hydrological model, and this will be investigated in the next chapter.

We will take a look at the inflows changes in six major estuaries of seven river basins located in the Gulf of Mexico: Mission-Aransas Estuary in San Antonio-Nueces River (SanioNues), Guadalupe Estuary (Guadsan), Lavaca-Colorado Estuary (ColLavaca), Nueces Estuary (Nueces), Trinity-San Jacinto Estuary (Trinity, San

Jacinto), Sabine-Neches Estuary (Neches River). These are the economically and ecologically targeted areas by the Texas Parks and Wildlife Department (TPWD) and the Texas Water Development Board (TWDB).

The IBT causes increase of water flowing into the estuaries of the destination basins. The Guadsan and San Jacinto River basin show distinct increases in FWI. FWI of the Trinity River basin is severely reduced as water is transferred out (Table III-14).

Table III-14. Freshwater Inflows to Seven Major Estuaries (unit: acre feet)

Estuaries	without IBT	with IBT	changes	% change
Guadsan (D)	1,903,993	1,957,821	53,828	2.83
Neches	5,519,204	5,519,262	57	0.00
Trinity (S, D)	6,020,715	5,873,003	-147,712	-2.45
San Jacinto (D)	1,937,978	1,998,595	60,617	3.13
ColLavaca	78,104	78,104	0	0.00
SanioNues	565,403	565,403	0	0.00
Nueces	504,298	504,298	0	0.00
Total	16,529,695	16,496,486	-33,209	-0.20

Notes: IBT denotes Interbasin Water Transfers. S/D denote IBT source/destination basin.

We find a relationship among water transferred, return flows and FWI in Table III-15. For example in the Guadsan River basin, IBT water transferred into the basin is 98,574 acre feet and its returned flows back in the basin is 54,216 acre feet when we apply the municipal return flow rate (0.55; 98,574 acre feet*0.55=54,216 acre feet). Its final FWI in the simulation program reaches 53,828 acre-foot of water which is close to the amount of returned water computed with the return flow rate, which we call the expected FWI. Its error is 0.72%.

In the case of the Trinity River basin, net remaining water in the basin after IBT water is transferred in and out is negative 147,552 acre feet (-169,260 acre feet transferred out + 21,708 acre feet returned from water transferred in). The error between the expected and final FWI is -0.11% in the Trinity River basin.

However, the expected and final FWI in the San Jacinto River basin shows rather big difference (-5.06%) unlike the other two basins. This will be related to the fact that municipal water use diminishes by 8,305 acre feet in the San Jacinto River basin after IBT. This decreased amount is not accounted for in the expected FWI. But the decreased water use should have contributed to increasing the final FWI in the basin.

There was not much change of water use and flows till water flows out of the basin as form of FWI ever since water is transferred into is used and returns back to the basin.

Table III-15. Water Transferred, Return Flows and FWI (unit: acre feet)

IBT project	Source	Destination	Return flow rate (A)	IBT water in dest. basin (B)	Returned water (A*B=C)	Expected FWI (D)	Final FWI (E)	Difference (D-E) *
LB IBT	Trinity	San Jacinto	0.34 (ind)	169,260 (=X)	57,548	57,548	60,617	-3,069 (-5.06%)
LS IBT	Colorado	Guadsan	0.55 (mun)	98,574	54,216	54,216	53,828	388 (0.72%)
CB IBT	Cypress	Trinity	0.55 (mun)	39,469	21,708 (=Y)	-147,552 (=Y-X)	-147,712	160 (-0.11%)
Total				307,303	133,472	-35,788	-33,267	-2,521 (7.04%)

Notes: The percentage rates in parentheses stand for difference rates (%) of the expected freshwater inflows (FWI) from the final FWI, say, (Expected FWI - Final FWI)/Final FWI. LB/LS/CB IBT denote Luce Bayou/ Lower Colorado - San Antonio/Cypress Basin Interbasin Water Transfers.

3.2.7. Effects on flows of water

Table III-16 shows the monthly flows of major river basins. For this flows computation, we took a weighted average flows of each control point of a river basin in each month, which is weighted with probabilities depending on the states of nature. For example, there are 77 control points in the Brazos River basin. We obtained the 77 weighted average flows of Brazos in each month. Then, we computed the arithmetic average flows of Brazos in each month by adding the 77 monthly weighted average flows of Brazos and dividing the summed number by 77. The flow levels computed are those monthly arithmetic average flows across the control points of each river basin. We wanted to look at overall average impacts of water flows in the source and destination basins when water is transferred from “somewhere” of a basin to “somewhere” of another, rather than in a specific IBT in- and out- point. This is because identification of the exact IBT points was difficult. The Colorado and Cypress are exporting basins, and the Guadsan and San Jacinto are importing basins. Trinity is a net exporting basin.

Table III-16. Monthly Flows of Water (unit: thousand acre feet)

without IBT	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
Brazos	88	55	34	42	82	54	16	10	16	38	16	45	496
Colorado	71	32	18	24	48	37	14	13	23	85	11	24	400
Canadian	1	1	1	1	8	11	14	12	5	3	2	17	75
Red	57	21	47	24	86	48	51	14	53	25	27	17	469
Sabine	59	313	104	78	119	64	27	10	51	29	180	160	1,194
Guadsan	22	20	17	23	47	38	16	12	25	21	17	16	273
Sulphur	35	48	50	54	69	33	14	4	10	23	38	50	427
Cypress	35	15	20	24	22	10	8	6	3	5	21	28	197
Neches	168	66	66	65	69	37	16	6	10	18	32	294	848
Trinity	89	168	55	79	108	49	15	5	9	22	123	85	807
SanJacinto	37	30	23	29	30	29	7	5	11	26	17	34	278
Lavaca	15	17	9	17	25	24	4	2	17	15	11	11	168
Nueces	5	6	5	6	13	18	8	10	17	18	7	4	117
Total	681	791	449	465	727	450	211	109	251	327	501	786	5,750

Table III-16. Continued

with IBT	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
Brazos	69	66	35	42	87	50	16	9	16	35	18	52	496
Colorado	21	82	18	20	47	35	17	11	24	85	10	31	400
Canadian	1	1	1	2	7	9	10	11	8	4	2	18	75
Red	46	27	54	39	70	56	30	14	54	41	23	16	469
Sabine	65	77	130	141	134	70	20	10	47	110	348	41	1,194
Guadsan	22	19	17	23	47	39	18	13	26	22	18	16	278
Sulphur	34	48	51	54	69	33	14	4	11	23	38	49	427
Cypress	30	14	16	27	18	10	7	5	9	7	11	35	189
Neches	164	142	66	65	73	33	14	8	13	47	94	128	848
Trinity	95	76	46	69	120	50	9	5	7	20	113	183	793
SanJacinto	35	31	23	31	30	25	7	5	11	27	23	32	280
Lavaca	15	17	9	17	26	24	4	2	17	15	11	11	168
Nueces	5	6	5	6	13	18	8	10	17	18	7	4	117
Total	603	605	472	535	740	450	173	106	262	455	716	615	5,735

% change	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
Brazos	-21.47	20.39	3.82	-1.95	5.34	-6.91	3.16	-13.41	2.62	-6.31	17.1	14.5	-0.02
Colorado	-69.89	153.07	3.11	-17.11	-1.9	-4.76	17.94	-15.02	3.92	0.13	-14.98	26.38	-0.01
Canadian	5.1	-26.8	68.82	183.48	-12.46	-17.56	-28.14	-3.51	66.38	57.79	4.7	4.55	0
Red	-18.36	28.95	14.64	65.24	-18.21	15.2	-42.07	2.04	2.29	63.47	-15.77	-7.53	0
Sabine	11.25	-75.41	24.76	80.32	12.33	9.72	-25.8	-2.39	-7.1	281.12	93.54	-74.39	0
Guadsan	1.37	-2.05	1.83	0.15	-0.28	1.26	10.13	5.57	2.86	1.56	3.91	0.4	1.71
Sulphur	-1.88	0.93	1.34	-0.95	0.49	-1.33	-0.87	0.38	5.44	1.66	-0.09	-1.29	0
Cypress	-12.92	-7.82	-23.34	14.92	-16.21	4.37	-12.69	-21.87	153.42	48.73	-45.95	24.54	-3.67
Neches	-2.5	114.25	0.44	0.45	5.95	-11.82	-12.58	26.79	34.05	159.01	194.72	-56.36	0
Trinity	6.41	-54.89	-16.35	-13.06	10.21	3.03	-41.2	0.7	-20.56	-7.44	-7.84	116.03	-1.79
SanJacinto	-5.62	4.44	0.34	7.43	-1.04	-14	-2.25	4.1	-2.83	3.54	35.53	-7.59	0.45
Lavaca	0	0	-0.05	0.58	2.76	0.69	-13.93	9	0	0	0	0	0.33
Nueces	0	0	-0.04	-0.33	-0.08	0.21	-0.33	-0.01	0	0	0.34	0	0
Total	-11.39	-23.56	5.04	15.04	1.9	-0.01	-17.99	-2.15	3.99	39.1	42.89	-21.68	-0.26

Notes: IBT denotes Interbasin Water Transfers.

After IBT, annual water flows decrease by 0.26% on average.[8] The largest portion (44.56%) of annual IBT water is transferred in summer from May to August. During the same period, flows decrease (-1.78%) and occupy the least portion (25.64%) of annual flows (Table III-17). Flows tend to decrease when water is more transferred.

Water flows in all source basins decrease. The Cypress and Trinity River basins decrease flows by 3.67% and 1.79%. The other source basin Colorado also decreases its flows by 0.01% after IBT, and one reason would be that the LCRA-SAW IBT begins from the Lower Colorado region so that its impact to flows will not be significant.

As for water flows in the destination basins, the Guadsan River basin shows increased flows (1.71%). IBT water transferred to San Antonio is designed to be reserved in the reservoir (control point CP31 in the Guadsan River basin) which does not have an upward control point but several downward control points. The flows of the San Jacinto River basin also increase by 0.45%.

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[8] [(Annual total water flows with IBT – Annual total water flows without IBT)/ Annual total water flows without IBT]*100

Among the IBT-neutral basins, flows in Brazos decrease (-0.02%) but flows in Lavaca increases (0.33%). These are the basins where their water use increased / decreased respectively. Other rivers show no significant changes of flows compared to their flows without IBT.

Table III-17. IBT Water Transferred and Water Flows

IBT water and flows		Jan-Apr	May-Aug	Sep-Dec	Annual
IBT water transferred (acre feet)		88,193	136,940	82,170	307,303
Composition (%)		28.7	44.56	26.74	100.00
Water flows	without IBT (acre feet)	2,386,448	1,497,258	1,866,104	5,749,810
	with IBT (acre feet)	2,215,182	1,470,619	2,048,801	5,734,602
	% change	-7.18	-1.78	9.79	-0.26
	Composition (with IBT,%)	38.63	25.64	35.73	100.00

Notes: IBT denotes Interbasin Water Transfers.

3.2.8. Relationship among water use, flows and freshwater inflows

IBT relocates water and increase economic efficiency, contributing to increase of net benefit, say, IBT gain. We find the tendency that water use increases and water flows decrease in the IBT source and neutral basins. But they all increase in the destination basins. This is summarized in Table III-18.

Table III-18. Summary: Changes of Water Use, Inflows/Flows (unit: % changes)

Source/ Destination	River basins	Water use (After IBT)	FWI (7 basins)	Water flows
Source	Cypress	0	---	-3.67
Source	Colorado	0.45	---	-0.01
Net source	Trinity	23.32	-2.45	-1.79
Destination	Guadsan	35.55	2.83	1.71
Destination	San Jacinto	63.61	3.13	0.45
IBT-neutral	Brazos	2.19	---	-0.02
IBT-neutral	Lavaca	-2.10	---	0.33
Total	All rivers	18.09	-0.20	-0.26
Total amount (acre feet)		307,361	-33,209	-15,208

Note: Increasing rate (%) = (increased water with IBT / water amount without IBT)*100. Water amount is based on average after applying probabilities depending on the states of nature. IBT/FWI denotes Interbasin Water Transfers/freshwater inflows**.**

Water use in the source basin Colorado increases in the agricultural sector, which is exactly offset by decrease of the sector in the Lavaca River basin. The Trinity River basin also increases its water use triggered by the water transferred into the basin. But water use in the Cypress River basin remains the same. One of the possible reasons would be that the Cypress River basin surrounded by the Sulphur and Sabine River basin is isolated from any other IBT source/destination basins, so that there might be no offsetting use changes. Water flows of all source basins decrease as are expected.

In IBT-neutral basins, municipal water use in the Brazos River basin increases and its increase is offset by decrease of use in the San Jacinto River basin. And flows in

Brazos decrease as its water use increases. Water use in the Lavaca River basin decreases while water use increases by the same amount in the Colorado River basin, and water flows increase in Lavaca.

In the destination basins, water use in the all three destination basins has increased. Water flows and freshwater inflows also increase in the Guadsan and San Jacinto River basin. As water is transferred in to the basins, water use increases and water returns back to flows which eventually flow out to bays and estuaries.

Across all basins after IBT projects are implemented, total water use increases by 18.09% (307,361 acre feet), but flows decrease by 0.26% (15,208 acre feet) and freshwater inflows in seven river basins decrease by 0.20% (33,209 acre feet).

3.3. Conclusion

This Chapter III investigates the implication of IBT implementation using the model developed in Chapter II. Three scenarios of the without- and with-IBT were analyzed: the first one is the baseline scenario without IBT projects; the second one is the IBT scenario without any restriction on IBT construction; the third one is the environmental restriction scenario which excludes twelve environmentally sensitive IBT projects categorized by TWDB and regional planning groups.

Three User IBT projects are selected: Luce Bayou Channel Project by Region H (Trinity to San Jacinto River basin); Cypress Basin Supplies Project by Region C (Cypress to Trinity River basin); LCRA-SAWS Water Project by Region L (Colorado to Guadsan River basin). Three big cities are related to these User IBT projects: Houston in Region H, Fort Worth in Region C and San Antonio in Region L. Water is mostly transferred during the summer season from May to August generally in all three IBT projects.

IBT gains of the three optimal IBT projects and IBT costs for the non-optimal projects are provided. The annualized IBT gain from IBT projects amounts to $203 million. We introduced the climate-driven water demand shifting factor to the municipal water demand to capture the economic effect of an uncertain climate factor.

Agricultural users are unaffected by the IBT projects overall across Texas irrespective of minor changes, not altering crop mix, planting and harvesting decisions nor switching from irrigated to dry land production. This is because IBT water is not dedicated to agricultural purpose at all and agricultural water demand is not limited in the model.

Industrial and mining water users contribute 62.5% ($127 million) of the IBT gain due to Luce Bayou Channel Project. Municipal water users capture 37.5% ($76 million) of the IBT gain from LCRA-SAWS Water Project and Cypress Basin Supplies Project respectively for the San Antonio and Forth Worth municipalities. The contribution of the municipal water use could be explained by its climate-driven water demand shifting factor, especially in dry seasons (HDry, MDry, Dry) when the climate-driven demand shifting factor coefficients are very high.

The aggregate of freshwater inflows to economically and ecologically important seven estuaries in the Gulf of Mexico decreases by 0.20%. However, the IBT destination basin San Jancinto and Guadsan emit freshwater inflows after the IBT projects. The definitions of environmental water flows such as instream flows and freshwater inflows are still being discussed in Texas Congress and state agencies. However, it is believed to be the first endeavor to introduce an environmental freshwater inflows factor in an economic and hydrological model.

In summary, our finding is that implementing the IBT projects increases water use in the destination basins and generates substantial IBT gains. IBT generally reduces freshwater inflows and water flows in the IBT source and neutral basins. In the destination basins, however, water use and water flows/freshwater inflows all increase. The overall impact in all basins is that water use increases but flows and freshwater inflows decrease. The relationship between water use and flows is also found seasonal. The largest portion of annual IBT water is transferred in summer from May to August. During the same period flows decrease and occupy the least portion of annual flows.

In the IBT-neutral but IBT-adjacent basins, increasing water use and decreasing water flows are also observed and some interaction exists between these basins. The Brazos-San Jacinto-Colorado-Lavaca river basins are geographically interrelated where IBT influences each of the basins directly and indirectly. The ultimate basin-wide net effect of water uses reverts back to changes in water uses of the three destination basins, Guadsan, Trinity and San Jacinto after changes in water uses are offset with each other in the other neighboring basins.

There are some limitations in our analysis. One is that the groundwater component is not introduced in our model, although it is partially considered in San Antonio, Houston and Harris County where they heavily count on the groundwater. Our modeling and analysis are based upon the surface water. This will restrict comprehensive understanding on water use, flows/inflows, necessities of IBT and their resulting changes in social welfare.

Another is that more accurate information on IBT water in- and out-points in each basin must be identified to measure quantitative economic impacts of IBT. Qualitatively, more field based analysis should be carried out to see positive and negative impacts in each of agricultural, municipal, and industrial and mining sectors and their consequences to net benefits. The junior water rights status of water transferred needs to be incorporated in the future research.

CHAPTER IV

ECONOMIC AND ENVIRONMENTAL EFFECTS OF FRESHWATER INFLOWS TO TEXAS BAYS AND ESTUARIES

4.1. Introduction

In 1985, Texas passed legislation directing the Texas Commission on Environmental Quality (TCEQ) to consider the effect of granting a water right to instream uses and inflows to bays and estuaries. Instream use includes water that supports recreation, fish and wildlife habitat and water quality. Presently, TCEQ uses default values for calculating instream maintenance flows for perennial streams based on the 7Q2 value or the monthly median flows, whichever is higher.

The 7Q2, the seven-day, two-year low flow, is defined as the lowest average flow for seven consecutive days which is expected to recur every two years based on historical daily flow data. But 7Q2 is not generally accepted as an appropriate tool for regulating instream flows because it does not allow for a buffer of safety between waste assimilation and degradation.

The monthly median flows are defined as: the water flow level that is 40% of the average median flow from October to February; the water flow level that is 60% of the average median flow from March to September. This is called the modified Lyon's Method (Lyons, 1979; Loeffler, 2004). It results in two seasonal flow levels and each one should be met in every month during each of the two periods. This method has not been tested rigorously in the field and may not be acceptable for all of Texas basins. It also fails to address seasonal and monthly changes in flows.

For these reasons, the instream flow studies which have been done by state water agencies so far are not comprehensive so that instream flow restrictions are conducted on a case-by-case basis, independent of basin-wide water uses. The instream flow restrictions are difficult to apply for several over-appropriated basins. Moreover, the vast majority of water rights were granted before 1985, and most surface water rights were issued without any environmental flow restrictions (Bradsby, 1994).

Closely related to the instream flows studies, the Texas Parks and Wildlife Department (TPWD) and the Texas Water Development Board (TWDB) have jointly developed recommendations for freshwater inflows to bays and estuaries which will maintain the health and productivity of Texas estuaries. Legislatively mandated studies to determine beneficial inflows necessary to conserve health and productivity of Texas major estuaries have been completed although some are being updated. (Loeffler, 2006).

However, the instream flows and bay/estuary inflow restrictions have been discussed and evaluated so far without any consideration for their economic implications. Regarding this, the State of Texas Joint Committee on the Study Commission on Water for Environmental Flows suggests: “Further evaluation of existing and alternative regulatory and market-based approaches should be explored to provide for a more comprehensive and effective environmental flow program that addresses both river and estuarine needs for the state.” (The State of Texas Congress, 2004)

This study attempts to look at the economic, hydrological and environmental implications of the recommended water levels on the Freshwater Inflows to Bays and Estuaries (FWIB recommendations) under a market-based approach, using the Interbasin Water transfers (IBT) model, TEXRIVERSIM developed in Chapter II. We attempted to investigate the acceptable levels of Texas instream flows and freshwater inflows but these two targets were too extensive to deal with in a single modeling setting.

The FWIB recommendations by TPWD and TWDB were already too strict to be satisfied in every terminal control point of the FWIB-recommended river basins. Our simulation results showed that just five out of seven river basins met the FWIB recommendations on average, but not in every state of nature, even when instream flows were not restricted at all. Only three FWIB recommendations were fully met when the FWIB recommendations were constrained in each state of nature. When we examined the instream flows restrictions simultaneously based on the monthly median flows, we found that it was very difficult to find the minimum instream flow levels that balance the hydrological flow balance equation. That is why we decided to resolve the FWIB recommendations first.

The goal of the TEXRIVERSIM model structure is to maximize the annualized expected net benefit of water use under the constraints of the FWIB recommendations, IBT implementation, environmentally sensitive IBT restrictions, along with other constraints discussed in Chapter II and III.

This will be the first academic and professionally evaluated study of the economic and environmental impacts of implementing the FWIB recommendations as well as IBT in Texas. The study results will constitute a test of the feasibility of Texas basin-wide water use and environmental flow management.

4.1.1. Definition of freshwater inflows to bays and estuaries

Beneficial inflows are defined as the minimum inflows necessary to provide a "salinity, nutrient and sediment loading regime adequate to maintain an ecologically sound environment in the receiving bay and estuary system that is necessary for the maintenance and productivity of economically important and ecologically characteristic sport or commercial fish and shellfish species and estuarine life upon which such fish and shellfish are dependent." (Loeffler, 2006) Seven target species are considered: Blue crab, Eastern oyster, Red drum, Black drum, Spotted sea-trout, Brown shrimp and White shrimp.

Based on this definition and target species, TPWD and TWDB developed the TxEMP optimization model which is an optimization model to obtain a range of inflow levels for estuarine health and productivity. The FWIB recommendations were generated using a statistical relationship between harvest or catch per unit effort and inflows. Finally, TPWD and TWDB obtained the minimum requirement levels of freshwater inflows two of which are called MinQ and MaxH. MinQ is a set of the minimum inflows that maintain 80% of the average historic harvest and all other physical constraints such as salinity, nutrient and sediment needs. MaxH is a set of the inflows necessary to sustain the historic fisheries harvest as evaluated against existing fisheries data, which can meet the legislative definition of beneficial inflows. We will use the FWIB recommendations based on the MinQ definition in this analysis, which are less restrictive than the MaxH definition.

4.2. Recommended MinQ Freshwater Inflows: The FWIB Recommendations

We will treat inflows for six estuaries over seven river basins: Mission-Aransas Estuary that is fed by the San Antonio-Nueces River basin (SanioNues), Guadalupe Estuary (as fed by the Guadsan River basin), Lavaca-Colorado Estuary (ColLavaca), Nueces Estuary (Nueces), Trinity-San Jacinto Estuary (Trinity, San Jacinto), and Sabine-Neches Estuary (Neches). These areas have the predefined FWIB MinQ levels recommended by TPWD and TWDB except for Lavaca-Colorado Estuary in which MinQ-salinity (MinQ-sal)[9] is applied. The inflows are also recommended for estuaries fed by the Rio Grande River basin but are not treated here due to its omission in the TEXRIVERSIM model. We also should note that the FWIB recommendations have not

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[9] MinQ-salinity is based on maintaining estuary salinity level, not related to achieving fisheries harvest level. MinQ is not designated in the ColLavaca River basin.

been enforced to date.

The FWIB recommendations are imposed on a monthly basis at the last control points of the major river basins where water flows out to bays and estuaries. The FWIB recommendations for freshwater inflows (MinQ) are summarized in Table IV-1. Annually, Neches Estuary has the highest FWIB levels and Mission-Aransas estuary in the SanioNues River basin has the lowest FWIB levels.

Table IV-1. Recommended Freshwater Inflows (MinQ) to Estuaries (unit: acre feet)

Estuaries	Jan	Feb	Mar	Apr	May	Jun	Jul
ColLavaca	79,600	84,700	141,200	175,400	274,100	266,100	129,700
Guadsan	111,200	124,200	52,420	52,420	186,050	135,980	60,860
SanioNues	2,940	5,010	2,980	2,890	4,020	3,330	1,480
Nueces	2,230	2,780	4,410	5,180	32,140	19,990	6,980
TrinitySanJac	150,500	216,700	363,900	352,600	679,700	448,100	232,700
Neches	624,000	770,590	853,700	882,300	691,900	478,700	424,470

	Aug	Sep	Oct	Nov	Dec	Annual
ColLavaca	65,500	123,300	120,200	80,100	77,600	1,617,500
Guadsan	60,850	52,420	52,420	73,830	66,200	1,028,850
SanioNues	1,990	6,250	3,650	3,760	2,780	41,080
Nueces	9,750	11,040	8,690	7,780	4,670	115,640
TrinitySanJac	154,000	330,200	251,900	351,500	626,800	4,158,600
Neches	361,810	574,600	537,900	237,510	574,020	7,011,500

Source: Longley, W.L., ed. 1994, http://www.tpwd.state.tx.us/

Notes: MinQ-sal is applied instead of MinQ in the ColLavaca River basin.

4.3. Adding Freshwater Inflow Constraints to TEXRIVERSIM

We will augment and use the model TEXRIVERSIM, developed in Chapter II and applied in Chapter III, to evaluate the economic, hydrological and environmental effects of the FWIB recommendations along with the IBT implementation. To depict the FWIB recommendations in the model, we added constraints. Freshwater inflows are captured with the variable ESCAPETOBAY and OUTTOBAY. The variable OUTTOBAY is defined for each river basin, the last river place (control point), state of nature, and month. Then, ESCAPETOBAY is the expected annual summation of OUTTOBAY for all of the last control points for the major river basins.

The FWIB recommendations and the FWIB constraints will be interchangeably used throughout the analysis, though the former emphasizes the recommended water levels while the latter focuses on the constrained equations.

We applied two types of the FWIB constraints. The first constraint is stricter and needs to be satisfied in every state of nature. The constraints will be called the FWIB State of Nature constraints (FWIB-SON constraints), in the form of:

$OUTTOBAY_{RB,RP,s,m} \geq MinQ_{RB,m}$ where RB = river basin, RP = river place (control point), s = state of nature, m = month.

The corresponding GAMS code for the FWIB-SON constraints is:

```
FWIB-SON (riverbasins, mriverplace, state, month)..
OUTTOBAY (riverbasins, mriverplace, state, month)
     ≥  MinQ (riverbasins, month);
```

The second type of the FWIB constraints is the FWIB Average constraints (FWIB-Avg constraints) in the form of:

$$\sum_s prob_s \times OUTTOBAY_{RB,RP,s,m} \geq MinQ_{RB,m}$$ where *prob* = probability.

The corresponding GAMS code for the FWIB-Avg constraints can be written as:

```
FWIB-Avg (riverbasins, mriverplace, month)..
Sum(state, prob(state)*OUTTOBAY(riverbasins, mriverplace, state, month)
     ≥  MinQ (riverbasins, month);[10]
```

The FWIB-Avg constraints are defined for each riverbasin, riverplace and month while the variable OUTTOBAY is also a function of the state of nature as well as each riverbasin, riverplace and month. The FWIB-Avg constraints are weighted by the probabilities of the states of nature to give some flexibility to accommodate more cases of the FWIB recommendations.

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[10] The exact GAMS code for the inequality notation "≥" is "=g=". And "mriverplace" denotes a riverplace where an effective data set in the riverplace is available. The riverplace where a data set is not available is defined as "eriverplace" and was removed from the river flow linkage.

The river basins in which the FWIB recommendations are set by the state agencies are originally six but seven basins will be constrained in the model. We set the FWIB recommendations on the last control point. But both of the control points in the FWIB-targeted TrintiySanJac River basin did not have the relevant data set available and were removed from the river flow linkage. As a result, there are no control points applicable for the FWIB recommendations in the TrinitySanJac River basin. To apply the FWIB recommendations, we separated the TrinitySanJac River basin into two river basins and set the recommendations in each basin. We divided the recommendations between the two basins based on the percentages of optimal freshwater inflow levels of the Trinity and San Jacinto River basins with no IBT, which were determined in Chapter III. That is to say, of the monthly FWIB recommendations in the TrinitySanJac River basin, 25% was applied to the San Jacinto River basin and the remaining 75% was allotted to the Trinity River basin.

4.4. Decomposition of Welfare Gain: Total Gain, IBT Gain, FWIB Gain

Total gain in net benefit is defined as the difference between the net benefit (NB) taking into account the FWIB recommendations and IBT *and* NB without taking into account them. For clear notational purposes, the total gain is defined as: total gain = NB with FWIB and with IBT[11]–NB without FWIB and without IBT. We ran four scenarios as follows and obtained four types of net benefits: NB without FWIB and without IBT; NB without FWIB and with IBT; NB with FWIB and without IBT; NB with FWIB and with IBT.

To trace the net effect of the FWIB recommendations and IBT implementation, we separated the total gain into two types of gain: IBT gain and FWIB gain.

IBT gain is the gain from just the IBT implementation given the without- or with-FWIB recommendations. We will focus on the IBT gain under the given *with*-FWIB recommendations to see the IBT cost saving effect when the FWIB recommendations are being exercised. In Chapter III, we have seen that IBT tends to increase water use and net benefit.

On the other hand, FWIB gain is the gain arising only from the FWIB recommendations given the without- or with- IBT implementation. And the FWIB gain under the given *without*-IBT implementations will be primarily used to obtain the pure

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[11] When “FWIB” is solely used without any other explanation, FWIB represents “the FWIB recommendations”. Likewise, “IBT” represents “the IBT implementation”.

FWIB gain without the impact of the IBT implementation. In the case of net benefits and water use, the FWIB gain is actually expressed as the FWIB “loss” because the FWIB recommendations will restrict water use and tend to decrease the net benefit. But the FWIB gain in terms of instream flows/freshwater inflows is expressed as the FWIB “gain” that protects and increases flows/inflows.

The FWIB gain can be defined to cover both the “gain” (positive gain) and “loss” (negative gain). But for the purposes of this model, we will use the FWIB loss in terms of net benefits and water use while the FWIB gain will be defined in terms of flows and inflows. By the same token, the IBT gain will be used in terms of net benefit and water use while the IBT loss will be used in terms of flows and inflows as in Chapter II and III.

From the definitions, we see their conflicting nature between FWIB and IBT. If the IBT gain is positive but the FWIB gain is negative (FWIB loss), the total gain depends on which dominates between the IBT gain and the FWIB loss.

It would be convenient to formally define the notation of the FWIB gain or loss to avoid confusion for different consequences of the FWIB constraints: FWIB-NB is the change in Net Benefits due to the FWIB recommendations, FWIB-U is the change in water Use, FWIB-F is the change in water Flows, and FWIB-I is the change in freshwater Inflows to bays and estuaries. IBT gain or loss is similarly defined as IBT-NB, IBT-U, IBT-F and IBT-I. The notations will be defined again in each section of the chapter to improve readability.

4.5. Results

We analyzed the two scenarios of simulation: one with the FWIB-SON (state of nature) constraints and the other with the FWIB-Avg (average) constraints.

First of all, the FWIB constraints were imposed to be satisfied for each and every state of nature (FWIB-SON). However, the FWIB-SON constraints could not satisfy the recommendations in the four basins, SanioNues, Trinity, ColLavaca and Neches, only satisfying the recommendations fully in the three basins, Guadsan, Nueces and San Jacinto. The recommendations for the basins ColLavaca and Neches were hardly satisfied almost in every state of nature in every month whereas the basins SanioNues and Trinity could meet them on average but not in some states of nature, depending on the month.

Since the model TEXRIVERSIM found that the freshwater inflow recommendations could not be satisfied, we modified the constraints in order to consider an option that is both feasible and to reflect the policy objectives of TPWD and TWDB. We applied the FWIB-Avg constraints instead of the FWIB-SON constraints.

There are three reasons why this alternative constraint specification was adopted. First, the FWIB-SON constraints are simply impossible when the average constraints cannot be satisfied. Satisfaction of the average constraints is a required but not a sufficient condition for the satisfaction of the FWIB-SON constraints. The recommendations for the average constraints must be met first.

Secondly, when there are large variations of inflow levels dependent on each state of nature, it is more difficult to meet the recommendations in some states of nature, and accordingly the recommended inflow levels under the FWIB-SON constraints should be lowered to satisfy the inflow levels in every state of nature than those needed under the FWIB-Avg constraints. The FWIB-Avg constraints can be more realistic if the policy mix of alternative approaches described below could achieve the policy goal and cost less, not needing to lower the recommended inflow levels further below the average level.

Finally, even if the FWIB-SON constraints were possible, it will be costly to set the recommended inflow levels in each and every state of nature when the state is not realized but exists probabilistically. There should be opportunity costs and searching costs that cannot be ignored in order to find the comprehensive inflow level table. These costs will further increase when inflow levels for each state must be readjusted, even under a small change of modeling assumptions such as groundwater demand portion.

When the FWIB-Avg constraints are adopted, the FWIB recommendations could be met in five basins including SanioNues and Trinity, but still only partially in ColLavaca and Neches. To make the model feasible, we had to lower the minimum requirements of freshwater inflow levels in ColLavaca and Neches down to 1.5% and 80% of the originally suggested levels. In the case of the Trinity River basin, it seemingly satisfied only 3% of the FWIB recommendations[12] at one of the final control points of the basin where the FWIB constraints are applied.[13] But when the two final

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[12] We tried 3% and 3.5% but not numbers that fall on between these two numbers. The FWIB recommendations were met at 3% but not at 3.5% in Trinity. Likewise in ColLavaca, the recommendations were met at 1.5% but not at 2%. And in Neches, 80% but not 85% could be satisfied.

[13] Originally, there is the final river place in the Trinity River basin: 8TRGB. But this was removed because of unavailability of the data set. Then there are two river places in the basin where water flows out to the estuary: B4279A and B4279C. The FWIB recommendations are applied to each of these two river places.

control points were integrated and managed as one control point, Trinity met almost 100% of the FWIB recommendations on average but not in every month.

Nevertheless, the model TEXRIVERSIM found that it was not possible to satisfy 100% of all the FWIB recommendations simultaneously in both of the FWIB-SON and the FWIB-Avg constraints. To check the model feasibility, we added an artificial variable that is called ARTFLOWBALANCE in the flow balance equation and in the objective function. The artificial variable in the objective function has a very big negative coefficient. When the model cannot satisfy the flow balance equations due to the strict FWIB recommendations, the artificial variable would have a strictly positive value and allow the constraint to be satisfied. And the strictly positive value causes a very big negative objective function value to signal that the model is "infeasible." The amount of the artificial variable accounts for the approximate water level that needs to be compensated artificially to satisfy the FWIB recommendations. The policy options that enable the recommendations satisfied will be investigated in the freshwater inflows section that will follow.

From here forward, we will report and analyze the FWIB results based on the FWIB-Avg constraints: the FWIB recommendations in the five river basins including the

SanioNues and Trinity River basin, after the minimum requirements of the FWIB recommendations in the ColLavaca River basin was lowered down to 1.5% of the originally suggested FWIB recommendations, and down to 80% of the original FWIB recommendations in the Neches River basin. The results will be based on the annualized expected values if there is no specific term in tables or texts to differentiate them from monthly or each state-of-nature based value.

4.5.1. Optimal IBT projects chosen

With the introduction of the FWIB recommendations and IBT implementation, the same three IBT projects were chosen as in Chapter III when there were no FWIB recommendations: Luce Bayou Channel Project (LB IBT); LCRA-SAWS Water Project (LS IBT); Cypress Basin Supplies Project (CB IBT). These will be discussed in the section of Quantity of transferred water via IBTs.

LB IBT must have been selected by its low IBT costs, big size (annual maximum of 540,000 acre feet) and resulting contribution to the industrial and mining sectoral net benefit. The FWIB constraints also did not affect the choice of two municipal IBT projects. This implies that the IBT gain of these three projects in terms of the net benefit

(IBT-NB) are the greatest among all IBT projects and surpass the FWIB loss in net benefit (FWIB-NB) most.

4.5.2. Overall and distributional economic gains from FWIB and IBT

Overall, imposition of the FWIB recommendations will result in water use reductions which ultimately costs money. The FWIB induced loss in net benefits is the change (decrease) in net benefits due to the FWIB recommendations, and will be denoted as FWIB-NB. FWIB-NB, the opportunity cost estimate of the FWIB recommendations is denoted by the difference between the net benefit which was obtained due to the FWIB recommendations *and* the net benefit which could have been obtained without the FWIB recommendations. The total gain in net benefit is increased value in net benefit as a result of mutual reaction between IBT gain in net benefits (IBT-NB) and FWIB loss in net benefits (FWIB-NB). Table IV-2 summarizes the net benefits and FWIB-NB according to the different FWIB constraint scenarios in the without- and with- IBT scenario.

When there are no FWIB constraints, the total gain in net benefit is $203 million. This is the baseline scenario.

After the FWIB-SON constraints are applied, the constraints restrict 100% of three river basins in every state of nature, leaving four unsatisfied basins unrestricted. The total gain in net benefit from the FWIB recommendations and the IBT implementation is $199 million ($203-$4 = $288-$89). We will now focus on IBT-NB *with* the FWIB recommendations ($288 million) and FWIB-NB *without* the IBT implementation ($-89 million).

The case of the FWIB-Avg constraints is that the FWIB recommendations of the five river basins are met on average after lowering the minimum requirements of the ColLavaca River basin to 1.5% and those of the Neches River basin to 80% of the current recommendations. The total loss of $8 million in net benefit was generated, which consists of FWIB-NB without the IBT implementation ($-211 million) and IBT-NB with the FWIB recommendations ($203 million). This total loss comes primarily from FWIB-NB in the Neches River basin where 80% of the FWIB recommendations were barely satisfied after a series of simulation.

It is characteristically realized that the FWIB-Avg constraints, weighted by the probability of each state of nature, exhibit the same IBT-NBs in total and each sectoral net benefit in both of the without- and with- FWIB scenarios (Table IV-2).

Unlike the FWIB-Avg constraints, the net benefit of the FWIB-SON constraints without IBT is reduced more than that with IBT. FWIB-NB due to the FWIB-SON constraints is $89 million without IBT and $4 million with IBT. In other words, FWIB-NB to the Guadsan, Nueces and San Jacinto River basins is greatly reduced to just $4 million due to IBT, from FWIB-NB of $89 million when IBT is not available. We see that IBT greatly relieves the FWIB loss, FWIB-NB, by $85 million when the FWIB-SON constraints are adopted.

Table IV-2. Annual Net Benefit (NB) under the FWIB Constraint Scenarios

FWIB Constraint scenarios	Satisfied % of each river basin to the FWIB							NB (unit: $ million)		
	Guad-san	**Nueces**	**San Jacinto**	**Sanio-Nues**	**Trinity**	**Neches**	**Col-Lavaca**	**without IBT**	**with IBT**	**IBT-NB**
No (=A)	0	0	0	0	0	0	0	200,520	200,723	203
FWIB - SON (=B)	100	100	100	0	0	0	0	200,431	200,719	288
FWIB - Avg (=C)	100	100	100	100	100	80	1.5	200,309	200,512	203
FWIB-NB (=B-A)								-89	-4	85
FWIB-NB (=C-A)								-211	-211	0

Notes: FWIB/IBT denotes freshwater inflows constraints/Interbasin Water transfers. SON/Avg represent state of nature/average.

Gains by sector

FWIB-NB, which is obtained from the difference between NB with the FWIB recommendations and NB without the FWIB recommendations, recorded \$178.64 million in the industrial and mining sector and \$32.63 in the municipal sector. The magnitude of these FWIB-NBs is the same in the without- and with- IBT scenarios (Table IV-3). Each sectoral IBT-NB also does not change.

The contribution of IBT in net benefits is greatest in the industrial and mining sector (\$126.98 million). This is attributed by LB IBT. But FWIB-NB dominates IBT-NB in the industrial and mining sector whereas the IBT-NB dominates FWIB-NB in the municipal and freshwater inflows (FWI) sectors. Due to the industrial and mining sector, FWIB-NB dominates IBT-NB overall, leading to the total loss of \$8 million with the introduction of the FWIB recommendations and the IBT implementation. Agricultural net benefit remains the same.

Finally, FWI in the whole basins decreases by 0.09 million acre feet as IBT-NB (-0.18 million acre feet) dominates FWIB-NB (0.09 million acre feet). This will be discussed later in the Freshwater inflows section.[14]

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[14] The value of freshwater inflows is assigned \$1 per an acre foot of water.

Table IV-3. NB under the FWIB-Avg by Sector (unit: million dollars)

	NB without FWIB			NB with FWIB			FWIB -NB
	without IBT	with IBT	IBT-NB	without IBT	with IBT	IBT-NB	
ag	4.16	4.16	0.00	4.16	4.16	0.00	0.00
ind	3,149.23	3,276.21	126.98	2,970.59	3,097.57	126.98	-178.64
city	197,318.46	197,394.84	76.38	197,285.83	197,362.21	76.38	-32.63
FWI	47.83	47.66	-0.18	47.92	47.75	-0.18	0.09
Total	200,519.69	200,722.88	203.19	200,308.51	200,511.70	203.19	-211.18

Notes: FWIB-Avg/IBT denotes freshwater inflows constraints/Interbasin Water transfers. ag/ind/city/FWI stand for agricultural/industrial & mining/municipal/freshwater inflow.

Gains by basin

After the FWIB constraints, the IBT implementation affects the industrial and mining net benefit of the San Jacinto River basin to increase by \$127 million as IBT-NB (Table IV-4). But the industrial/mining sectoral net benefit from the Neches River basin with the FWIB constraints decreases sharply by \$179 million, as FWIB-NB, from \$243.74[15] to \$65.10 million in both of the without- and with- IBT scenario. In Neches, 80% of the FWIB recommendations were strenuously met, which would restrict water use. The agricultural sector does not show differences. In the municipal sector, IBT-NB from Guadsan and Trinity dominates FWIB-NB. There is no FWIB-NB in four municipalities. Water uses for these cities are not affected by the FWIB constraints.

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[15] This amount comes from Chapter III, not from this table.

Table IV-4. NB under the FWIB-Avg by River Basin (unit: million dollars)

sector	rivers	city / county	without IBT	with IBT	IBT-NB
ag	Brazos		0.49	0.49	0.00
	Colorado		0.59	0.59	0.00
	Canadian		0.02	0.02	0.00
	Red		0.05	0.05	0.00
	Guadsan		2.13	2.13	0.00
	Nueces		0.89	0.89	0.00
	ag total		4.16	4.16	0.00
ind	Brazos		921.44	921.44	0.00
	Colorado		45.67	45.67	0.00
	Canadian		23.80	23.80	0.00
	Red		27.78	27.78	0.00
	Sabine		496.07	496.07	0.00
	Guadsan		540.51	540.51	0.00
	Cypress		45.82	45.82	0.00
	Neches		65.10	65.10	0.00
	Trinity		114.49	114.49	0.00
	San Jacinto	Harris County	689.90	816.89	126.98
	ind total		2,970.59	3,097.57	126.98
city	Guadsan	San Antonio	29,954.41	30,015.11	60.70
	Trinity	Fort Worth	22,640.88	22,656.56	15.68
	Trinity	Dallas	32,147.09	32,147.09	0.00
	San Jacinto	Houston	50,098.05	50,098.05	0.00
	four cities		134,840.44	134,916.82	76.38
	city total		197,285.83	197,362.21	76.38
FWI			47.92	47.75	-0.18
Total			200,308.51	200,511.70	203.19

Notes: NB/ FWIB-Avg/IBT denote net benefit/freshwater inflows constraint/interbasin transfers. ag/ind/city/FWI denote agricultural/industrial & mining/municipal/freshwater inflow sector respectively.

4.5.3. Effects on agricultural production

Agricultural production activities went through minor crop acre changes in two river basins, Canadian and Brazos, with the FWIB constraints, but those changes were offset between counties inside each of the basins (Table IV-5). The FWIB constraints and IBT did not affect the agricultural crop acres by basin, and agricultural water use did not change in any state of nature. This was already suggested when agricultural net benefits remained the same at the level of $4.16 million regardless of the FWIB recommendations and IBT implementations. In the agricultural sector, there were no costs of imposing the FWIB constraints and no gains from the IBT implementation.

However, in the agricultural sector, we find it is characteristic that the Colorado and Lavaca River basins did not change their crop acres but water use increased in Colorado and decreased in Lavaca by the same amount, so that there was no net change in water use by the agricultural sector. Colorado is an IBT-source basin, and Lavaca is an IBT-neutral but IBT-adjacent basin. These two basins are not directly affected by the FWIB recommendations individually, though ColLavaca (Colorado-Lavaca) is the FWIB- recommended basin. These issues will be discussed in the water use and flows section.

Table IV-5. Crop Acres under the FWIB-Avg for Irrigated Crops (unit: acre)

River	County	Crop	without FWIB			with FWIB		
			without IBT	with IBT	IBT gain	without IBT	with IBT	IBT gain
Canadian	Roberts	winter wheat	14.9	18.21	3.31	26.41	37.70	11.29
	Hansford	winter wheat	29.38	28.42	-0.95	29.38	29.38	0
	Hutchinson	winter wheat	31.81	28.5	-3.31	20.30	9.01	-11.29
	Dallam	winter wheat	20.86	21.82	0.95	20.86	20.86	0
	sub-total		96.95	96.95	0	96.95	96.95	0
Brazos	Fisher	cotton upland	1.1	1	-0.11	1.10	1.74	0.64
	Fisher	winter wheat	12.01	12.67	0.65	12.39	13.05	0.66
	Nolan	cotton upland	0.64	0.75	0.11	0.64	0.00	-0.64
	Nolan	winter wheat	78.39	77.73	-0.65	78.01	77.35	-0.66
	sub-total		92.14	92.14	0	92.14	92.14	0
All basins / all crops			12,825	12,825	0	12,825	12,825	0

Notes: FWIB-Avg/IBT denote freshwater inflows constraint/interbasin transfers

4.5.4. Quantity of transferred water via IBTs

Three IBT projects were chosen: Luce Bayou Channel Project (LB IBT); LCRA-SAWS Water Project (LS IBT); Cypress Basin Supplies Project (CB IBT). These projects were also chosen before the FWIB constraints were introduced. Between the with- and without- FWIB constraints, annual water transferred from IBT projects does not change on average but changes on a monthly and seasonal basis (Table IV-6).

Seasonal peak time for total water transferred via the IBT projects without the FWIB constraints was the summer season from May to August. 45.6% of water was transferred in summer. More water was transferred after the FWIB recommendations than before the FWIB recommendations (Table IV-7). IBT Water also increases during the months of September to December but decreases during the months of January to April, being contributed mainly by increase in November and decrease in February.

Table IV-6. IBT Water Transferred by Month (unit: acre feet)

without FWIB	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	annual
LB IBT	7,164	7,600	17,766	15,245	16,273	10,556	25,457	23,739	15,580	10,237	10,448	9,195	169,260
LS IBT	7,604	6,054	6,858	7,982	8,581	9,024	12,037	11,222	8,970	6,947	6,391	6,905	98,574
CB IBT	1,445	4,042	3,841	2,593	2,526	809	5,769	10,947	4,375	891	330	1,901	39,469
Total (A)	16,212	17,695	28,466	25,820	27,379	20,390	43,263	45,908	28,925	18,075	17,169	18,001	307,303
with FWIB													
LB IBT	5,557	3,953	19,942	18,113	17,093	9,307	24,743	24,600	16,769	5,910	17,436	5,838	169,260
LS IBT	7,522	6,012	6,858	8,106	8,581	9,024	12,037	11,222	8,970	6,947	6,391	6,905	98,574
CB IBT	2,637	724	1,656	1,712	4,339	623	7,996	10,572	1,938	2,455	1,162	3,656	39,469
Total (B)	15,716	10,689	28,457	27,930	30,013	18,955	44,775	46,393	27,677	15,312	24,988	16,398	307,303
B-A	-496	-7,006	-9	2,110	2,634	-1,435	1,512	485	-1,248	-2,763	7,819	-1,603	0

Notes: FWIB/IBT denote freshwater inflows constraint/interbasin transfers. LB/LS/CB denote Luce Bayou/ Lower Colorado - San Antonio/Cypress Basin.

Table IV-7. Seasonal IBT Water Transferred under the FWIB-Avg (unit: acre feet)

without FWIB	Jan-Apr	May-Aug	Sep-Dec	Annual
IBT water transferred (acre feet)	88,193	136,940	82,170	307,303
% of IBT water in each period	28.70	44.56	26.74	100
with FWIB				
IBT water transferred (acre feet)	82,792	140,136	84,375	307,303
% of IBT water in each period	26.94	45.60	27.46	100

Notes: FWIB-Avg/IBT denote freshwater inflows constraint/interbasin transfers.

4.5.5. Effects on water use

Use by sector

The FWIB loss in water use is the change (decrease) in water use due to the FWIB recommendations, denoted as FWIB-U.

Overall increase in water use results from IBT especially in the dry states of nature, HDry, MDry, Dry and Dnormal (Table IV-8, Table IV-9). We know that under the FWIB recommendations much water was transferred during the summer months from May to August. IBT-U dominated FWIB-U so that water use increased in every sector except for the agricultural sector where no changes were realized for IBT-U and FWIB-U.

FWIB-Us between the without- and with- IBT scenario are the same. IBT-Us are also the same between the without- and with- FWIB scenario. We confirm this through the average water use by sector. The FWIB constraints reduce water use in the industrial and mining and municipal sectors.

Table IV-8. Water Use under the FWIB-Avg (unit: acre feet)

	without FWIB	with FWIB	FWIB-U
without IBT			
ag	259,501	259,501	0
ind	790,617	700,188	-90,428
city	1,429,677	1,417,960	-11,717
total	2,479,794	2,377,649	-102,145
with IBT			
ag	259,501	259,501	0
ind	959,877	869,448	-90,428
city	1,567,778	1,556,061	-11,717
total	2,787,155	2,685,010	-102,145
IBT-U (=with-without IBT)			
ag	0	0	0
ind	169,260	169,260	0
city	138,101	138,101	0
total	307,361	307,361	0

Notes: FWIB-Avg/IBT denote freshwater inflows constraint/interbasin transfers. IBT-U/FWIB-U denote IBT gain in use/FWIB loss in use.

Table IV-9. Water Use under the FWIB-Avg by Sector (unit: acre feet)

without IBT										
SON	HDry	MDry	Dry	Dnormal	Normal	Wnormal	Wet	MWet	HWet	average
ag	248,497	243,818	247,188	235,018	281,652	231,834	276,532	228,319	265,192	259,501
ind	701,081	699,859	699,821	700,075	699,425	704,445	699,821	700,863	699,402	700,188
city	1,527,974	1,451,476	1,449,784	1,447,679	1,399,002	1,430,432	1,380,124	1,342,483	1,354,968	1,417,960
total	2,477,552	2,395,152	2,396,793	2,382,772	2,380,080	2,366,712	2,356,477	2,271,666	2,319,562	2,377,649

Table IV-9. Continued

with IBT										
SON	HDry	MDry	Dry	Dnormal	Normal	Wnormal	Wet	MWet	HWet	average
ag	248,497	243,818	247,188	235,018	281,652	231,834	276,532	228,319	265,192	259,501
ind	873,046	870,179	867,837	869,396	867,837	872,528	867,837	876,362	871,562	869,448
city	1,706,111	1,600,541	1,603,308	1,594,527	1,531,963	1,541,820	1,515,667	1,463,657	1,465,677	1,556,061
total	2,827,654	2,714,537	2,718,333	2,698,941	2,681,453	2,646,183	2,660,037	2,568,339	2,602,431	2,685,010
with-without IBT										
SON	HDry	MDry	Dry	Dnormal	Normal	Wnormal	Wet	MWet	HWet	average
ag	0	0	0	0	0	0	0	0	0	0
ind	171,965	170,320	168,017	169,321	168,412	168,082	168,017	175,499	172,160	169,260
city	178,137	149,065	153,524	146,848	132,961	111,388	135,543	121,174	110,709	138,101
total	350,103	319,385	321,541	316,169	301,373	279,471	303,560	296,673	282,869	307,361

Notes: FWIB-Avg/IBT denote freshwater inflows constraint/interbasin transfers. SON denotes states of nature from heavily dry (HDry) to heavily wet (HWet). ag/ind/city stand for agricultural/industrial & mining/municipal sector respectively.

Table IV-10 shows how much water use has increased/decreased in each sector and state of nature in both of the FWIB-Avg and FWIB-SON constraints. The absolute magnitude of the changes in water use cannot be compared between the two FWIB constraint scenarios because their constraint conditions are different: the FWIB-Avg constraints are satisfied in the five river basins along with two partially satisfied basins; but the FWIB-SON constraints are only fully met in the three basins, lifting the minimum requirements of the FWIB recommendations in four unsatisfied basins.

When the FWIB-Avg constraints are applied, changes in water use in each state of nature are not deviating far from the average of the changes (see the last column of

Table IV-10) in both the without- and with- IBT scenario. Also, the average of the changes in water use by sector is the same in the without- and with- IBT scenario.

However, compared to the FWIB-Avg constraints, when the FWIB-SON constraints are applied, the changes in water use in each state of nature are deviating further away from the average of those changes in both the without- and with- IBT scenario. The deviations from the average of those changes are higher in the without-IBT scenario than in the with-IBT scenario. The average of the changes in water use shows that the FWIB-U effect disappears distinctly in the industrial/mining and municipal sectors when IBT is implemented with the FWIB-SON constraints. The average of the changes in water use in these two sectors is zero. IBT shows the FWIB loss relieving effect in the FWIB-SON scenario.

Table IV-10. Water Use Changes: FWIB-Avg vs. FWIB-SON (unit: acre feet)

Under the FWIB-Avg constraints: water use with FWIB – water use without FWIB										
					without IBT					
SON	HDry	MDry	Dry	Dnormal	Normal	Wnormal	Wet	MWet	HWet	average
ag	0	0	0	0	0	0	0	0	0	0
ind	-90,659	-89,802	-89,500	-93,110	-89,581	-89,637	-90,009	-93,512	-94,047	-90,429
city	-13,658	-12,424	-11,930	-12,108	-11,679	-11,423	-10,920	-10,372	-10,919	-11,717
total	-104,317	-102,226	-101,431	-105,218	-101,259	-101,059	-100,930	-103,883	-104,966	-102,145
					with IBT					
ag	0	0	0	0	0	0	0	0	0	0
ind	-89,784	-91,325	-91,629	-88,937	-91,261	-86,002	-90,429	-88,515	-91,780	-90,429
mun	-13,658	-12,424	-11,930	-12,107	-11,679	-11,423	-10,920	-10,371	-10,918	-11,717
total	-103,442	-103,750	-103,560	-101,045	-102,939	-97,424	-101,348	-98,886	-102,699	-102,145
Under the FWIB-SON constraints: water use with FWIB – water use without FWIB										
					without IBT					
SON	HDry	MDry	Dry	Dnormal	Normal	Wnormal	Wet	MWet	HWet	average
ag	-56,352	-55,291	-55,594	-49,551	-45,944	-48,385	-45,979	-45,948	-45,961	-49,344
ind	-88,317	-27,909	-16,365	-12,057	7,409	-9,117	8,913	10,884	7,526	-7,718
city	3,014	-359	-38	-1,005	47	-133	-876	158	844	-3
total	-141,655	-83,558	-71,998	-62,613	-38,488	-57,635	-37,942	-34,906	-37,591	-57,064
					with IBT					
ag	-56,352	-55,291	-55,036	-49,374	-45,944	-46,253	-45,979	-45,948	-45,961	-49,082
ind	-5,270	-3,848	-1,750	4,600	-72	4,390	1,181	-1,346	2,281	0
mun	10,412	4,989	3,066	1,702	-3,508	2,399	-4,080	-2,923	-2,337	0
total	-51,211	-54,150	-53,720	-43,072	-49,524	-39,465	-48,877	-50,218	-46,017	-49,081

Notes: FWIB-Avg/IBT denote freshwater inflows constraint/interbasin transfers. SON denotes states of nature from heavily dry (HDry) to heavily wet (HWet). ag/ind/city stand for agricultural/industrial & mining/municipal sector respectively.

Water use by river basins

The total gain in water use (in the ninth column in Table IV-11) consists of IBT-U with the FWIB recommendations (=C in the seventh column) plus FWIB-U without IBT (=B-A in the eighth column). FWIB-U of each river basin may differ in the without- and with- IBT scenarios, unlike the sectoral gain or loss in the average constraints, but total FWIB-U in all river basins is the same in both of the IBT scenarios.

As a result of the implementation of IBT with the FWIB recommendations, water use has increased in the IBT destination basins, Guadsan, Trinity and San Jacinto, and in the IBT neutral basins, Brazos and Lavaca. However, along with the IBT source basin Colorado, water use is drastically reduced in the FWIB-recommended Neches River basin by 102,313 acre feet (150,080 → 47,767 acre feet) as total loss, which amounts to the magnitude of the entire FWIB-U (-102,145 acre feet) in all basins. This is caused by the fact that the basin had to barely satisfy 80% of the FWIB recommendations.

The FWIB loss, FWIB-U, are found to be distinct in Neches, San Jacinto (-19,388 acre feet in municipality) and Lavaca (-1,731 acre feet in agriculture).

Based on FWIB-U, changes in water use are offset between Brazos and San Jacinto as well as between Colorado and Lavaca, approximately. The net effect of FWIB-U in these four basins becomes zero. This effect is also visible based on the effect of IBT-U in detail by river and sector as follows.

Table IV-11. Water Use under the FWIB-Avg by River (unit: acre feet)

River	without FWIB			with FWIB			FWIB-U (B-A)	Total Gain (B-A+C)
	without IBT (A)	with IBT	IBT-U	without IBT (B)	with IBT	IBT-U (C)		
Brazos	380,866	389,210	8,344	400,391	389,164	-11,227	19,525	8,298
Colorado (S)	294,159	295,489	1,329	295,754	289,931	-5,823	1,595	-4,228
Canadian	9,015	9,015	0	9,015	9,015	0	0	0
Red	23,327	23,329	2	23,329	23,326	-3	2	-1
Sabine	98,349	98,362	14	98,379	98,379	0	30	30
Guadsan (D)	195,223	293,855	98,632	195,223	293,855	98,632	0	98,632
Sulphur	8,794	8,792	-2	8,792	8,795	3	-2	1
Cypress (S)	15,496	15,496	0	15,496	15,496	0	0	0
Neches	150,080	149,989	-91	47,767	47,767	0	-102,313	-102,313
Trinity (S, D)	169,578	209,125	39,546	169,716	209,185	39,469	138	39,607
SanJacinto (D)	253,016	413,971	160,955	233,628	414,379	180,751	-19,388	161,363
Lavaca	64,994	63,626	-1,368	63,263	68,822	5,560	-1,731	3,828
SanioNues	232	232	0	232	232	0	0	0
Nueces	35,557	35,557	0	35,557	35,557	0	0	0
Total	1,698,687	2,006,048	307,361	1,596,542	1,903,902	307,361	-102,145	205,215

Notes: FWIB-Avg/IBT denote freshwater inflows constraint/interbasin transfers. S/N denote source/destination. IBT-U denotes IBT gain in use.

Increased water use in a basin due to IBT is offset by the same amount of decreased water use in another basin. This was observed in Chapter III in the agricultural sector between the Colorado and Lavaca River basins, industrial and mining sector between the Neches and Trinity River basins, municipal sector between the Brazos, Colorado and San Jacinto River basins, and finally between the Sabine and Neches River basins (Table IV-12). These offsetting IBT effects also occur after the FWIB constraints, but the effects are intensified. The effects can be found again in agricultural water use between the Colorado and Lavaca River basins and also in municipal water use between the Brazos, Colorado and San Jacinto River basins. However, the offsetting effects of other basins vanish. Ultimately, basin-wide changes in water use occur only in the IBT destination basins, Guadsan, Trinity and San Jacinto.

It is interesting that water use has increased in the IBT/FWIB-neutral Lavaca River basin after IBT under the FWIB constraints. Water use decreased due to the FWIB recommendations (FWIB-U) in the Lavaca River basin but IBT-U dominated FWIB-U. As stated in Chapter III, some agricultural users of the Colorado and Wharton County belong to both the Colorado and Lavaca River basins. Before the FWIB recommendations but after the IBT implementation, the agricultural users drew more water from the Colorado River basin and less water was drawn from the Lavaca River basin. Part of the reason is that these agricultural users of Colorado and Wharton County are located in the neighborhood of the control point (K10000) of the Lower Colorado River basin where the IBT water began to be transferred from the basin. But after the FWIB recommendations, the situation was reversed, resulting in more water being drawn from Lavaca and less from Colorado.

Table IV-12. Water Use under the FWIB-Avg by Sector and River (unit: acre feet)

without FWIB		Brazos	Colorado	Sabine	Guadsan	Neches	Trinity	San Jacinto	Lavaca
ag	without IBT	40,293	114,560	0	55,302	0	0	0	7,286
	with IBT	40,293	115,928	0	55,302	0	0	0	5,918
	Changes	0	1,368	0	0	0	0	0	-1,368
ind	without IBT	180,130	13,531	81,776	130,633	102,679	23,464	91,496	0
	with IBT	180,130	13,531	81,776	130,633	102,602	23,542	260,756	0
	Changes	0	0	0	0	-77	77	169,260	0
city	without IBT	160,443	166,068	16,572	9,288	47,401	146,114	161,520	57,708
	with IBT	168,787	166,029	16,586	107,920	47,387	185,583	153,215	57,708
	Changes	8,344	-39	14	98,632	-14	39,469	-8,305	0
total	without IBT	380,866	294,159	98,349	195,223	150,080	169,578	253,016	64,994
	with IBT	389,210	295,489	98,362	293,855	149,989	209,125	413,971	63,626
	Changes	8,344	1,329	14	98,632	-91	39,546	160,955	-1,368
with FWIB									
ag	without IBT	40,293	116,292	0	55,302	0	0	0	5,554
	with IBT	40,293	110,732	0	55,302	0	0	0	11,114
	Changes	0	-5,560	0	0	0	0	0	5,560
ind	without IBT	180,130	13,531	81,776	130,633	12,114	23,602	91,496	0
	with IBT	180,130	13,531	81,776	130,633	12,114	23,602	260,756	0
	Changes	0	0	0	0	0	0	169,260	0
city	without IBT	179,968	165,931	16,603	9,288	35,653	146,114	142,132	57,708
	with IBT	168,740	165,667	16,603	107,920	35,653	185,583	153,623	57,708
	Changes	-11,227	-264	0	98,632	0	39,469	11,491	0
total	without IBT	400,391	295,754	98,379	195,223	47,767	169,716	233,628	63,263
	with IBT	389,164	289,931	98,379	293,855	47,767	209,185	414,379	68,822
	Changes	-11,227	-5,823	0	98,632	0	39,469	180,751	5,560

Notes: FWIB-Avg/IBT denote freshwater inflows constraint/interbasin transfers. ag/ind/city stand for agricultural/industrial & mining/municipal sector respectively.

The other offsetting change occurred in municipality between the Brazos and San Jacinto River basin. Before the FWIB recommendations, San Jacinto imported 169,260 acre feet of IBT water and used 160,955 acre feet of it in the basin. The difference of 8,305 acre feet went to the users of Brazos. After the FWIB recommendations, the amount that went to the users of Brazos contracted to 7,897 acre feet (169,260 acre feet of imported IBT water–161,363 acre feet of water use). Table IV-13 summarizes this.

In summary, agricultural water use in Lavaca and Colorado offset each other, and municipal use in Brazos, San Jacinto and Colorado offset one another as well.

We should note again that the issues involved in water rights are not incorporated in the simulation model. If water rights were introduced, it would not be possible for a user without water rights to divert the IBT water, even though the user is near the water basin. For instance, the water from LS IBT that runs from the Lower Colorado to the Guadsan River basins is allowed only for municipal use.

In case where the agricultural sector is not a specified user and has no water rights, that user may not divert the IBT water. But the consequence of the offsetting effect in water use deserves to be investigated in the future research.

Table IV-13. Water Use Changes in Some Basins (unit: acre feet)

County	River basin	Control point	without FWIB			with FWIB			FWIB gain	Total gain
			Without IBT	with IBT	IBT gain	without IBT	with IBT	IBT gain		
Agricultural water use										
Colorado	Colorado	K20000	46,326	31,621	-14,706	47,071	47,638	567	745	1,312
Wharton	Colorado	K20000	38,262	54,335	16,074	39,248	33,122	-6,126	986	-5,140
	Sub-total		84,588	85,956	1,368	86,320	80,760	-5,560	1,732	-3,828
Colorado	Lavaca	GS1000	74	68	-6	64	99	35	-10	25
Wharton	Lavaca	GS1000	3,159	2,233	-926	2,512	6,607	4,095	-647	3,448
Colorado	Lavaca	WGS800	831	856	25	397	592	194	-434	-240
Wharton	Lavaca	WGS800	3,221	2,760	-461	2,580	3,816	1,236	-641	595
	Sub-total		7,286	5,918	-1,368	5,554	11,114	5,560	-1,732	3,828
Municipal water use										
Fort Bend	Brazos	BRRO72	91,383	99,688	8,305	110,771	99,280	-11,491	19,388	7,897
	Sub-total		91,383	99,688	8,305	110,771	99,280	-11,491	19,388	7,897
Montgomery	San Jacinto	A4963A	26,853	21,008	-5,845	15,701	22,210	6,509	-11,152	-4,643
Harris	San Jacinto	A4964A	134,667	132,208	-2,460	126,432	131,413	4,981	-8,235	-3,254
	Sub-total		161,520	153,215	-8,305	142,132	153,623	11,491	-19,388	-7,897

Notes: FWIB/IBT denote freshwater inflows constraints/Interbasin Water Transfers.

Use by major cities

All of the four municipalities are not affected by the FWIB recommendations. There is no difference between municipal water use in the four municipalities before and after the FWIB constraints (Table IV-14).

One of the reasons would be that changes in municipal water use are offset between the Brazos, Colorado and San Jacinto River basins and not affect the municipal water use in these four cities.

IBT increases municipal water use in Forth Worth and San Antonio. However, municipal water use in Dallas and Houston does not change at all under both of the FWIB and IBT implementation.

Table IV-14. Water Use under the FWIB-Avg by Major Cities (unit: acre feet)

	without FWIB = with FWIB				
	Dallas	Forth Worth	Houston	San Antonio	City total
without IBT	389,548	110,127	252,903	7,441	1,417,960
with IBT	389,548	149,596	252,903	106,073	1,556,061
IBT-U	0	39,469	0	98,632	138,101

Notes: Groundwater uses in San Antonio (=108,473 acre feet) and Houston (=136,179 acre feet) are not included. FWIB_Avg/IBT denote freshwater inflows constraint/ Interbasin Water Transfers. IBT-U denotes IBT gain in use.

4.5.6. Freshwater inflows into bays and estuaries

The FWIB gain in freshwater inflows is the change (increase) in freshwater inflows due to the FWIB recommendations, denoted as FWIB-I. The FWIB recommendations are supposed to protect freshwater inflows. As a result of the FWIB recommendations, the total gain in freshwater inflows (FWI) shows that FWI increases because FWIB-I in the Neches River basin (+89,996 acre feet) dominates IBT-I in all basins (-42,218 acre feet). Water transferred to the IBT destination basins Guadsan and

San Jacinto contributes to increasing FWI (Table IV-15).

In the optimal state, most river basins fully satisfy the FWIB recommendations above the minimum requirements of FWI except in two basins. In the case of the ColLavaca River basin where it only functions to flow out to the estuary, only an annual maximum of 5% of the FWIB recommendations can be met in the optimal state when the minimum requirements in the FWIB-Avg constraints are given 1.5% of the FWIB recommendations. The Neches River basin satisfies up to 80% of the minimum requirements under no IBT, increasing FWI by 89,996 acre feet from the without-FWIB optimal level. There is no IBT-I but only FWIB-I in this basin based on the with-FWIB scenario.

In total, IBT reduces FWI by 42,218 acre feet as IBT-I under the with-FWIB scenarios. The FWIB-targeted and IBT destination basins, Guadsan and San Jacinto, show increases in FWI, partially offsetting decreases in the FWIB-targeted and IBT net source basin, Trinity.

Overall, FWIB-I dominates IBT-I so that the total gain in FWI reaches positive 56,477 acre feet in the whole river basins.

Table IV-15. Freshwater Inflows to Seven Major Estuaries (unit: acre feet)

Estuaries	without FWIB			with FWIB				
	without IBT	with IBT	IBT-I	without IBT	with IBT (=A)	IBT-I	FWIB* (=B)	(A/B)
Guadsan	1,903,993	1,957,821	53,828	1,903,993	1,957,821	53,828	1,028,850	1.90
Neches	5,519,204	5,519,262	57	5,609,200	5,609,200	0	7,011,500	0.80
Trinity	6,020,715	5,873,003	-147,712	6,020,596	5,872,936	-147,661	3,118,950	1.88
San Jacinto	1,937,978	1,998,595	60,617	1,946,795	1,998,410	51,614	1,039,650	1.92
ColLavaca	78,104	78,104	0	78,104	78,104	0	1,617,500	0.05
SanioNues	565,403	565,403	0	565,403	565,403	0	41,080	13.76
Nueces	504,298	504,298	0	504,298	504,298	0	115,640	4.36
Total	16,529,695	16,496,486	-33,209	16,628,390	16,586,171	-42,218	13,973,170	1.19

Notes: FWIB/IBT denote freshwater inflows constraint/Interbasin Water Transfers. IBT-I denotes IBT loss in freshwater inflows.

Policy options

Our analysis of the FWIB issue and its relationship to IBT reveals that the FWIB recommendations can be met in more river basins based on averages than when the model is based on each state of nature. This suggests the need for policy changes by TPWD and TWDB. Under the FWIB-Avg constraints, the policy options can work independent of others but sometimes they should be mixed together as follows:

(1) The first policy option is to lower the recommended inflow levels as the inflow levels of ColLavaca and Neches were lowered by the same percentage changes over the months. This alternative is feasible, less costly under the FWIB-Avg constraints

than under the FWIB-SON constraints, and merits study by ecologists. Table IV-16 (a, b, c) can be a basis to compute the shortages of optimal inflow levels against the recommended inflow levels.

Table IV-16a. Freshwater Inflows to ColLavaca-Colorado (unit: 1000 acre feet)

ColLavaca-Colorado interbasin		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	sum
ColLavaca	HDry	2	4	0	1	0	3	0	0	0	5	0	1	17
GS1300	MDry	3	6	1	2	2	5	1	1	3	4	1	1	28
	Dry	1	2	1	3	8	11	0	3	9	9	2	5	54
	Dnormal	8	4	3	1	19	3	0	0	2	30	4	2	78
	Normal	4	9	5	7	9	8	7	1	5	16	6	5	83
	Wnormal	6	2	1	3	8	10	3	2	2	24	0	9	72
	Wet	14	13	6	7	10	16	2	1	6	3	5	7	91
	MWet	33	16	12	24	10	4	15	2	40	1	2	20	176
	HWet	11	23	9	30	23	23	2	0	1	27	16	3	169
	average	7	8	4	7	10	9	3	1	6	13	4	5	78
Colorado	HDry	22	27	3	0	0	0	0	2	23	17	5	10	110
K10000	MDry	21	32	23	0	0	13	0	14	47	27	25	19	221
	Dry	34	36	29	13	34	3	0	15	63	144	203	113	685
	Dnormal	73	122	66	27	285	41	12	18	51	141	54	76	965
	Normal	64	1,435	249	368	352	407	146	23	133	1,703	159	216	5,255
	Wnormal	63	93	47	53	142	130	25	34	48	155	34	65	890
	Wet	199	113	271	71	388	652	83	41	139	135	91	72	2,256
	MWet	303	177	79	262	198	156	80	28	122	30	26	223	1,684
	HWet	226	1,664	412	403	1,722	626	62	38	140	343	134	76	5,847
	average	92	580	156	163	310	272	65	24	95	599	108	118	2,584
Two basin average (A)		99	588	160	170	320	282	69	25	101	612	112	123	2,662
ColLavaca FWIB (B)		80	85	141	175	274	266	130	66	123	120	80	78	1,618
A/B, %		124	695	113	97	117	106	53	38	82	509	140	159	165

Notes: FWIB denotes freshwater inflows constraint. HDry through HWet denote states of nature from heavily dry to heavily wet. GS1300 and K10000 are control points.

Table IV-16b. Freshwater Inflows to Neches-Sabine (unit: 1000 acre feet)

Neches-Sabine interbasin		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	sum
Neches	HDry	113	193	95	61	157	54	32	16	63	18	162	61	1,024
NEBA	MDry	166	189	270	308	144	34	44	43	72	21	170	232	1,692
	Dry	114	93	200	1,996	313	160	61	44	82	62	38	354	3,518
	Dnormal	160	272	499	601	827	117	33	30	49	264	57	78	2,987
	Normal	190	567	414	345	664	357	572	349	108	1,026	109	381	5,082
	Wnormal	519	3,307	637	331	856	1,091	719	206	81	620	72	105	8,545
	Wet	875	380	923	661	363	665	367	93	230	59	416	502	5,535
	MWet	3,885	716	788	1,907	843	609	564	3,340	3,493	140	157	3,795	20,236
	HWet	1,180	574	4,109	753	1,124	544	317	133	3,711	432	842	527	14,244
	average	499	616	683	706	554	383	340	289	460	430	190	459	5,609
Sabine	HDry	173	247	259	122	554	79	43	32	158	16	45	176	1,903
SRSL	MDry	235	226	558	573	124	151	76	147	68	40	39	112	2,349
	Dry	310	194	206	197	336	205	55	66	176	174	88	215	2,221
	Dnormal	245	285	265	301	607	226	28	50	45	185	120	140	2,496
	Normal	4,205	376	839	660	1,001	479	210	118	119	85	4,749	256	13,097
	Wnormal	330	313	1,159	686	334	468	771	122	77	171	189	107	4,726
	Wet	476	310	956	1,000	664	554	239	72	198	44	115	214	4,842
	MWet	365	314	960	457	319	831	293	136	262	118	98	272	4,426
	HWet	215	888	411	344	1,189	272	270	98	201	172	257	319	4,638
	average	1,479	335	663	548	645	375	206	96	137	105	1,504	208	6,300
Two basin average (A)		1,978	951	1,346	1,254	1,199	758	546	386	596	535	1,694	668	11,909
Neches FWIB (B)		624	771	854	882	692	479	424	362	575	538	238	574	7,012
A/B, %		317	123	158	142	173	158	129	107	104	99	713	116	170

Notes: FWIB denotes freshwater inflows constraint. HDry through HWet denote degrees of climate states of nature from heavily dry to heavily wet. NEBA and SRSL are control points.

Table IV-16c. Freshwater Inflows to Trinity (unit: 1000 acre feet)

Trinity basin	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	sum
HDry	1,906	0	16	85	1	8	1	1	2	1	85	47	2,152
MDry	83	240	40	198	63	51	2	1	0	0	3	36	717
Dry	16	13	34	85	280	2	2	24	17	0	1,915	4,749	7,136
Dnormal	56	2,019	53	326	5	180	2	2	37	41	0	38	2,758
Normal	2,569	67	547	694	1,396	764	227	28	65	1,943	92	123	8,516
Wnormal	2,201	387	60	244	142	134	262	43	0	408	1	356	4,237
Wet	160	55	1,193	76	1,101	130	223	76	36	1	1,883	101	5,033
MWet	282	2,373	80	380	145	175	169	4	234	45	12	1,941	5,841
HWet	261	159	231	245	2,244	295	173	2	79	4,259	138	2,256	10,343
Trinity average (A)	1,126	350	367	331	771	303	138	27	44	876	574	967	5,873
Trinity FWIB (B)	113	163	273	264	510	336	175	116	248	189	264	470	3,119
A/B, %	997	216	134	125	151	90	79	23	18	464	218	206	188

Notes: FWIB is freshwater inflows constraint. HDry through HWet is states of nature.

(2) The next policy option is the interbasin management of the FWIB recommendations: the ColLavaca-Colorado interbasin for ColLavaca; the Neches-Sabine interbasin for Neches; the Trinity basin. This is also shown in Table IV-16. ColLavaca is surrounded by Colorado and Lavaca, and Neches is geographically in the neighborhood of Sabine. In order to successfully and effectively manage the interbasin, the geographical and ecological integration of the targeted basins and their control points to the extended interbasin are critical. This is beyond the scope of this analysis and these conditions are assumed to be met.

Particularly in the case of ColLavaca, the FWIB recommended levels are too far above the optimal levels so that FWI should be managed in the extended interbasin of ColLavaca and Colorado. This should be implemented with the first policy option. In the ColLavaca-Colorado interbasin, the annual two basin optimal FWI (2,662 thousand acre feet) can meet 165% of the integrated two basin FWIB recommendations[16] (1,618 thousand acre feet) on annual average.

(3) Appropriate storage of the seasonal freshwater surpluses can make up for the shortages in conjunction with the second policy option. This must be implemented along with yearly management of FWI. In the extended interbasin of ColLavaca and Colorado, the recommendations could not be perfectly satisfied in some of the months. The FWIB recommendations in April and July through September still have not been met.

This conflict could be adjusted by seasonal management: for example, the appropriate storage of the seasonal freshwater surplus in February through May (563,000 acre feet) can make up for freshwater shortages in June through September (-108,000

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[16] Actually only the FWIB of the ColLavaca River basin is applied because the Colorado basin does not have the FWIB recommendations.

acre feet). After the critical summer season passes, the need for FWI lessens to meet the FWIB recommendations.

It will be indispensable to store the annual surpluses in wet years and dispense them in dry years. There are five states of nature in which annual interbasin FWI is short of the recommended levels: HDry, MDry, Dry, Dnormal and Wnormal. Their total annual shortage reaches -4,970 acre feet. This shortage could be compensated by appropriate storage and management of surpluses from the other four water-affluent wet years, which amounts to a total of 9,089 acre feet. The limitation of this strategy assumes some benign cycle of water-scarce dry and water-affluent wet years. This strategy may not justify uncertainty when a series of unexpected consecutive water-scarce wet years are repeated.

All monthly FWIB recommendations in the Neches-Sabine interbasin can be met except for very slight shortage in October. Neches can be extended into the Neches-Sabine interbasin if lowering the recommended levels is not possible. Sabine-Neches Estuary touches Sabine Lake but essentially belongs to the Neches River basin so that the FWIB constraints are set on Neches. But if the Neches-Sabine interbasin is managed as one unit, the annual two basin optimal FWI (11,909 thousand acre feet) satisfies 170% of the annual FWIB recommendations (7,012 thousand acre feet).

The annual shortage in four dry years (HDry, MDry, Dry and Dnormal) amounts to 9,858 acre feet whereas the surplus in the other five wet years are 50,311 acre feet in total. For example, the surplus of the Normal year (11,167 acre feet) can supply the total shortage in four dry years.

Extended basin-wide management of FWI are important especially when multiple FWI-out control points to bays and estuaries exist and their aggregated FWI must be comprehensively regulated, as in the case of Trinity. Trinity satisfies 188% of the FWIB recommendations on annual average.

But the FWIB recommendations in the Trinity River basin are not met in summer from June to September by 363,000 acre feet. This shortage could be supplied by the seasonal management of the water surplus gained from March to May (422,000 acre feet). There are three dry years in HDry, MDry and Dnormal where the total shortage reaches 3,730 acre feet which can be compensated by the surplus from the other six wet years which amounts to 22,392 acre feet. Only the surplus of the Normal year (5,397 acre feet) can supply the total shortage in the three dry seasons.

(4) Another possible option which is differentiated from the first policy option, is to relax the recommended FWI levels based on percentage ranges as is shown in the Tennant Method, meeting the FWIB recommendations by setting the “range” of recommended FWI levels that are flexibly relaxed in these months.

The Tennant Method suggests 8 levels of environmental flow recommendations: flushing (200% of mean annual flow), optimum (100-60% of mean annual flow), outstanding (40% of mean annual flow from October to March and 60% of it in the other months), excellent (30% of it and 50% of it in the same periods), good (20% of it and 40% of it), fair (10% of it and 30% of it), poor (10% of it), severe degradation (below 10% of it). (American Fisheries Society, 1976) The marginal FWI levels between the tiers could be relaxed.

(5) The last option is to lower the economic, biological and chemical standards of the FWIB recommendations, not just lowering the FWI levels. TPWD and TWDB define MinQ as the minimum inflows that maintain 80% of the mean historic harvest and all other physical constraints. Then, the average fish harvest rate from the current 80% could be reevaluated.

This alternative is beyond our current study because this will need some critical interdisciplinary evaluation and compromise between the economic and environmental factors: fisheries harvest and ecological conditions of the estuaries. This task will be left for the future study.

4.5.7. Effects on flows of water

The FWIB gain in water flows is the change (increase) in water flows due to the FWIB recommendations, denoted as FWIB-F. Water flows increase generally in the whole basins by 8,651 acre feet (0.15%) as FWIB-F when IBT effects are removed. This is mainly contributed by the FWIB-recommended basins, Neches and San Jacinto. Table IV-17 shows the decomposition of the total gain (bottom of the seventh column), FWIB-F (top of the fourth column) and IBT-F (bottom of the sixth column).

Total gain in water flows is the change (increase or decrease) in flows due to both the FWIB recommendations and IBT implementation from none of them. Overall, water flows decrease by 11,837 acre feet, 0.21%, in the whole basins. This reflects the dominance of IBT-F over FWIB-F. That is to say, the IBT flow decreasing effect (-20,488 acre feet) dominates the FWIB flow increasing effect (8,651 acre feet).

In IBT-neutral but IBT-adjacent basins which is geographically close to those regions where IBT is actually realized, Lavaca’s flow decrease in terms of the total gain (-1,769 acre feet) is caused by increase in water use in the basin.

FWIB-F takes effect in the FWIB-recommended basins such as Neches and San Jacinto. Water flows in the Neches River basin increase by 5,697 acre feet as FWIB-F effects, and this is resulting from the strict 80% satisfaction of the FWIB recommendations. In the San Jacinto River basin, FWIB-F surpasses the IBT-F. FWIB-F effects increase water flows by 2,660 acre feet while IBT-F effects decrease them by 1,562 acre feet.

Water flows in the Guadsan River basin increase by 4,689 acre feet in terms of the total gain. However, there are no FWIB-F effects but only IBT-F effects. Water flow increases in the Guadsan River basin are due to water flows completely from IBT into the basin, but not due to the FWIB recommendations.

The Cypress and Trinity River basin are the IBT source/net source basins. Water flows in the Cypress and Trinity River basin decrease by 7,224 acre feet and 14,417 acre feet in terms of the total gain, respectively, as IBT-F effects are dominating.

Table IV-17. Flows of Water under the FWIB-Avg by River (unit: acre feet)

without IBT	without FWIB(A)	with FWIB(B)	FWIB-F (B-A)	FWIB-F % change	IBT-F	Total gain (B-A)
Brazos	496,260	495,992	-268	-0.05	0	-268
Colorado	400,298	400,285	-13	0	0	-13
Canadian	74,758	74,758	0	0	0	0
Red	469,382	469,381	-1	0	0	-1
Sabine	1,193,648	1,193,643	-5	0	0	-5
Guadsan	273,457	273,457	0	0	0	0
Sulphur	427,255	427,255	0	0	0	0
Cypress	196,610	196,621	11	0.01	0	11
Neches	847,962	853,659	5,697	0.67	0	5,697
Trinity	807,056	807,040	-16	0	0	-16
SanJacinto	278,291	280,951	2,660	0.96	0	2,660
Lavaca	167,881	168,468	587	0.35	0	587
Nueces	116,951	116,952	1	0	0	1
Total	5,749,810	5,758,461	8,651	0.15	0	8,651
with IBT	without FWIB(C)	with FWIB(D)	FWIB-F (D-C)	FWIB-F % change	IBT-F (D-B)	Total gain (B-A+D-B)
Brazos	496,153	496,122	-31	-0.01	130	-138
Colorado	400,278	400,426	148	0.04	141	128
Canadian	74,758	74,758	0	0	0	0
Red	469,382	469,380	-2	0	-1	-2
Sabine	1,193,652	1,193,661	9	0	18	13
Guadsan	278,143	278,146	3	0	4,689	4,689
Sulphur	427,255	427,255	0	0	0	0
Cypress	189,391	189,386	-5	0	-7,235	-7,224
Neches	848,005	853,745	5,740	0.68	86	5,783
Trinity	792,645	792,639	-6	0	-14,401	-14,417
SanJacinto	279,546	279,389	-157	-0.06	-1,562	1,098
Lavaca	168,442	166,112	-2,330	-1.38	-2,356	-1,769
Nueces	116,952	116,952	0	0	0	1
Total	5,734,602	5,737,973	3,371	0.06	-20,488	-11,837

Notes: FWIB_Avg/IBT denote freshwater inflows constraint/Interbasin Water Transfers. IBT-F/FWIB-F denote IBT loss/FWIB gain in flows.

4.5.8. Relationship between water use, freshwater inflows and flows

Once constructed, an IBT project relocated water to increase economic use efficiency and forced FWIB-U to be reduced. And the process of mutual interaction between IBT-F and FWIB-F moved to finally reduce water flows because of the dominant IBT-F effect. But in the freshwater inflows, FWIB-I dominated IBT-I. Table IV-18 summarizes the water use and flows/inflows relationships.

In terms of the total gain in the whole basins, water use increased (12.08%) and FWI increased (0.34%) in the seven basins, but water flows decreased (-0.21%). We have seen that FWI has decreased in the IBT-only scenario in Chapter III. The IBT destination basins contributed to increasing water use and FWI, and the major IBT source basins contributed to decreasing water flows. The FWIB recommendations played a role of protecting FWI. FWI decreased in the IBT net source basin Trinity. However, in the IBT-neutral Neches River basin where 80% of the FWIB recommendations were barely met after a series of simulation efforts, the recommendations contributed to 91.2% (89,996 acre feet) of the FWIB-I (98,695 acre feet) in the whole basins under no IBT scenario. And this contribution of Neches turned FWI to increase (positive total gain) overall in the seven basins against the FWI decreasing effect of IBT, with the help of increasing FWI in the IBT destination basin Guadsan and IBT-FWIB simultaneously applied basin San Jacinto. The inverse relationship between water use and flows was also realized in the IBT-neutral but IBT-adjacent basins such as the Brazos and Lavaca River basin. But in the destination basin Guadsan and San Jacinto, water use, flows and FWI all increased. Water use in all three of the destination basins absolutely increased.

Table IV-18. IBT, FWIB, Total Gains under the FWIB-Avg Constraints (unit: %)[17]

Source/ Destination	River	Water use			FWI (7 basins)			Water flows		
		IBT gain	FWIB gain	Total gain	IBT gain	FWIB gain	Total gain	IBT gain	FWIB gain	Total gain
Source	Cypress	0	0	0	---	---	---	-3.68	0.01	-3.67
Source	Colorado	-1.97	0.54	-1.44	---	---	---	0.04	0	0.03
Net source	Trinity	23.26	0.08	23.36	-2.45	0.00	-2.45	-1.78	0	-1.79
Destination	Guadsan	50.52	0	50.52	2.83	0.00	2.83	1.71	0	1.71
Destination	San Jacinto	77.37	-7.66	63.78	2.65	0.45	3.12	-0.56	0.96	0.39
IBT-neutral	Brazos	-2.80	5.13	2.18	---	---	---	0.03	-0.05	-0.03
IBT-neutral	Lavaca	8.79	-2.66	5.89	---	---	---	-1.4	0.35	-1.05
FWIB	Neches	0	-68.17	-68.17	0	1.63	1.63	0.01	0.67	0.68
Total	All rivers	19.25	-6.01	12.08	-0.25	0.60	0.34	-0.36	0.15	-0.21
Total amount (acre feet)		307,361	-102,145	205,216	-42,218	98,695	56,476	-20,488	8,651	-11,837

Notes: FWIB_Avg/IBT denote freshwater inflows constraint/Interbasin Transfers.

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[17] Increasing rate (%) = (increased water due to IBT / water amount without IBT)*100. Water amount is based on average after applying probabilities depending on the states of nature.

FWI significantly increased in both of the destination basins where they received enough water from the IBT projects for use and also enough water to increase the flow levels. The FWIB recommendations in the San Jacinto River basin showed relatively strong flow protection effects against the flow decreasing effect of IBT.

The Colorado, Lavaca, Brazos and San Jacinto River basins are interesting areas. Colorado is an IBT source basin but Lavaca and Brazos are IBT-neutral. All three basins are not constrained by the FWIB recommendation, but Colorado and Lavaca are close to the FWIB-recommended basin ColLavaca. San Jacinto is not only an IBT destination but also a FWIB-recommended basin. We have seen that the changes in agricultural water use were exactly offset between Colorado and Lavaca while the changes in municipal water use were also exactly offset between Brazos, Colorado and San Jacinto. Furthermore, in Colorado, Lavaca and Brazos, as is shown in Table IV-19, the FWIB recommendations reinforced the IBT gain effect more in the with-FWIB than in the without-FWIB recommendations, probably as a result of the interaction between the FWIB recommendations and IBT implementation.

This phenomenon tells of the complicated relationships between changes in water use and flows before and after the FWIB recommendations and IBT implementation. These four river basins are all close in proximity to the basins where the FWIB and IBT are interconnected. This implies that water use and flows are interacting with the neighboring IBT source/destination and FWIB-recommended basins.

Table IV-19. Gain of Geographically and IBT-FWIB Interconnected Basins (unit: %)

Source/ Destination	River	IBT gain without FWIB		IBT gain with FWIB	
		Water use	Water flows	Water use	Water flows
Source	Colorado	0.45	-0.01	-1.97	0.04
IBT-neutral	Brazos	2.19	-0.02	-2.80	0.03
IBT-neutral	Lavaca	-2.10	0.33	8.79	-1.40
Total	All rivers	18.09	-0.26	19.25	-0.36

Notes: FWIB/IBT denote freshwater inflows constraint/Interbasin Transfers.

4.6. Conclusions

This chapter focuses on the economic, hydrological and environmental effects of imposing minimum requirement levels for freshwater inflows to bays and estuaries (FWIB). Such an imposition causes a welfare loss due to decreases in water use and net benefits. Using the model TEXRIVERSIM developed in Chapter II and III, we examined the changes in welfare gains, interactions and conflicts between water use and environmental flows according to the different freshwater inflow constraints by TPWD and TWDB on the seven river basins as well as the IBT implementation.

This will be the first academic and professional evaluation study of the economic and environmental impacts of the IBT implementation and the FWIB recommendations in Texas.

We developed simulation results for the imposition of two types of FWIB constraints. First the FWIB constraints were imposed for each state of nature (FWIB-SON). However, the FWIB-SON constraints could not satisfy the recommendations in the four basins, SanioNues, Trinity, ColLavaca and Neches, only just satisfying them in the three basins, Guadsan, Nueces and San Jacinto. In ColLavaca and Neches, the recommendations were hardly satisfied almost in every state of nature in every month.

SanioNues and Trinity could meet the recommendations on average but not in some states of nature depending on the month.

As TEXRIVERSIM found that the FWIB recommendations could not be satisfied, we modified the constraints in order to consider an option that is both feasible and to reflect the policy objectives of TPWD and TWDB. We introduced the FWIB-Avg (average) constraints instead of the FWIB-SON (state of nature) constraints. There are three reasons behind this alternative constraint specification. First, the FWIB-SON constraints are simply impossible when average constraints cannot be satisfied. Satisfaction of the average constraints is a required (not a sufficient) condition for the satisfaction of the FWIB-SON constraints.

Second, when there are large variations of FWI levels depending on each state of nature, it is harder to meet the recommendations in some state of nature, and accordingly the recommended FWI levels under the FWIB-SON constraints should be lowered to meet them in every state of nature than those needed under the FWIB-Avg constraints. The FWIB-Avg constraints can be more realistic if the policy mix of alternative approaches described below could achieve the policy goal and cost less, not needing to lower the recommended FWI levels further below the average level. The FWIB-Avg constraints exhibit the flexibility of the constraints which keep each sectoral IBT gain (FWIB loss) in net benefit and water use to be the same in both of the without- and with-FWIB (IBT) scenarios, unlike the FWIB-SON constraints.

Third, even if the FWIB-SON constraints were possible, it will be costly to set the recommended FWI levels in each and every state when the state is not realized but exists just probabilistically: opportunity costs and searching costs of finding the comprehensive FWI level table. And FWI levels for each and every state must be readjusted even under a small change of the model assumption such as groundwater demand portion.

When The FWIB-Avg constraints are adopted, the FWIB recommendations could be met feasibly in five basins adding SanioNues and Trinity. To make the model feasible, we had to reduce the minimum requirements of the FWI levels in ColLavaca and Neches to 1.5% and 80% of the originally suggested FWI levels, lowering the inflow levels by 98.5% and 20% of them in the two basins, respectively.

Our analysis of the FWIB issue and its relationship to IBT shows that the FWIB recommendations can be met in more basins based on averages than in each and every state of nature. This suggests the need for policy changes by TPWD and TWDB. Under the FWIB-Avg constraints, the policy options can work independent of others but sometimes they should be mixed. (1) The first policy option is to lower the average recommended FWI levels as are the cases of ColLavaca and Neches. This alternative is feasible and less costly, and merits study by ecologists. (2) However, in the case of ColLavaca, the FWIB recommended levels are too far above the optimal levels so that FWI should be managed in the extended interbasin of ColLavaca and Colorado, and this should be implemented with the first policy option. FWI in Neches can be managed in the extended interbasin of Neches and Sabine if lowering the recommended levels is not possible. Extended basin-wide management of FWI is especially important when multiple FWI-out control points to bays and estuaries exist and their aggregated FWI must be comprehensively regulated, as in the case of Trinity. (3) Appropriate storage of the seasonal freshwater surpluses can make up for the shortages in conjunction with the second policy option. In the extended interbasin of ColLavaca and Colorado, the recommendations could not be perfectly satisfied in some months but the seasonal FWI surpluses from February to May can compensate for the shortages from June to September if the seasonal storage is assumed to be feasible. This seasonal management strategy must be implemented along with the yearly management of FWI to be prepared for the shortages of dry years.

(4) Another possibility that would be differentiated from the first policy option is to relax the recommended FWI levels based on percentage ranges as is shown in the Tennant method which suggests seasonally different 8 levels of environmental flows recommendations. (5) The last option is to lower the economic, biological and chemical standard of the FWIB recommendations, not just lowering the inflow levels: for example, we may need to agree on the average fish harvest rate from current 80%. This alternative is beyond our current study because there should be some compromise between economics and ecology/environment when the FWI levels are reevaluated and enforced.

Under the FWIB-Avg constraints after lowering the recommended inflows levels in ColLavaca and Neches, the same three IBT projects as are in chapter III were chosen with the IBT implementation and the FWIB-Avg constraints: Luce Bayou, LCRA-SAWS and Cypress IBT. The FWIB provisions absolutely cost money as they decrease water use and net benefits. The FWIB loss in net benefit (FWIB-NB) directly from the FWIB recommendations without IBT projects was -$211 million, and the total loss was -$8 million after FWIB-NB and The IBT gain in net benefit (IBT-NB) are all considered. This total loss came primarily from FWIB-NB dominance in the industrial and mining sector (Neches) over IBT-NB in the same sector (San Jacinto) and in the municipal sector (Guadsan and Trinity). The FWI sector made negative contribution to the net benefit while agricultural sector showed no change.

An IBT implementation relocates water to increase economic use efficiency and forces the FWIB loss in water use (FWIB-U) to be reduced. And the process of mutual interaction between the IBT loss in water flows (IBT-F) and the FWIB gain in water flows (FWIB-F) moved to finally reduce water flows because of the dominant IBT-F effect. But in the freshwater inflows, the FWIB gain in freshwater inflows (FWIB-I) dominated the IBT loss in freshwater inflows (IBT-I).

In terms of the total gain, water use increased primarily in the IBT-destination basins, FWI also increased due to contribution of the Neches River basin unlike the IBT-only scenario, but water flows decreased mainly in the IBT source basins. The IBT destination basins contributed to increasing water use and FWI, and the major IBT source basins contributed to decreasing water flows. The FWIB recommendations served to protect FWI. FWI decreased in the IBT net source basin Trinity. But the decreasing effect was overwhelmed by the increasing effect in the IBT destination basin Guadsan, and IBT-FWIB simultaneously applied basin San Jacinto and especially in the FWIB-recommended basin Neches.

In the IBT destination basin Guadsan and San Jacinto, water use, flows and FWI all increased due to sufficient injection of water. The FWIB flow protection effect was relatively strong in the FWIB-recommended basin San Jacinto.

The Colorado, Lavaca, Brazos and San Jacinto River basins are all geographically close and interconnected with the IBT implementation and the FWIB recommendations. Changes in water use were exactly offset by the same sector of a neighboring basin: agricultural water use is offset between Colorado and Lavaca, and municipal water use is offset between Brazos, Colorado and San Jacinto. The FWIB recommendations reinforced the IBT gain effect more in the simultaneous implementation of the FWIB-Avg constraints and IBT than in the IBT-only scenario. These facts imply that water use and flow patterns in these basins are interacting with those in the IBT and FWIB-neighboring basins.

CHAPTER V

MULTIPLE MARKETS IN ENVIRONMENTAL POLLUTION MARKETS: THEORETICAL AND SIMULATION ANALYSIS

5.1. Overview[18]

5.1.1. Introduction

Market-based approaches to environmental management are expanding at a remarkable rate. Driven by the simple intuition that it makes sense to minimize the cost of pursuing environmental improvements, since the early 1990s a wide range of programs have been established that differ in an important way from the traditional "command-and-control" approach. In what we will call "market-based" approaches, a regulatory mechanism exists that allows environmental harm at one point to be offset through environmental improvements elsewhere. Such programs may take a variety of forms, from a pure market in which uniform credits are traded at a market-determined

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[18] This overview section is based on the paper to be presented at the annual meeting of the American Agricultural Economics Association, Denver, Colorado, August 2004, by Richard Woodward and Manseung Han, associate professor and Ph.D candidate of the department of agricultural economics at Texas A&M University.

price, to offset programs in which the agency gives regulated parties flexibility to comply with regulations by offsetting damages at other locations.

Market-based (MB) approaches are being applied to a wide range of environmental problems; the highly visible SO_2 trading program is but the tip of the iceberg. Air pollution trading ranges from California's Reclaim program to the multi-state Ozone Transport Commission. In the water pollution arena, a recent report to the U.S. Environmental Protection Agency (EPA) lists sixteen programs in various stages of implementation and nine more programs under development (Environomics 1999). MB elements appear in wetland mitigation banking, in Habitat Conservation Plans that can be used to comply with the Endangered Species Act, in transferable development rights programs, in climate change policies, and virtually every new environmental policy in the U.S. presents an extensive list of environmental goods and services that are either covered by MB programs or are under consideration (the table on page 270).

As the number of market-based programs grows, so does the potential for interaction among the programs. As a result, there is a rising interest in the concept of "multiple markets" (e.g., Kieser & Associates, 2003), the notion that generators of environmental credits might be able to sell credits in many markets, what we will call “double dipping”. Suppose that a single action, such as a land management change, can generate environmental benefits of two types, such as carbon sequestration and nutrient reduction. And suppose that markets exist such that credits might be sold in two different markets. If double dipping is allowed then the returns to those that implement these management practices can increase, increasing the incentives to implement the most environmentally effective projects. On the other hand, if one project can sell credits in two markets, then this will reduce the number of projects that are included, diminishing the environmental benefits achieved. Hence, it is not immediately obvious that allowing double dipping will be socially efficient.

In this paper we explore the issues that arise when considering multiple environmental markets. We begin with a straightforward analysis building on Montgomery of multiple rights markets when there are caps placed on each such pollutant. In this case, it follows immediately that allowing double-dipping will achieve the efficient allocation of the pollution rights. Building on this framework we show that when pollution credits are generated as a joint product, it may be that the prices of some rights might go to zero. This adds a new twist to the standard policy advice that the socially efficient level of abatement is where the marginal benefit is equal to the marginal cost. This leads us to the complete planner's problem in which we also consider the societal benefits of pollution abatement. This problem is considered in both a first-best and second-best economy. In the first-best case, we again find that double-dipping leads to the optimal solution. However, in a second-best setting in which the caps are set suboptimally on incomplete information, the results are mixed and double-dipping may not be socially optimal. The paper concludes with a discussion of problems for future investigation.

5.1.2. Literature review

Dales (1968a, 1968b) and Crocker (1966) are credited with coming up with the idea of pollution permits to control pollution. The first formal treatment of this problem was provided by Montgomery (1972). As we discuss below, Montgomery's model incorporated the general features of a multiple pollutant problem, although he characterized it as a single pollutant with multiple receptor points.

There are several recent papers that have addressed issues involving tradable credits programs involving multiple permits, though none of these considers the same problem that we look at here. Montero (2001) is the first author to carefully analyze a problem similar to that we consider here. Montero considers the question as to whether cross-pollutant trading should be allowed, i.e., whether a firm should be allowed to increase emissions of pollutant A by buying credits generated by reducing pollutant B. Such cross pollutant trading runs counter to the piecemeal approach that is pervasive in most environmental policy. Nonetheless, at a conceptual level it is appropriate to ask what would be the optimal mix of pollution reduction across the pollutants. Cross pollutant trading with the appropriate trading ratio could yield the optimal allocation. In a fashion akin to Weitzman (1974), Montero finds that the relative slopes of the marginal benefit and marginal cost curves prove critical to determining if cross-pollutant trading should be allowed or not. If the marginal damage curves are steep, then it is less efficient to allow cross pollutant trading.

Perhaps most closely related to the theme in the current paper, Horan et al. (2004) examine the case of double dipping for water quality improvements in which the same abatement is paid twice from two programs differently run by an agricultural agency and a state agency. They show that efficiency gains occur under double dipping when two payments scheme is coordinated. But under the uncoordinated or stand-alone setting, double dipping increases efficiency with well-targeted payment incentives. The trading program between point and nonpoint sources provides better incentives when payment incentives are not well-targeted.

Caplan and Silva (2005) investigate correlated externalities that cause regional and global impacts. Their “correlated” pollutants mean multiple pollutants such as smog and global warming which are jointly produced by the same source. They justify that joint domestic and international permit markets over different jurisdictions are Pareto efficient using a sub-game equilibrium model.

The issue of double-dipping is particularly important in programs in which there is not a hard cap on aggregate pollution. As highlighted by Dewees (2001), many of pollution trading programs do not have caps. Instead, a source obtains a credit by reducing emissions below its historic levels generating an Emission Reduction Credit (ERC). Interest in the use of ERCs, also known as baseline-and-credit programs, is rising since such instruments can be used to control sources that are not typically regulated so that implementation of a cap is problematic. For example, ERCs are used to reduce nonpoint source pollution (Woodward, Kaiser and Wicks, 2002), or to offset wetland losses. The idea of taking advantage of multiple markets is receiving substantial attention in ERC programs (Kieser & Associates, 2003). For example, a created wetland might reduce nutrient runoff, sequester carbon and provide habitat for species: four environmental services are provided and quadruple-dipping could generate substantial revenue to the landowner.

For ERC type programs, there is a great deal of attention to the issue of “additionality”, i.e., a credit is only real if it is in excess of a baseline that the firm would otherwise be providing. When multiple markets are in place, this becomes extremely difficult. For example, a firm that establishes a containment pond to create nutrient credits might also be creating a wetland that provides habitat for water-fowl. If someone nearby needs to offset wetland loss, should the containment pond also be allowed to count for that? Would this second transaction be permitted? From a cost minimization perspective the answer is, “Probably yes.” From a social efficiency perspective the answer is, “Perhaps no” (Woodward and Han, 2004).

5.1.3. Multiple cap-and-trade markets to achieve cost efficiency

We begin our analysis of multiple pollution rights markets building on the familiar model of Montgomery (1972). Montgomery considered the use of transferable permits for the case of a market in which firms, i=1,…, n, emit a single pollutant, e_i, which is dispersed to m receptors according to the dispersion coefficients h_{ij}.

Licenses, l_{ij}, in this case place a cap on the i^{th} firm's emissions of the j^{th} pollutant, j=1,…, m. The firm's initial allocation of permits is denoted l_{ij}^0.

Define $F_i(e_{i1},...e_{im})$ as the i^{th} firm's cost of reducing emissions to a particular level, i.e., the difference between the firm's profit at the unconstrained maximum and the profits that can be achieved given that emissions are reduced to $e_{i1},...e_{im}$. Following Montgomery, we assume that $F(\cdot)$ is convex. The problem of each firm is to minimize its cost of emission reduction, $F(\cdot)$, plus its license cost, $l_{ij}-l_{ij}^0$, subject to emission constraint, and non-negativity conditions as follows.

$$\begin{aligned}
&\underset{e_{ij},\, l_{ij}}{Min}\ F_i(e_{i1},...e_{im})+\sum_{j=1}^{m} p_j(l_{ij}-l_{ij}^0)\\
(1)\quad &subject\ to\ e_{ij}\le l_{ij},\ \forall j\\
&\qquad\qquad e_{ij}\ge 0,\ l_{ij}\ge 0,\ \forall j
\end{aligned}$$

where p_j is the price for the j^{th} pollution license, which is defined in the market. Like Montgomery, we assume zero transaction costs.

A market equilibrium can be defined as solution vectors of the above minimization problem for all i, e_{ij}^*, l_{ij}^*, such that the following market clearing conditions are also satisfied.

$$(2) \sum_{i=1}^{n}(l_{ij}^{*}-l_{ij}^{0}) \leq 0,\ p_{j}^{*}\left[\sum_{i=1}^{n}(l_{ij}^{*}-l_{ij}^{0})\right]=0,\ \forall j\,.$$

Now, the social cost minimum that is efficient is obtained by solving a following social problem.[19]

$$\underset{e_{ij}}{Min}\sum_{i=1}^{n}F_{i}(e_{i1},...e_{im})$$

$$(3)\ \ subject\ to \sum_{i=1}^{n}e_{ij} \leq l_{j}^{0},\ \ \forall\ j$$

$$e_{ij} \geq 0,\ \forall i,\ j$$

As in Montgomery, from this individual firm and social planner's problem, two lemmas follow (all proofs are provided in APPENDIX B).

Lemma 1: A market equilibrium of the license market exists for $l_{j}^{0}=\sum_{i=1}^{n}l_{ij}^{0}$

Lemma 2: Any emission vector $(e_{11},...,e_{nm})$ that satisfies the market equilibrium conditions with $\left(l_{1}^{0},l_{2}^{0},....,l_{m}^{0}\right)=L^{0}$ is a social cost minimum.

As in the single pollutant with multiple locations case considered by Montgomery, Lemmas 1 and 2 establish that a pollution trading market can lead to a cost-minimizing equilibrium if a cap exists for all pollutants and all pollutants are traded.

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[19] The dispersion coefficients in Montgomery's model, h_{ij}, are omitted. This does not affect the implication of the result.

Under the assumptions maintained here, it also follows that the initial allocation of rights does not affect the final allocations or the price of the pollution licenses:

Lemma 3: If $l_{ij}^{0} \geq 0$ *and* $\sum_{i} l_{ij}^{0} = l_{j}^{0}$, then, vectors of emission, price and license demand for firm *i*, $(e_{i1}^{*},...,e_{im}^{*}), (p_{1}^{*},..., p_{m}^{*}), (l_{i1}^{*},...,l_{im}^{*})$, are independent of initially distributed license vector to firm *i*, $(l_{i1}^{0},...,l_{im}^{0})$.

We find, therefore, that multiple markets can achieve the cost-minimizing allocation of rights across producers. This result is not surprising, but we did not find similar results anywhere else in the literature.

We should note that the assumption of convexity in the cost function in this case is more restrictive than in the single-pollutant case though it remains intuitively plausible. If two pollutants are under consideration, the cost function is convex if it has a bowl-like shape, with the slope increasing as the firm's pollutions differ from the unconstrained optimum. Convexity of the cost function implies that for any price vector, $P=\{p_1,\ldots, p_m\}$, there is a unique point at which $DF(\cdot)=P$, where D*F* denotes the gradient of *F*. Hence, there is a unique global maximum to the firm's optimization problem.

Graphical analysis of the firm's problem in a multiple-market setting

In a fashion similar to Helfand (1991), in Figure V-1 we present the iso-cost curves associated with differing levels of the two pollutants for a representative firm. The ellipses in the figures indicate combinations of e_1 and e_2 that yield equal costs to the firm relative to the profit maximizing levels of emissions, e_1^* and e_2^* , where $F\left(e_1^*,e_2^*\right)=0$ and $F_1\left(e_1^*,e_2^*\right)=F_2\left(e_1^*,e_2^*\right)=0$.[20] Along the lines traversing the ellipses the marginal cost of reducing the pollutants independently are equal to zero. These lines indicate, therefore, the reaction functions of the firm's emissions of one pollutant to restrictions on the other pollutant. In Figure V-1-a, these reaction curves are horizontal and vertical, so that the optimal levels of emissions of the two pollutants are independent of the emissions of the other pollutant. In the b and c, the cost-minimizing level of emissions of the pollutants is related to the emissions of the other pollutant. In Figure V-1-b the pollutants are complements – if the firm is forced to reduce e_1, then to minimize costs it will also reduce e_2. In Figure V-1-c, on the other hand, the pollutants are substitutes – a requirement to reduce e_1 will lead the firm to increase its emissions of e_2.

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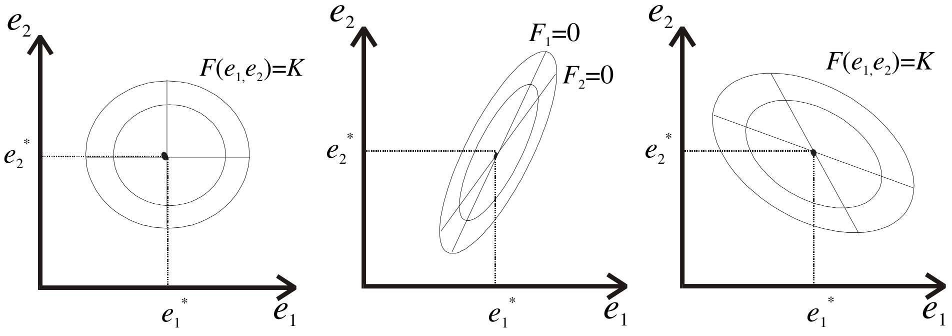
[20] The first derivatives F_1 and F_2 actually are negative so that negative signs should precede them.



(a) **(b)** **(c)**

Figure V-1. Iso-cost curves for two pollutants where costs are independent (a) where the pollutants are complements (b) and substitutes (c)

As can be seen in Figure V-1, the relationship between the two emissions in the firm's cost function is central to determining the optimal emissions. Moreover, the marginal cost of reducing emissions is critically dependent upon the full set of emissions. Although some analysis below can apply to situations in which the marginal cost of abatement is independent across pollutants (Figure V-1-a) or when the pollutants are substitutes (Figure V-1-c), we will focus on the case in which the pollutants are complements (Figure V-1-b). This is an important set of cases for it is often true that a single intervention will lead to reductions in more than one pollutant.

In Figure V-2, we present the case of a firm that faces a tradeable permits program on pollutant 1 at price p_1. This price on its emissions of e_1 causes it to reduce its emissions from e_1^* to $\underline{e}_1$, where $-F_1 = p_1$. As can be seen in the figure, the marginal cost of abating the second pollutant changes depending on the level of abatement of the pollutant 1. In order to efficiently regulate pollutant 2, i.e. set abatement such that the marginal benefit equals the marginal cost, the emission level of pollutant 1 must first be known. If the marginal cost for e_2 were evaluated at point A, the original level for e_2 and the new level for e_1, the marginal cost of reducing emissions of 2 is positive ($F_2>0$ from point A to C) – costs go down by reducing e_2. At B, the new level for e_2 but at the original level of e_1, e_1^*, then the marginal cost of reducing e_2 would be negative ($F_2<0$). At C, where the firm has optimally adjusted e_2 to the new level of e_1, $F_2=0$. We see, therefore, that when pollutants are joint products it is important to consider the levels of all other pollutants when evaluating the marginal cost of controlling any one pollutant.

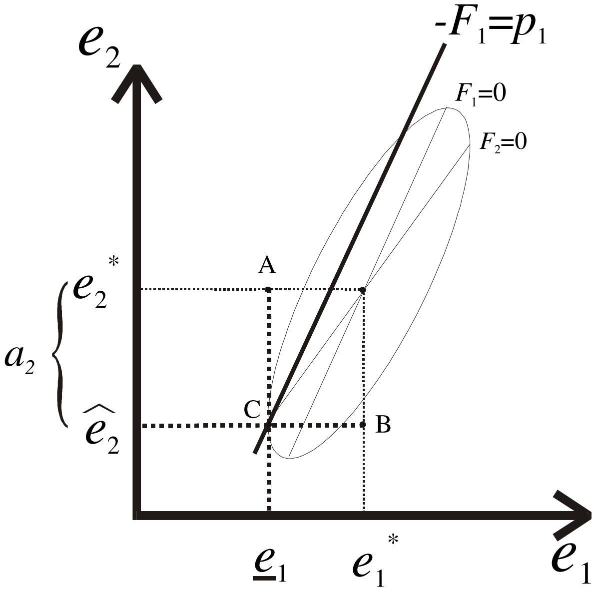


Figure V-2. Iso-cost curves and optimal responses to reducing pollutant 1

5.1.4. Social efficiency and multiple cap and trade programs

Following the Montgomery model, we have seen that when multiple pollutants are emitted, allowing for multiple emissions trading programs can identify the cost-minimizing allocation of emissions. In this section we consider the relationship between multiple markets and the socially efficient level of emissions. The conclusion is quite straightforward: the socially optimal level of pollution reduction is achieved by allowing multiple markets, but the cap on pollutants should reflect this. As we show in the section that follows, however, if the cap is not set optimally, taking into account the complementarities in abatement, then it is not always socially preferred to allow multiple markets.

Define a firm's emission abatement, a_{ij}, as the difference between e_{ij}^{*} and actual emissions e_{ij}, i.e., $a_{ij}=e_{ij}^{*}-e_{ij}$. Aggregate abatement of the j^{th} pollutant is written $A_j = \sum_i a_{ij}$. The industry costs (TC) are simply the sum across all firms: $TC = \sum_i F\left(e_{i1},\ldots,e_{im}\right) = \sum_i g_i\left(a_{i1},\ldots,a_{im}\right)$. Our focus here is on the interactions between the pollutants in the firms' cost functions, hence for simplicity we assume that the social benefits of abatement (TB) are additively separable and that, since all pollutants are assumed to be uniformly dispersed, are functions of aggregate abatement: $TB = \sum_j B_j\left(A_j\right)$.[21] The planner's problem, therefore, is to maximize total net benefits:

(4) $\underset{a_{ij},}{Max} \sum_j B_j(A_j) - \sum_i g_i(a_{i1,} \ldots a_{im})$

At the optimum, for all pollutants the marginal cost of abatement must be equal across firms, that is to say, $\frac{\partial g_i(\ )}{\partial a_{ij}} = \frac{\partial g_k(\ )}{\partial a_{kj}}$ for all i, $k (i \neq k)$. The optimal cap will be set at a level where the marginal benefit equals the marginal cost, $TB' = TC'$ for all j. If the caps for all pollutants are set simultaneously at the optimal levels, then by Lemma 2,

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[21] There has been some attention to cases where pollutants jointly interact in the environment (e.g., Schmieman et al., 2002).

a multiple-markets program where sources are able to trade credits in all pollution credit markets will lead to the social optimum.

Social optimum for fixed-coefficient technology

As an interesting example, consider the case which $j = 1, 2$ and the firms' abatement of the two pollutants occurs in fixed proportions, i.e. $a_{i2}=\gamma_i a_{i1}$, for all i. In this case the optimization problem becomes:

$$(5)\quad \underset{a_{ij}}{Max}\ B_1\left(\sum_i a_{i1}\right)+B_2\left(\sum_i a_{i2}\right)-\sum_i g_i(a_{i1},a_{i2})$$

Because abatement occurs in fixed proportions, we can rewrite a_{i2} in terms of a_{i1} and the cost function, $g(\cdot)$, can be expressed in terms of a single argument, that is to say, $g_i(a_{i1},a_{i2})=g_i(a_{i1},\gamma_i a_{i1})=\tilde{g}_i(a_{i1})$ when $a_{i2}=\gamma_i a_{i1}$, $\dfrac{\partial g_i(\cdot)}{\partial a_{i1}}=\dfrac{\partial \tilde{g}_i(\cdot)}{\partial a_{i1}}$, and

$$\frac{\partial g_i}{\partial a_{i2}}=\frac{\partial \tilde{g}_i}{\partial a_{i1}}\frac{\partial a_{i1}}{\partial a_{i2}}=\frac{\partial \tilde{g}_i}{\partial a_{i1}}\frac{1}{\gamma_i}$$

The first order condition of the planner's problem for a_{i1} is $B_1'+\gamma B_2'-g_{i1}'=0$. What is significant here is that the optimal level of total abatement is set not where $B_j'=g_{ij}'$, because of the joint production of a_1 and a_2, the benefits across both pollutants must be taken into account.

If an aggregate abatement goal were set where the marginal cost equals the marginal benefit on a pollutant-by-pollutant basis, then suboptimal pollution abatement would be sought. This fact points out a weakness in simplistic formulations of the standard guidance for policy: abate pollution up to the point where the marginal benefit equals the marginal cost. It is our impression that to the extent that any criterion of optimality is being sought in such policies, it almost certainly is being done on a pollutant-by-pollutant basis. Hence this implies that the standard policy is a second-best resulting in suboptimal caps.

5.1.5. Multiple markets in a second-best economy

To motivate our analysis of multiple markets in a second-best setting, we consider a very simple case presented in Figure V-3. We assume that some polluters emit two pollutants and that regulation of e_1 will lead to abatement of a_2 by those firms as in Figure V-2 above. As a result of the reduction from e_1^* to $\underline{e}_1$, the marginal cost of abating e_2 will shift from $\underline{MC}_2$ to MC*, taking into account the “free” abatement of a_2. Hence, the socially optimal level of abatement of pollutant 2 is $\bar{A}_2^*$, where the social marginal cost equals the social marginal benefit, B'(A_2). To optimally set this cap, however, the planner must know not only the cost functions and benefit functions, but how the cost functions interact between the two pollutants. If policy is mistakenly set without taking into account of the interactions in the cost function, then the cap would be set at $\bar{A}_2$, where MC$_2$=B'(A_2). This is the second-best cap that will be considered in detail below.

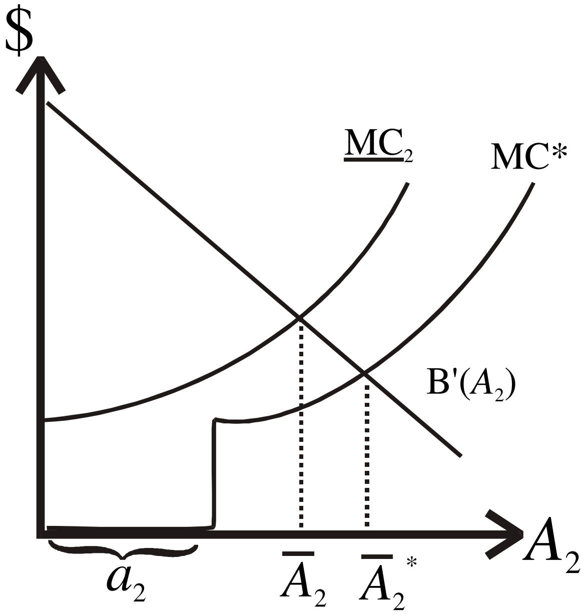

Figure V-3. Marginal benefit and marginal cost of abating pollutant 2

If the cap is set at $\bar{A}_2^*$, then it is efficient to allow double-dipping. If the cap is set inappropriately at $\bar{A}_2$, however, then it is not so clear that double dipping is the socially optimal response. Note that regardless of whether double-dipping is allowed, the a_2 units of abatement created by the regulation of pollutant 1 will take place and will yield social benefits. If multiple markets are not allowed, then the remaining firms must supply $\bar{A}_2$ units of abatement, leading to total abatement of $\bar{A}_2 + a_2$. If double-dipping is allowed, then only $\bar{A}_2$ units of abatement would be provided, with a_2 and $\bar{A}_2 - a_2$

units supplied by the firms presented in Figure V-2 and by remaining respectively.

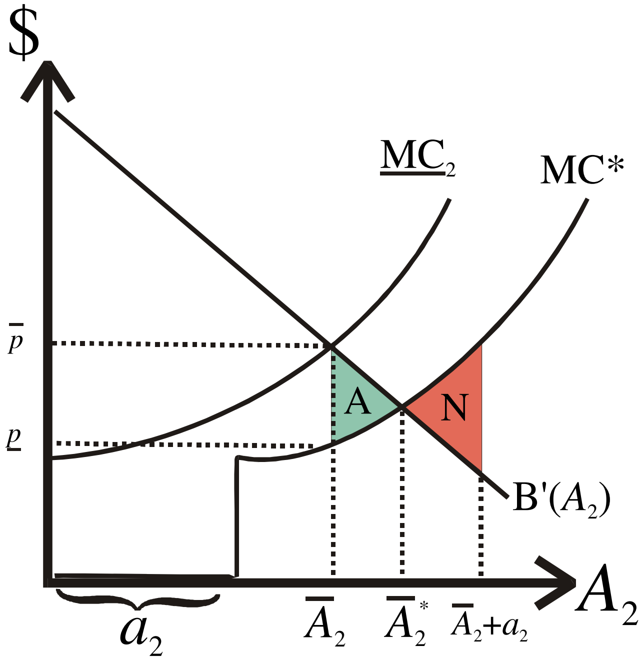

Figure V-4. Welfare losses under a second-best cap if double-dipping is allowed (A) or not allowed (N)

Because $\bar{A}_2$ is not socially optimal, a welfare loss will result; the question is whether the loss is greater with or without double-dipping. If double-dipping is allowed, then as seen in Figure V-4, total abatement will be $\bar{A}_2$ and the equilibrium price in the market will be at $\underline{p}$. Relative to $\bar{A}_2^*$, an inefficiently low level of total abatement results leading to welfare cost, the triangle A in Figure V-4. The alternative is to not allow double-dipping. In this case the a_2 credits would not be counted in the pollutant 2 market and total abatement would be $\overline{A}_2 + a_2$, an oversupply of abatement. From $\overline{A}_2^*$ to $\overline{A}_2 + a_2$, the social marginal benefit is less than the social marginal cost, and the welfare loss is indicated by the shaded triangle labeled N.

In this simple example, the efficiency of allowing for multiple markets depends on the relative slopes of the MC and MB curves. If the MB curve is relatively steep, then the N triangle grows implying that it is more efficient to allow double-dipping. Intuitively, this makes sense since a steep MB curve indicates that total abatement goal is fairly well defined, and multiple markets allow us to achieve that goal at the lowest possible cost. On the other hand, if the MB curve is relatively flat, then the total abatement goal is not so well defined but is quite sensitive to the marginal cost. As the MB curve becomes more horizontal, the triangle A grows and the triangle N shrinks. In this case, allowing multiple markets would be more inefficient. At the extreme, if the MB curve is horizontal, then it clearly holds that it is inefficient to allow double dipping.

The simplistic analysis in Figure V-4 shows when the caps are not set optimally, it is not clear whether allowing double-dipping is more efficient (or less inefficient) than not allowing it.

As general analytical results are not available, we turn to a specific case with quadratic cost and benefit functions. Even for this simplistic model, however, we find that analytical results cannot be obtained, so the use of numerical analysis is required.

5.2. Multiple Markets in an Economy with Quadratic Abatement Costs

5.2.1. Firm's cost function and its basic conditions

In this section, we analyze the multiple market problem in the context of an economy in which the abatement cost curves of the firms are quadratic in abatement with an interaction term across the two pollutants. This analytical work is the precursor to the numerical simulations which are presented in the next section and allow us to explore how changes in parameter values will affect whether it is socially preferred to allow double dipping.

Perfectly competitive market structure is assumed, in which there are *n* firms (*i*=1,…,*n*) and two pollutants (*j=1,2*). We assume a quadratic abatement cost function for a firm *i* which is a negative function of emission e_{i1}, e_{i2}, but a positive function of pollution abatement a_{i1}, a_{i2} when $a_{ij} = \bar{e}_{ij} - e_{ij}$ with an interaction term:

$$\begin{aligned} F_i(e_{i1}, e_{i2}) &= \frac{\alpha_{i1}\left(\bar{e}_{i1} - e_{i1}\right)^2}{2} + \frac{\alpha_{i2}\left(\bar{e}_{i2} - e_{i2}\right)^2}{2} + \gamma_i\left(\bar{e}_{i1} - e_{i1}\right)\left(\bar{e}_{i2} - e_{i2}\right) \\ &= g_i(a_{i1}, a_{i2}) = \frac{\alpha_{i1}}{2}a_{i1}^2 + \frac{\alpha_{i2}}{2}a_{i2}^2 + \gamma_i a_{i1} a_{i2} \qquad (6) \\ &\textit{where } \left(\bar{e}_{ij} - e_{ij}\right) = a_{ij} \geq 0,\ e_{ij} \geq 0,\ \alpha_{i1} > 0,\ \alpha_{i2} > 0,\ \gamma_i < 0,\ i = 1,\ldots,n,\ j = 1,2. \end{aligned}$$

As equation (6) shows, $\bar{e}_{ij}$ is the equivalent of e_{ij}^{*} in the first section, standing for the optimum emission level that achieves a firm's maximum profit without any restriction on emissions. If the coefficient of the interaction term between e_{i1} and e_{i2}, γ_i, is positive, then the pollutants 1 and 2 are substitutes. If γ_i is negative, they are complements. We focus on the case of complements where the reaction curves of an iso-cost ellipse are positively sloped as are the cases of Figure V-1-b and Figure V-5.

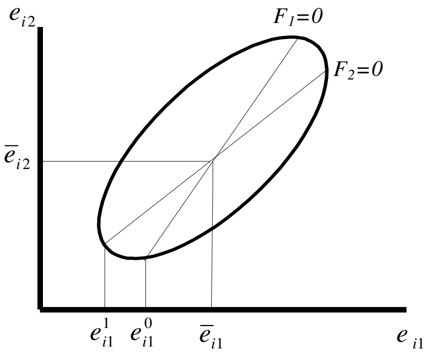

Figure V-5. Iso-cost curve for quadratic cost function

For the simulation exercise in the next section, this cost function must be defined to take on reasonable value in the first quadrant. Hence, the inequalities $e_{ij}^{0} \geq e_{ij}^{1}$ should be satisfied and parameters must be chosen for these inequalities to be satisfied. As we see below, a positive price on pollution abatement will cause firms to abate their pollution as long as $\alpha_{i1}\alpha_{i2} - \gamma_i^2 > 0$.[22]

5.2.2. Two ways of firm's cost minimization: emission or abatement

A firm minimizes the sum of abatement cost plus license purchase cost with the restrictions that emission must be limited by the licenses the firm holds (l_{ij}). When two license markets are available a firm's problem becomes[23]

$$(7)\ \underset{e_{i1},e_{i2},l_{i1},l_{i2}}{Min}\ F_i(e_{i1,}e_{i2}) + \sum_j p_j\left(l_{ij} - l_{ij}^0\right) =$$

$$\underset{e_{i1},e_{i2},l_{i1},l_{i2}}{Min}\ \frac{\alpha_{i1}\left(\bar{e}_{i1} - e_{i1}\right)^2}{2} + \frac{\alpha_{i2}\left(\bar{e}_{i2} - e_{i2}\right)^2}{2} + \gamma_i\left(\bar{e}_{i1} - e_{i1}\right)\left(\bar{e}_{i2} - e_{i2}\right) + p_1\left(l_{i1} - l_{i1}^0\right) + p_2\left(l_{i2} - l_{i2}^0\right)$$

$$s.t. \quad e_{ij} \le l_{ij},\ e_{ij} \ge 0,\ l_{ij} \ge 0,\ \ j = 1,\ 2$$

where l_{ij}^0 denotes the initial distribution of tradable permits to a firm *i* for the pollutant *j* and p_j is the price at which the tradeable rights are transacted.

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[22] See APPENDIX B for proof. The conditions for $e_{ij}^1 \ge 0$ also must be satisfied. These conditions are summarized as $-\dfrac{\gamma_i}{\alpha_{ij}}\bar{e}_{ik} \ge \bar{e}_{ij} - e_{ij}\ (j \ne k$ in Appendix C. But these depend on the exogenously given individual firm's technological parameter ($\bar{e}_{ij}$) which is not explicitly controlled in this analysis. These hidden conditions are assumed to hold.

[23] Non-negativity conditions of variables are absolutely assumed even if those are omitted hereafter.

This minimization problem is equivalent to the following problem in terms of abatements which will be adopted when $a_{ij} = \bar{e}_{ij} - e_{ij}$ and $l_{ij}^{d} = l_{ij} - l_{ij}^{0}$ where $l_{ij}^{d} > 0$ is license demand and $l_{ij}^{d} < 0$ is license supply of a firm *i* for a pollutant *j*.

$$(8)\ \underset{a_{i1},a_{i2},l_{i1},l_{i2}}{Min}\ g_i(a_{i1},a_{i2}) + \sum_j p_j\left(l_{ij} - l_{ij}^{0}\right) =$$

$$\underset{a_{i1},a_{i2},l_{i1},l_{i2}}{Min}\ \frac{\alpha_{i1}a_{i1}^{\ 2}}{2} + \frac{\alpha_{i2}a_{i2}^{\ 2}}{2} + \gamma_i a_{i1}a_{i2} + p_1\left(l_{i1} - l_{i1}^{0}\right) + p_2\left(l_{i2} - l_{i2}^{0}\right)$$

$$s.t.\quad \bar{e}_{ij} - l_{ij} \le a_{ij},\ j = 1, 2$$

The optimization problem must satisfy the following market clearing conditions when no transaction costs are assumed.

$$(9)\ \sum_i p_j\left(l_{ij}^{*} - l_{ij}^{0}\right) = 0,\ \sum_i \left(l_{ij}^{*} - l_{ij}^{0}\right) \le 0\ \ j = 1, 2$$

Where l_{ij}^{*} denotes optimum licenses a firm holds with the restriction on abatements

5.2.3. Supply function for tradable permits with double-dipping

When multiple markets are allowed, the Lagrangian of a firm *i*'s problem is

$$(10)\quad \begin{aligned} L_{FB}(a_{i1},a_{i2},l_{i1},l_{i2},\lambda_{i1},\lambda_{i2}) = {} & \frac{\alpha_{i1}a_{i1}^{\ 2}}{2} + \frac{\alpha_{i2}a_{i2}^{\ 2}}{2} + \gamma_i a_{i1}a_{i2} + p_1\left(l_{i1} - l_{i1}^{0}\right) + p_2\left(l_{i2} - l_{i2}^{0}\right) \\ & + \lambda_{i1}\left(\bar{e}_{i1} - l_{i1} - a_{i1}\right) + \lambda_{i2}\left(\bar{e}_{i2} - l_{i2} - a_{i2}\right) \end{aligned}$$

The Kuhn-Tucker conditions for the minimization problem are

$$\begin{aligned}
&\alpha_{i1}a_{i1}+\gamma_i a_{i2}-\lambda_{i1}\ge 0,\ a_{i1}\left(\alpha_{i1}a_{i1}+\gamma_i a_{i2}-\lambda_{i1}\right)=0\\
&\alpha_{i2}a_{i2}+\gamma_i a_{i1}-\lambda_{i2}\ge 0,\ a_{i2}\left(\alpha_{i2}a_{i2}+\gamma_i a_{i1}-\lambda_{i2}\right)=0\\
&p_1-\lambda_{i1}\ge 0,\ l_{i1}\left(p_1-\lambda_{i1}\right)=0\\
&p_2-\lambda_{i2}\ge 0,\ l_{i2}\left(p_2-\lambda_{i2}\right)=0\\
&\left(\overline{e}_{i1}-l_{i1}-a_{i1}\right)\le 0,\ \lambda_{i1}\left(\overline{e}_{i1}-l_{i1}-a_{i1}\right)=0\\
&\left(\overline{e}_{i2}-l_{i2}-a_{i2}\right)\le 0,\ \lambda_{i2}\left(\overline{e}_{i2}-l_{i2}-a_{i2}\right)=0\\
&a_{i1}\ge 0,\ a_{i2}\ge 0,\ l_{i1}\ge 0,\ l_{i2}\ge 0,\ \lambda_{i1}\ge 0,\ \lambda_{i2}\ge 0
\end{aligned}$$

It should hold that $a_{ij}>0$ in the first two conditions.[24] Thus at the optimum, the marginal cost of abatement equals its shadow price, $MC_{ij}=\alpha_{ij}a_{ij}+\gamma_i a_{ik}=\lambda_{ij}, j\ne k$. The following three graphs show relationship among the exogenously given maximum emission level of a firm to maximize its profit "without" restriction on abatement $(\overline{e}_{ij})$,

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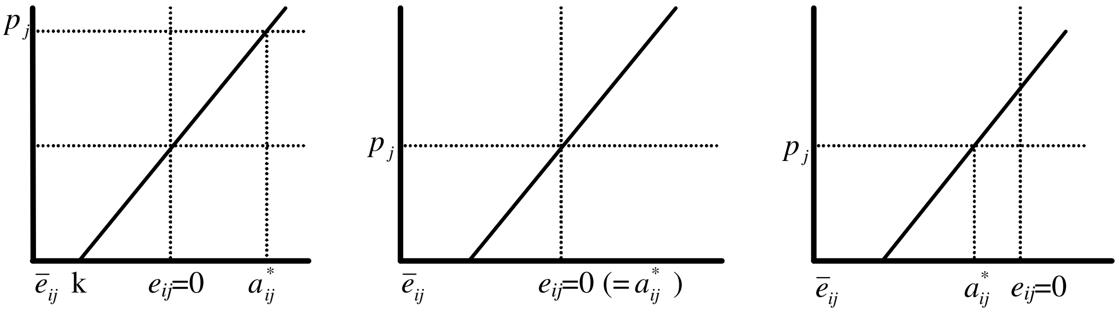
[24] From the first condition $\alpha_{ij}a_{ij}+\gamma_i a_{ik}-\lambda_{ij}\ge 0,\ a_{ij}\left(\alpha_{ij}a_{ij}+\gamma_i a_{ik}-\lambda_{ij}\right)=0\ \ \forall j,k,\ j\ne k$, (1) if $\left(\alpha_{ij}a_{ij}+\gamma_i a_{ik}-\lambda_{ij}\right)>0$, then $a_{i1}=0$ *and* $a_{i2}=0$ from the first two conditions. If $a_{i1}=0$ *and* $a_{i2}=0$ are put into $\left(\alpha_{ij}a_{ij}+\gamma_i a_{ik}-\lambda_{ij}\right)>0$, it leads to contradictive $\lambda_{ij}<0$. Therefore, it must hold that $\left(\alpha_{ij}a_{ij}+\gamma_i a_{ik}-\lambda_{ij}\right)=0$. (2) If $a_{i1}=a_{i2}=0$, then $\lambda_{i1}=\lambda_{i2}=0$. We can exclude this case which will be explained immediately next. (3) And when one of abatement is strictly greater than zero, the other abatement should be also strictly greater than zero because technical complementarity exists, say, the case that $a_{ik}>0$ and $a_{im}=0\ (k\ne m)$ does not exist in this technology. Therefore, there is no such case as $a_{i1}=a_{i2}=0$ simultaneously.

optimum abatement level "with" restriction on abatement (a_{ij}^{*}) , market price and marginal cost.

The Lagrange multiplier λ_{ij} is interpreted as an intrinsic value or shadow price; it represents the maximum willingness to pay (WTP) for abatement or license purchase or combination of abatement and license purchase by a firm at the optimum incurred by the unit change of maximum emission capacity of the firm *i* ($\overline{e}_{ij}$).

In Figure V-6, we present the three possible cases of firm's cost minimization. In Figure V-6-a, we present the case that $a_{ij}^{*} > \overline{e}_{ij}$, i.e., the case in which the optimal pollution level would be negative. But this is impossible from $e_{ij} = \overline{e}_{ij} - a_{ij} \geq 0$. No firm would abate more than its maximum emission level and such a corner solution is not possible. There is also no such case as $\lambda_{i1} = \lambda_{i2} = 0$ simultaneously. This is the case only when $MC_{ij} = \alpha_{ij} a_{ij} + \gamma_i a_{ik} = \lambda_{ij} = 0, \forall j, j \neq k$. Since α_{ij}>0 and γ_i<0, this could only hold if $a_{i1} = a_{i2} = 0$ which means p_1=p_2=0. We do not have any reason to analyze this case. Hence, in this situation, a firm's WTP is strictly greater than zero in at least one market. Figure V-6-b is the interior solution case of cost minimization, where $p_j = MC_{ij} = \lambda_{ij}^{*}$ with $l_{ij}^{*} = 0,\ a_{ij}^{*} = \overline{e}_{ij}$. Finally, Figure V-6-c presents the case where $p_j = MC_{ij} = \lambda_{ij}^{*}$, $l_{ij}^{*} > 0,\ a_{ij}^{*} < \overline{e}_{ij}$. In either case, we find the relationship $p_j = MC_{ij} = \lambda_{ij}^{*} \geq 0$ with at least one of λ_{ij}^{*} strictly greater than zero and $l_{ij}^{*} \geq 0,\ a_{ij}^{*} \leq \bar{e}_{ij}$ at the optimum**.**



(a) $a_{ij}^{*} > \bar{e}_{ij},\ l_{ij}^{*} = 0$ (b) $p_j = MC_{ij} = \lambda_{ij}, l_{ij}^{*} = 0$ (c) $p_j = MC_{ij} = \lambda_{ij}, l_{ij}^{*} > 0$

Figure V-6. Marginal Cost (MC) curves

Finally, the optimum conditions for a cost minimizing firm *i* from pollution abatement efforts are set at $p_j = MC_{ij}(a_{i1}, a_{i2}) = g_{ij}(a_{i1}, a_{i2})$ where g_{ij} denotes the first derivative of the cost function g_i with respect to a_{ij}. Hence, the following holds:

$$MC_{i1} = \alpha_{i1}a_{i1} + \gamma_i a_{i2} = \lambda_{i1} = p_1,\ MC_{i2} = \alpha_{i2}a_{i2} + \gamma_i a_{i1} = \lambda_{i2} = p_2,\ l_{i1} \geq 0,\ l_{i2} \geq 0$$

Then, each firm's supply function is derived as follows.

$$(11) \quad a_{i1} = \frac{\alpha_{i2}p_1 - \gamma_i p_2}{\alpha_{i1}\alpha_{i2} - \gamma_i^2} = \hat{\alpha}_{i2}p_1 - \hat{\gamma}_i p_2$$

$$(12) \quad a_{i2} = \frac{\alpha_{i1}p_2 - \gamma_i p_1}{\alpha_{i1}\alpha_{i2} - \gamma_i^2} = \hat{\alpha}_{i1}p_2 - \hat{\gamma}_i p_1$$

where $\hat{\alpha}_{i1} = \dfrac{\alpha_{i1}}{\alpha_{i1}\alpha_{i2} - \gamma_i^2},\ \hat{\alpha}_{i2} = \dfrac{\alpha_{i2}}{\alpha_{i1}\alpha_{i2} - \gamma_i^2},\ \hat{\gamma}_i = \dfrac{\gamma_i}{\alpha_{i1}\alpha_{i2} - \gamma_i^2}$

Because the denominator $(\alpha_{i1}\alpha_{i2} - \gamma_i^2)$ is strictly greater than zero by assumption

(APPENDIX C), each firm's supply is a positive function of own and complement abatement prices as is clearly expected since we assumed $\alpha_{ij} > 0,\ \gamma_i < 0$. Whether a firm is a buyer or seller in the market will be determined by the optimal abatement levels identified in (11) and (12).

Aggregate supply function is just a horizontal sum of each firm's supply in terms of pollution abatement, say, $A_j = \sum_i a_{ij}$. By Lemma 2, individual optimization leads to the social optimum. Therefore, the aggregate supply function is a positive function of own and complement abatement prices.

$$(13)\quad AS_1 = p_1 \sum_i \frac{\alpha_{i2}}{\alpha_{i1}\alpha_{i2} - \gamma_i^2} - p_2 \sum_i \frac{\gamma_i}{\alpha_{i1}\alpha_{i2} - \gamma_i^2} = p_1 \sum_i \hat{\alpha}_{i2} - p_2 \sum_i \hat{\gamma}_i$$

$$(14)\quad AS_2 = p_2 \sum_i \frac{\alpha_{i1}}{\alpha_{i1}\alpha_{i2} - \gamma_i^2} - p_1 \sum_i \frac{\gamma_i}{\alpha_{i1}\alpha_{i2} - \gamma_i^2} = p_2 \sum_i \hat{\alpha}_{i1} - p_1 \sum_i \hat{\gamma}_i$$

5.2.4. The social benefit function

Social benefit function (B_j) for a pollutant *j* is assumed to be quadratic. The aggregate social benefit function is additively separable as $B(A) = \sum_j B_j(A_j)$ with

$$(15)\, B_j(A_j) = \Omega_j A_j - \frac{\theta_j}{2} A_j^2 \text{ where } \Omega_j > 0,\ \theta_j > 0,\ A_j = \sum_i a_{ij},\ j = 1,2\,.$$

The optimum will exist at the values of A_j such that $B_j'(A_j) \geq 0$, which leads to the condition, $A_j \leq \frac{\Omega_j}{\theta_j}$. Diminishing marginal benefit automatically holds in this function, that is to say, $B_j''(A_j) = -\theta_j < 0$.

5.2.5. The first best and second best case

Market equilibrium in the first best case

In the context of the parametric assumptions made above, we consider now the first best case where an environmental regulatory agency is fully aware of the technological complementarity among each firm's pollution abatement efforts, say, $\gamma_i < 0$. Then, the agency determines the abatement cap for the pollutant j by maximizing the net social benefit function.[25]

$$\text{(16)} \quad \begin{aligned} &\underset{a_{ij}}{Max} \sum_j \left(\Omega_j A_j - \frac{\theta_j}{2} A_j^2 \right) - \sum_i \left(\frac{\alpha_{i1}}{2} a_{i1}^2 + \frac{\alpha_{i2}}{2} a_{i2}^2 + \gamma_i a_{i1} a_{i2} \right) \\ &s.t. \ \sum_i a_{ij} = A_j, \ j = 1,2 \end{aligned}$$

Under the first best case the social optimum is found taking into account the full degree to which prices will adjust. Hence, the social optimum will be set where

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[25] $\sum_i \left(g_i(a_{i1}, a_{i2}) + \sum_j p_j \left(l_{ij} - l_{ij}^0 \right) \right) = \sum_i g_i(a_{i1}, a_{i2})$ because $\sum_i p_j \left(l_{ij} - l_{ij}^0 \right) = 0$

$MB_j(A_j) = p_j$ and then aggregate demand function is

$$(17) \quad AD_j = A_j = \frac{\Omega_j - p_j}{\theta_j}$$

Now, we can generate the market clearing prices that satisfy both the aggregate supply function (13) and (14), and the aggregate demand function (17). The optimum will clear the market, $AS_j = AD_j = A_j^*$. A_j^* is, therefore, the abatement cap in the first-best case for the pollutant *j,* which will be set by the agency. In the first best case, double-dipping provides the first best outcome as is explained previously.

The resulting optimal market clearing prices are shown as follows:

$$(18) \quad p_1^* = \frac{\Omega_1\theta_2\sum_i \hat{\alpha}_{i1} + \Omega_2\theta_1\sum_i \hat{\gamma}_i + \Omega_1}{\theta_1\theta_2\{\sum_i \hat{\alpha}_{i1}\sum_i \hat{\alpha}_{i2} - (\sum_i \hat{\gamma}_i)^2\} + \theta_1\sum_i \hat{\alpha}_{i2} + \theta_2\sum_i \hat{\alpha}_{i1} + 1}$$

$$(19) \quad p_2^* = \frac{\Omega_2 + \theta_2\sum_i \hat{\gamma}_i p_1^*}{1 + \theta_2\sum_i \hat{\alpha}_{i1}}$$

It is assumed that $\sum_i \hat{\alpha}_{i1}\sum_i \hat{\alpha}_{i2} - (\sum_i \hat{\gamma}_i)^2 > 0$ for a positively sloped social supply curve as equation (24) and (25) show. Prices must be positive so that numerators $\Omega_1\theta_2\sum_i \hat{\alpha}_{i1} + \Omega_2\theta_1\sum_i \hat{\gamma}_i + \Omega_1 \geq 0$ and $\Omega_2\theta_1\sum_i \hat{\alpha}_{i2} + \Omega_1\theta_2\sum_i \hat{\gamma}_i + \Omega_2 \geq 0$ are assumed using symmetry between prices and parameters. The positive prices conditions guarantee that the marginal social benefit must be positive, $A_j \leq \frac{\Omega_j}{\theta_j}$.

Market equilibrium in the second best case

As we have indicated above, to optimally choose the caps on pollution (i.e. to choose A_1^* and A_2^*) the regulatory agency must know the parameters of the cost functions and be able to anticipate the response of the firms that result due to the complementarities in the abatement cost functions. This seems like an unrealistic level of knowledge. In practice, to the extent that optimal policies are sought, it might be more realistic to assume that regulators look at the marginal cost curves of each pollutant separately, ignoring the interactions between the two pollutants. This would be roughly equivalent to assuming that if the environmental regulatory agency does not consider the technologically complementary relationship among each firm's pollution abatement efforts, a_{i1}, a_{i2}, the agency ignores the interaction effect, i.e., for some reason, it acting as if $\gamma_i = 0$. In this case, the agency determines the abatement cap for the pollutant *j* by maximizing the following net social benefit function which is additively separable with the equality constraint in order to set up the cap.

$$\text{(20)} \quad \begin{aligned} &\underset{a_{ij}}{Max} \sum_j \left(\Omega_j A_j - \frac{\theta_j}{2} A_j^2 \right) - \sum_i \left(\frac{\alpha_{i1}}{2} a_{i1}^2 + \frac{\alpha_{i2}}{2} a_{i2}^2 \right) \\ &s.t. \quad \sum_i a_{ij} = A_j, \;\; j = 1,2 \end{aligned}$$

The abatement cap on the second best case (A_j^{**}) can be obtained from the first-order conditions which is $\Omega_j - \theta_j A_j - \alpha_{ij} a_{ij} = 0 \;\; \forall i, j$ .We can, therefore, write the second best abatement cap as the solution to a system of linear equations as follows.

$$(21) \quad \begin{aligned} &\theta_j A_j + \alpha_{ij} a_{ij} = \Omega_j \;\; \forall i, j \\ &\sum_i a_{ij} = A_j^{**}, \; j = 1,2 \end{aligned}$$

The linear system of equations that would satisfy the optimum could, therefore, be rewritten as a linear equation system for the pollutant j as

$$\begin{bmatrix} \alpha_{1j} \; 0..................0 \;\; \theta_j \\ 0 \;\; \alpha_{2j} \;\; 0...........0 \;\; \theta_j \\ .... \\ .... \\ 0.....................0 \; \alpha_{nj} \;\; \theta_j \\ 1......................1 \;\; 1 \; -1 \end{bmatrix} \begin{bmatrix} a_{1j} \\ a_{2j} \\ \cdots \\ \cdots \\ a_{nj} \\ A_j^{**} \end{bmatrix} = \begin{bmatrix} \Omega_j \\ \Omega_j \\ \cdots \\ \cdots \\ \Omega_j \\ 0 \end{bmatrix}$$

From this linear equation system with (n+1) variables and (n+1) equations, we can solve it for a_{ij} and A_j^{**}.

However, this does not explicitly express the relationship of price and abatement. Let’s use the method in the first best case to go around this computational problem. The environmental agency faces the aggregate demand function in terms of price as in equation (17). In order to compute a socially optimal abatement cap, the agency needs to obtain each individual firm’s optimal abatement from $p_j = MC_{ij} = \alpha_{ij} a_{ij}$, ignoring the term $\gamma_i a_{ik}$ where $j \neq k$. Then, the second best abatement cap that it computes equals

$AS_j(\gamma_i = 0) = \sum_i a_{ij} = \sum_i \frac{p_j}{\alpha_{ij}}$. From the relationship $AS_j(\gamma_i = 0) = AD_j = A_j^{**}$, the resultant prices which are not actual market prices but needed to compute the second best cap are obtained as follows. Actual market prices at these abatement caps will be given by the prices of the equation (24) and (25), which are denoted by p_j^{MM} .

$$(22)\quad \hat{p}_j = \frac{\Omega_j}{1 + \theta_j \sum_i \frac{1}{\alpha_{ij}}} \qquad j = 1,2$$

Finally, A_j^{**}, the abatement cap on the second best case for the pollutant *j*, can be computed from AS_j or AD_j with $\hat{p}_j$. These prices and caps are shown in Figure V-7.

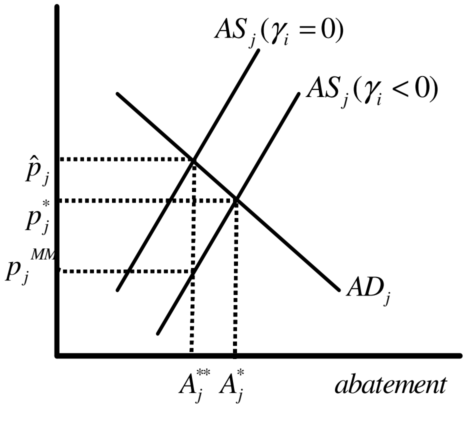

Figure V-7. Demand, supplies and prices[26]

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[26] AS, A^*, A^{**} denote aggregate supply, first best and second best caps. γ is a complementary abatement term in the supply function and *p* is a price.

Multiple Market (MM) case with the second best cap

In the multiple market case, firms can sell the permits in both markets. We assume that although the planner is unaware of γ_i, each firm surely knows $\gamma_i < 0$ and makes optimal choices accordingly. Then, each firm will minimize the following equation, subject to the inequality constraints on minimum abatement requirement.

$$(23)\quad \underset{a_{i1},a_{i2},l_{i1},l_{i2}}{Min} C_i(a_{i1},a_{i2},l_{i1},l_{i2}) = \underset{a_{i1},a_{i2},l_{i1},l_{i2}}{Min} \frac{\alpha_{i1}a_{i1}^2}{2} + \frac{\alpha_{i2}a_{i2}^2}{2} + \gamma_i a_{i1}a_{i2} + p_1\left(l_{i1} - l_{i1}^0\right) + p_2\left(l_{i2} - l_{i2}^0\right)$$

$$s.t.\quad \bar{e}_{ij} - l_{ij} \le a_{ij},\ j = 1,\ 2$$

We know the solution of firm's supply and aggregate supply functions as are generated in the equation (11), (12), (13) and (14) above, which was the interior solution. If the linear equations (13) and (14) are solved in terms of p_1 and p_2 with the given second best abatement caps A_j^{**} instead of the first best abatement caps A_j^*, the solutions are shown as follows:

$$(24)\quad p_1^{MM} = \frac{\sum_i \hat{\alpha}_{i1} A_1^{**} + \sum_i \hat{\gamma}_i A_2^{**}}{\sum_i \hat{\alpha}_{i1} \sum_i \hat{\alpha}_{i2} - (\sum_i \hat{\gamma}_i)^2}$$

$$(25)\quad p_2^{MM} = \frac{\sum_i \hat{\alpha}_{i2} A_2^{**} + \sum_i \hat{\gamma}_i A_1^{**}}{\sum_i \hat{\alpha}_{i1} \sum_i \hat{\alpha}_{i2} - (\sum_i \hat{\gamma}_i)^2}$$

An individual firm's behavior was already analyzed as is summarized as follows.

$$(26)\quad a_{i1}^{MM} = \frac{\alpha_{i2} p_1 - \gamma_i p_2}{\alpha_{i1}\alpha_{i2} - \gamma_i^2} = \hat{\alpha}_{i2} p_1 - \hat{\gamma}_i p_2$$

$$(27)\quad a_{i2}^{MM} = \frac{\alpha_{i1} p_2 - \gamma_i p_1}{\alpha_{i1}\alpha_{i2} - \gamma_i^2} = \hat{\alpha}_{i1} p_2 - \hat{\gamma}_i p_1$$

Single Market (SM) case with the second best cap

In the single market case in which firms are allowed to sell permits in only one market, they will choose the market that generates the highest profits or lowest costs. Each firm decides which market to participate by comparing its cost function C_i^1 and C_i^2.

Let us assume temporarily that a firm participates in market 1 to know a typical behavior of a firm, the cost function that will be minimized becomes[27]

$$\begin{aligned} &\underset{a_{i1},a_{i2},l_{i1}}{Min}\ C_i(a_{i1,} a_{i2}, l_{i1}) = \underset{a_{i1},a_{i2},l_{i1}}{Min} \frac{\alpha_{i1} a_{i1}{}^2}{2} + \frac{\alpha_{i2} a_{i2}{}^2}{2} + \gamma_i a_{i1} a_{i2} + p_1\left(l_{i1} - l_{i1}^0\right) \\ (28)\quad & s.t. \quad a_{i1} \geq \bar{e}_{ij} - l_{i1} \\ & \qquad\quad a_{i2} \geq \bar{e}_{ij} - l_{i2}^0 \end{aligned}$$

The second constraint comes from $l_{i2}^d = l_{i2} - l_{i2}^0$.[28] Here, $l_{i2}^d = -l_{i2}^d = 0$ because market 2 is assumed to be not available. We also assumed that initial license distribution is

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[27] This cost function is symmetric so that solution of participating in market 2 is also symmetric.

[28] If $l_{i2}^d > 0$, it is excess license demand. If $l_{i2}^d < 0$, it is excess license supply.

grandfathered $(l_{ij}^0 > 0)$.

The Lagrangian for the second best (SB) case is

$$L_{SB}(a_{i1}, a_{i2}, l_{i1}, \lambda_{i1}, \lambda_{i2}) = \frac{\alpha_{i1} a_{i1}^2}{2} + \frac{\alpha_{i2} a_{i2}^2}{2} + \gamma_i a_{i1} a_{i2} + p_1 \left(l_{i1} - l_{i1}^0\right) + \lambda_{i1}\left(\bar{e}_{i1} - l_{i1} - a_{i1}\right) + \lambda_{i2}\left(\bar{e}_{i2} - l_{i2}^0 - a_{i2}\right) \tag{29}$$

The Kuhn-Tucker conditions are:

$$\begin{aligned}
&\alpha_{i1} a_{i1} + \gamma_i a_{i2} - \lambda_{i1} \geq 0,\ a_{i1}\left(\alpha_{i1} a_{i1} + \gamma_i a_{i2} - \lambda_{i1}\right) = 0 \\
&\alpha_{i2} a_{i2} + \gamma_i a_{i1} - \lambda_{i2} \geq 0,\ a_{i2}\left(\alpha_{i2} a_{i2} + \gamma_i a_{i1} - \lambda_{i2}\right) = 0 \\
&p_1 - \lambda_{i1} \geq 0,\ l_{i1}\left(p_1 - \lambda_{i1}\right) = 0 \\
&\left(\bar{e}_{i1} - l_{i1} - a_{i1}\right) \leq 0,\ \lambda_{i1}\left(\bar{e}_{i1} - l_{i1} - a_{i1}\right) = 0 \\
&\left(\bar{e}_{i2} - l_{i2}^0 - a_{i2}\right) \leq 0,\ \lambda_{i2}\left(\bar{e}_{i2} - l_{i2}^0 - a_{i2}\right) = 0 \\
&a_{i1} \geq 0,\ a_{i2} \geq 0,\ l_{i1} \geq 0,\ \lambda_{i1} \geq 0,\ \lambda_{i2} \geq 0
\end{aligned}$$

Again, a_{i1} and a_{i2} are strictly greater than zero. At the optimum it must be that $p_1 = \lambda_{i1}$, otherwise the price exceeds the marginal cost in the first condition so that cost minimization is not achieved. There was no such case as $\lambda_{i1} = \lambda_{i2} = 0$ as was examined.

The shadow price or maximum willingness to pay for abatement 1 (λ_{i1}) must be greater than zero and the constraint for abatement 1 binds when a firm is committed in market 1.[29] Therefore, there are two solutions accordingly with $\lambda_{i1} > 0, \lambda_{i2} \geq 0$ when the

---

[29] See the case when $\lambda_{i1} = 0, \lambda_{i2} > 0$ because there is no such case as $\lambda_{i1} = \lambda_{i2} = 0$. Then, $a_{i1} = \frac{-\gamma_i\left(\bar{e}_{i2} - l_{i2}^0\right)}{\alpha_{i1}}$, $a_{i2} = \bar{e}_{i2} - l_{i2}^0$. This firm is not price-responsive and does not

firm is committed in market 1.

The first solution is when $\lambda_{i1} > 0, \lambda_{i2} = 0$. The equilibrium point corresponds to B in Figure V-8 below. At such an equilibrium, the Kuhn-Tucker conditions become:

$$\begin{aligned}
&\alpha_{i1}a_{i1} + \gamma_i a_{i2} = \lambda_{i1} = p_1 > 0 \\
&\alpha_{i2}a_{i2} + \gamma_i a_{i1} = \lambda_{i2} = 0 \\
&\bar{e}_{i1} - l_{i1} - a_{i1} = 0 \\
&\bar{e}_{i2} - l_{i2}^0 - a_{i2} \le 0 \\
&a_{i1} > 0,\ a_{i2} > 0,\ l_{i1} \ge 0.
\end{aligned}$$

The solution for this system of equations yields

(30) $a_{i1}^B = \hat{\alpha}_{i2} p_1,\ a_{i2}^B = -\hat{\gamma}_i p_1$ where $\hat{\alpha}_{i2} = \dfrac{\alpha_{i2}}{\alpha_{i1}\alpha_{i2} - \gamma_i^2},\ \hat{\gamma}_i = \dfrac{\gamma_i}{\alpha_{i1}\alpha_{i2} - \gamma_i^2}$.

The second solution is when $\lambda_1 > 0,\ \lambda_2 > 0$. In this case the firm participates only in market 1, but must take additional steps in order to come into compliance with market 2. The equilibrium point corresponds to C in Figure V-8, which will be graphically investigated in detail in the following two cases, say, case 1 and case 2, depending on the amount of initially given licenses.[30]

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have any incentive to join market 1. The firm should have joined market 2 with abatement, $a_{i1} = -\gamma_i p_2, a_{i2} = \hat{\alpha}_{i1} p_2$.

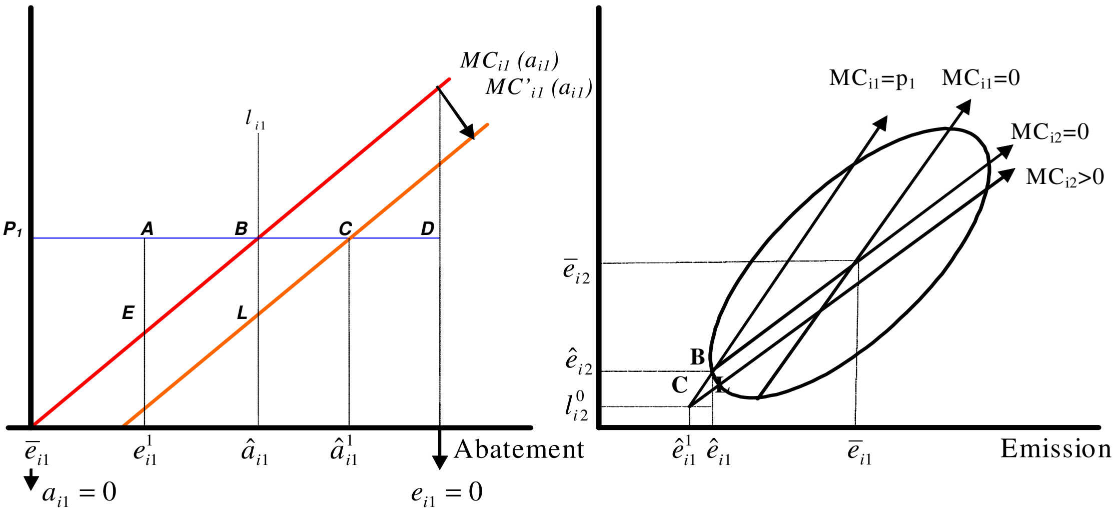
[30] At the point C of the right hand side graph, $a_{ij}^C > a_{ij}^B$. Then, the conditions,

$$\begin{aligned}
&\alpha_{i1}a_{i1} + \gamma_i a_{i2} = \lambda_{i1} = p_1 > 0\\
&\alpha_{i2}a_{i2} + \gamma_i a_{i1} = \lambda_{i2} > 0\\
&\bar{e}_{i1} - l_{i1} - a_{i1} = 0\\
&\bar{e}_{i2} - l_{i2}^0 - a_{i2} = 0\\
&a_{i1} > 0,\ a_{i2} > 0,\ l_{i1} \geq 0.
\end{aligned}$$

The solution is

(31) $a_{i1}^C = \dfrac{p_1 - \gamma_i\left(\bar{e}_{i2} - l_{i2}^0\right)}{\alpha_{i1}}$, $a_{i2}^C = \bar{e}_{i2} - l_{i2}^0$

$p_j < -\dfrac{\left(\bar{e}_{ik} - l_{ik}^0\right)\left(\alpha_{i1}\alpha_{i2} - \gamma_i^2\right)}{\gamma_i}$, $\left(j \neq k\right)$ must be satisfied. But these depend on the exogenously given individual firm's technological parameter ($\bar{e}_{ik}$) which is not explicitly controlled. These conditions are assumed to hold.



l_{i1}^* **: optimum license demand**

$\hat{a}_{i1}$ **: optimum abatement**

Figure V-8. Marginal Cost (MC) and license market: second best case

The initial distribution of license (l_{ij}^0) does matter to find the optimum, B or C on the above graph in the second best case when double dipping is not allowed.

There are four possibilities about the decision on which market to participate. Depending on the initial distribution of licenses, the firm compares the cost of participating in market 1 to that of participating in market 2 and decides which market it enters. The firm sells in market 1 if the cost function shows the relationship $C_i^1 \le C_i^2$.

Case 1 is when the initial distribution is given as $l_{i2}^0 \ge \hat{e}_{i2}$, $l_{i1}^0 \ge \hat{e}_{i1}$. If l_{i2}^0 is initially given relatively abundant between $\hat{e}_{i2}$ and $\bar{e}_{i2}$ in the right-hand side graph, the equilibrium occurs at point B because $MC_{i1} = \lambda_{i1} = p_1 > 0$ and $MC_{i2} = \lambda_{i2} = 0$ as the first case above and the firm satisfies the requirement of abatement for the pollutant 2, say, $\bar{e}_{i2} - \hat{e}_{i2} = \hat{a}_{i2} \geq \bar{e}_{i2} - l_{i2}^0$, which is the last inequality Kuhn-Tucker condition of the first case. The abatement of the participant of market 1 is determined as

$a_{i1} = \hat{\alpha}_{i2} p_1$, $a_{i2} = -\hat{\gamma}_i p_1$ because $l_{i2}^0 \geq \hat{e}_{i2}$.

When these values are substituted in the cost function, its value becomes a function of parameters as follows.[31]

$$(32)\quad C_i^1(a_{i1}, a_{i2}, l_{i1}) = \frac{\alpha_{i1} a_{i1}^2}{2} + \frac{\alpha_{i2} a_{i2}^2}{2} + \gamma_i a_{i1} a_{i2} + p_1 \left(l_{i1} - l_{i1}^0\right) = p_1 \left(\bar{e}_{i1} - l_{i1}^0\right) - \frac{p_1^2 \hat{\alpha}_{i2}}{2}$$

If a firm participates in market 2 and initial distribution is given as $l_{i1}^0 \geq \hat{e}_{i1}$, then the same logic applies as above and the firm decides the abatement as

$a_{i1} = -\hat{\gamma}_i p_2, a_{i2} = \hat{\alpha}_{i1} p_2$ because $l_{i1}^0 \geq \hat{e}_{i1}$, and cost functions are

$$(33)\quad C_i^2(a_{i1}, a_{i2}, l_{i2}) = \frac{\alpha_{i1} a_{i1}^2}{2} + \frac{\alpha_{i2} a_{i2}^2}{2} + \gamma_i a_{i1} a_{i2} + p_2 \left(l_{i2} - l_{i2}^0\right) = p_2 \left(\bar{e}_{i2} - l_{i2}^0\right) - \frac{p_2^2 \hat{\alpha}_{i1}}{2}$$

Case 2 is when $l_{i2}^0 < \hat{e}_{i2}$, $l_{i1}^0 < \hat{e}_{i1}$. If the firm participates in market 1 and l_{i2}^0 is distributed below the level of $\hat{e}_{i2}$ as shown in the graph, the firm cannot meet the

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[31] See the APPENDIX D.

regulation for the pollutant 2 at the point B since the amount of pollution that this firm is willing to emit $(\hat{e}_{i2})$ is greater than the initial distribution (l_{i2}^0) but it cannot participate in market 2. Therefore, it must just abate more of the pollutant 2 until $\hat{a}_{i2} = \overline{e}_{i2} - l_{i2}^0$, which is the last equality Kuhn-Tucker condition of the second case. This occurs at point L where $MC_{i1} = \lambda_{i1} < p_1, MC_{i2} = \lambda_{i2} > 0$. MC_{i1} decreases when the firm increases a_{i2} from the point B with a given level of a_{i1} since $\gamma_i < 0$ in the equation, $MC_{i1} = \alpha_{i1}a_{i1} + \gamma_i a_{i2} = p_1$. The MC_{i1} curve moves to the right in the left-hand side graph. At the point L, the firm can minimize the cost or maximize the profit by abating more of pollutant 1 because $MC_{i1} < p_1$ until the point C is reached $(\hat{a} \to \hat{a}^1 \; or \; \hat{e}_{i1} \to \hat{e}_{i1}^1)$. MC_{i1} increases along the new MC_{i1} curve in the left-hand side graph as the abatement for the pollutant 1 increases until $a_{i1} = \hat{a}^1$. The abatements and cost function are

$$
\begin{aligned}
&a_{i1} = \frac{p_1 - \gamma_i\left(\overline{e}_{i2} - l_{i2}^0\right)}{\alpha_{i1}}, \; a_{i2} = \overline{e}_{i2} - l_{i2}^0 \text{ because } l_{i2}^0 < \hat{e}_{i2} \\
(34)\quad &C_i^1(a_{i1}, a_{i2}, l_{i1}) = \frac{-\left[p_1 - \gamma_i\left(\overline{e}_{i2} - l_{i2}^0\right)\right]^2 + \alpha_{i1}\alpha_{i2}\left(\overline{e}_{i2} - l_{i2}^0\right)^2}{2\alpha_{i1}} + p_1\left(\overline{e}_{i1} - l_{i1}^0\right)
\end{aligned}
$$

If a firm participates in market 2 and initial distribution is given as $l_{i1}^0 < \hat{e}_{i1}$, then the same logic applies as above, and the abatements and cost function are

$$\begin{aligned} &a_{i1} = \bar{e}_{i1} - l_{i1}^0,\ a_{i2} = \frac{p_2 - \gamma_i\left(\bar{e}_{i1} - l_{i1}^0\right)}{\alpha_{i2}} \text{ because } l_{i1}^0 < \hat{e}_{i1} \\ &C_i^2(a_{i1}, a_{i2}, l_{i2}) = \frac{-\left[p_2 - \gamma_i\left(\bar{e}_{i1} - l_{i1}^0\right)\right]^2 + \alpha_{i1}\alpha_{i2}\left(\bar{e}_{i1} - l_{i1}^0\right)^2}{2\alpha_{i2}} + p_2\left(\bar{e}_{i2} - l_{i2}^0\right) \end{aligned} \tag{35}$$

Case 3 is when $l_{i2}^0 < \hat{e}_{i2},\ l_{i1}^0 \geq \hat{e}_{i1}$. If a firm participates in market 1 the abatement levels and cost function are summarized as

$$\begin{aligned} &a_{i1} = \frac{p_1 - \gamma_i\left(\bar{e}_{i2} - l_{i2}^0\right)}{\alpha_{i1}},\ a_{i2} = \bar{e}_{i2} - l_{i2}^0 \text{ because } l_{i2}^0 < \hat{e}_{i2} \\ &C_i^1(a_{i1}, a_{i2}, l_{i1}) = \frac{-\left[p_1 - \gamma_i\left(\bar{e}_{i2} - l_{i2}^0\right)\right]^2 + \alpha_{i1}\alpha_{i2}\left(\bar{e}_{i2} - l_{i2}^0\right)^2}{2\alpha_{i1}} + p_1\left(\bar{e}_{i1} - l_{i1}^0\right) \end{aligned} \tag{36}$$

But if a firm participates in market 2,

$$\begin{aligned} &a_{i1} = -\hat{\gamma}_i p_2,\ a_{i2} = \hat{\alpha}_{i1} p_2 \text{ because } l_{i1}^0 \geq \hat{e}_{i1} \\ &C_i^2(a_{i1}, a_{i2}, l_{i2}) = p_2\left(\bar{e}_{i2} - l_{i2}^0\right) - \frac{{p_2}^2 \hat{\alpha}_{i1}}{2} \end{aligned} \tag{37}$$

Case 4 is when $l_{i2}^0 \geq \hat{e}_{i2},\ l_{i1}^0 < \hat{e}_{i1}$, If a firm participates in market 1,

$$\begin{aligned} &a_{i1} = \hat{\alpha}_{i2} p_1,\ a_{i2} = -\hat{\gamma}_i p_1 \text{ because } l_{i2}^0 \geq \hat{e}_{i2} \\ &C_i^1(a_{i1}, a_{i2}, l_{i1}) = p_1\left(\bar{e}_{i1} - l_{i1}^0\right) - \frac{{p_1}^2 \hat{\alpha}_{i2}}{2} \end{aligned} \tag{38}$$

If a firm participates in market 2

$$\begin{aligned} &a_{i1} = \bar{e}_{i1} - l_{i1}^0,\ a_{i2} = \frac{p_2 - \gamma_i\left(\bar{e}_{i1} - l_{i1}^0\right)}{\alpha_{i2}} \text{ because } l_{i1}^0 < \hat{e}_{i1} \\ &C_i^2(a_{i1}, a_{i2}, l_{i2}) = \frac{-\left[p_2 - \gamma_i\left(\bar{e}_{i1} - l_{i1}^0\right)\right]^2 + \alpha_{i1}\alpha_{i2}\left(\bar{e}_{i1} - l_{i1}^0\right)^2}{2\alpha_{i2}} + p_2\left(\bar{e}_{i2} - l_{i2}^0\right) \end{aligned} \tag{39}$$

Case 1 seems likely in the real world when the initial distribution is given as

$l_{i1}^0 \geq \hat{e}_{i1}, l_{i2}^0 \geq \hat{e}_{i2}$. The special but reasonable case is $\bar{e}_{i1} = l_{i1}^0 > 0, \bar{e}_{i2} = l_{i2}^0 > 0$. This is the allocation that would be used in programs in which emission rights to (some) polluters are grandfathered based on pre-existing levels, especially for non-point source polluting firms. Baseline and credit programs, in which nonpoint polluters are allowed to sell credits if they reduce their emissions, would fit into exactly this case. In this case the firm does not have any legal obligation to abate or it has abundant initial distribution of license enough to not reduce emission; the transferable credit program is simply a positive incentive to reduce pollution. The firm participates in the market just to make profits by selling the abatement product, and a governmental agency mainly endeavors to facilitate the effectiveness of the multiple markets rather than to reduce pollution itself. We can find many of these examples in the real world. For example, a containment pond to create nutrient emission abatement credits for improving water quality might also be creating a wetland that can be exchanged in the market. At the same time, this has a role of reducing greenhouse gases and offers habitat for species. These complementary environmental goods for non-point source polluting firms may have little to do with governmental restriction on abatement or emission. In this chapter, we focus primarily on such cases.

The case 2, tight pollution control, is generally the typical case of traditional pollution reduction, for instance, SO_2 reduction, to protect from hazardous effects of pollution emission. The governmental agency has been reinforcing the environmental standard stricter than before as damage has increased and/or been accumulated.

Cases 3 and 4 are basically the same since the equations are symmetric depending on the market index 1 and 2, so that either case is analyzed in the same way. These cases will not be easily found as long as the environmental agency is rational and traces the complementarity. If one environmentally hazardous pollutant should be reduced, another complementary pollutant should also be reduced, so that these two pollutants should be regulated in a complementary way. It will not be very realistic that the agency will distribute one pollution license abundantly and the other complementary license scantly.

The Multiple Market problem with point and non-point sources

Let's assume that there are two types of polluting firms: Nonpoint source (NPS) firms and Point source (PS) firms. For the nonpoint firms we assume that we are in case 1 above where each firm i ($=1,2,\ldots n$) chooses which market to participate in and has abundant initial distribution of licenses.

The condition to sell in market 1 is rearranged as follows starting from $C_i^1 \leq C_i^2$.

(40) $\frac{p_1^2 \hat{\alpha}_{i2}}{2} - \frac{p_2^2 \hat{\alpha}_{i1}}{2} \geq p_1\left(\bar{e}_{i1} - l_{i1}^0\right) - p_2\left(\bar{e}_{i2} - l_{i2}^0\right)$

It is assumed that the initial distribution l_{i1}^0 and l_{i2}^0 are set as $\bar{e}_{i1} = l_{i1}^0, \bar{e}_{i2} = l_{i2}^0$. In this case it follows that:[32]

(41) If $\frac{p_1^2}{p_2^2} > \frac{\alpha_{i1}}{\alpha_{i2}}$, the firm sells in market 1;

(42) If $\frac{p_1^2}{p_2^2} < \frac{\alpha_{i1}}{\alpha_{i2}}$, the firm sells in market 2;

(43) If $\frac{p_1^2}{p_2^2} = \frac{\alpha_{i1}}{\alpha_{i2}}$, the firm is indifferent between market 1 or 2.

The cost functions are summarized as:

(44) $C_i^1(a_{i1}, a_{i2}) = -\frac{\hat{\alpha}_{i2} p_1^2}{2}$, for the firms selling in market 1

(45) $C_i^2(a_{i1}, a_{i2}) = -\frac{\hat{\alpha}_{i1} p_1^2}{2}$, for the firms selling in market 2

These cost functions are negative so that the negative cost functions become the profit functions, that is to say, $-C_i^j(\cdot) = \pi_i^j(\cdot)$.

We assume that the point source firms in our model *t* (= *n+1, n+2,..., m*) do not produce multiple pollutants; either they emit pollutant 1 or pollutant 2, or, mathematically equivalently, they produce both pollutants but without an interaction

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[32] This simplifies as follows:
$\frac{p_1^2 \hat{\alpha}_{i2}}{2} \geq \frac{p_2^2 \hat{\alpha}_{i1}}{2} \Rightarrow \frac{p_1^2}{p_2^2} \geq \frac{\hat{\alpha}_{i1}}{\hat{\alpha}_{i2}} \Rightarrow \frac{p_1^2}{p_2^2} \geq \frac{\alpha_{i1}}{\alpha_{i2}}$ since $\alpha_{i1}\alpha_{i2} - \gamma_i^2 > 0$.

term γ. The key point is that their cost minimization problem is additively separable, and they will minimize the cost of abating pollutant 1 without reference to the level of abatement of pollutant 2. They are allowed to participate in either market. The initial distribution will not matter to their optimal level of abatement; they will always abate up to the point where the marginal benefit equals the price. If a firm received initial distribution of license that does not fully satisfy its need to reduce emission, then, the firm would buy the licenses supplied by non-point source firms in the market, say, $l_{t1}^{d} = l_{t1} - l_{t1}^{0} > 0.$

A point source firm would minimize the following cost function that does not have an interaction term between a_{t1} and a_{t2}.

$$(46)\quad \begin{aligned} &\underset{a_{t1},a_{t2},l_{t1},l_{t2}}{Min}\ C_t(a_{t1},a_{t2},l_{t1},l_{t2}) = \underset{a_{t1},a_{t2},l_{t1},l_{t2}}{Min}\ \frac{\alpha_{t1}a_{t1}^{\ 2}}{2} + \frac{\alpha_{t2}a_{t2}^{\ 2}}{2} + p_1\left(l_{t1} - l_{t1}^{0}\right) + p_2\left(l_{t2} - l_{t2}^{0}\right) \\ &s.t.\quad \bar{e}_{tj} - l_{tj} \le a_{tj},\ j = 1,\ 2 \end{aligned}$$

If the interior solution for the point source firms is assumed, it will make a decision when $MC_{tj} = \alpha_{tj}a_{tj} = p_j$ with $\bar{e}_{tj} - l_{tj} - a_{tj} = 0,\ j = 1,2$. The solution and cost functions would be

$$(47)\quad \begin{aligned} &a_{t1} = \frac{p_1}{\alpha_{t1}},\ a_{t2} = \frac{p_2}{\alpha_{t2}} \\ &C_t(a_{t1},a_{t2},l_{t1},l_{t2}) = p_1\left(\bar{e}_{t1} - l_{t1}^{0}\right) + p_2\left(\bar{e}_{t2} - l_{t2}^{0}\right) - \left(\frac{p_1^2}{2\alpha_{t1}} + \frac{p_2^2}{2\alpha_{t2}}\right) \end{aligned}$$

where $\bar{e}_{tj} \geq e_{tj} > l_{tj}^{0}, \forall j = 1,2$

We will make some assumptions to simplify the simulation analysis which follows this section. First, only one PS firm exists but it is still a price taker. Second, this firm is very cost-inefficient for abatements since its abatement cost is too high, so that it will demand credits from the relatively efficient NPS polluters. Third, social abatement cap is set at the level, $\bar{e}_{tj} - l_{tj}^{0} = A_j^{**}$. This implies that the PS firm buys all licenses for pollutant 1 and 2 which all NPS firms supply in the market.[33] Let's assume the cost function of the PS firm is $g_t(a_{t1}, a_{t2}) = \frac{\alpha_{t1} a_{t1}^2}{2} + \frac{\alpha_{t2} a_{t2}^2}{2} + k_{t1} a_{t1} + k_{t2} a_{t2}$. According to the assumptions above, the solution of this firm's cost minimization would be:

$$MC_{t1} > \lambda_{t1}, MC_{t2} > \lambda_{t2},\ a_{t1} = a_{t2} = 0$$
$$\bar{e}_{t1} = l_{t1} > 0,\ \bar{e}_{t2} = l_{t2} > 0,\ p_1 = \lambda_{t1},\ p_2 = \lambda_{t2}$$
$$C_t(a_{t1} = a_{t2} = 0) = p_1\left(l_{t1} - l_{t1}^{0}\right) + p_2\left(l_{t2} - l_{t2}^{0}\right) = p_1 l_{t1}^{d} + p_2 l_{t2}^{d} = p_1 A_1^{**} + p_2 A_2^{**}$$

The NPS firms supply abatements without purchasing those and one PS firm demands all credits without any abatements. The PS firm's cost function becomes the costs of purchasing the social abatement cap which collapses when cost functions of all

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[33] $\bar{e}_{tj} - l_{tj} = \bar{e}_{tj} - (l_{tj}^{d} + l_{tj}^{0}) \leq a_{tj}$, then $A_j^{**} - l_{tj}^{d} \leq a_{tj} = 0.$

NPS firms and the PS firm are aggregated[34] since we assumed that the markets are perfectly competitive and there are no transaction costs. Actually, the social abatement cost function ends up with the summation of the *n* NPS firms' abatement cost functions since the PS firm does not abate and terms for transaction of licenses between the NPS firms and the PS firm vanish.

The Solution algorithm for the second best case

In our simulation analysis, we are able to find analytical solutions to the case when multiple markets are allowed. However, when polluters are only allowed to sell credits in one market, a numerical solution method is required. Here we outline NPS firms are ordered in terms of the ratio $(\alpha_{i1} / \alpha_{i2})$.

The market equilibrium is defined as a division k and a price vector, p_1, p_2 subject to three conditions. (1) Out of *n* firms, firms *i=1…k* participate in market 1. The k^{th} participant will be that with the highest ratio $\frac{\alpha_{k1}}{\alpha_{k2}}$. (2) The constraints, $\sum_{i=1}^{k} \hat{a}_{i1} \geq A_1^{**}$ and $\sum_{i=k+1}^{n} \hat{a}_{i2} \geq A_2^{**}$ must be satisfied, where A_1^{**} and A_2^{**} are the total number of credits

---

[34] $\sum_j p_j \left(l_{tj} - l_{tj}^0\right) + \sum_i \sum_j p_j \left(l_{ij} - l_{ij}^0\right),\ l_{ij}^0 = \bar{e}_{ij}$

$$= \sum_j p_j l_{tj}^d - \sum_i \sum_j p_j \left(\bar{e}_{ij} - l_{ij}\right) = \sum_j p_j A_j^{**} - \sum_j p_j A_j^{**} = 0 \ .$$

that must be purchased by the point sources in markets 1 and 2 respectively, and $\hat{a}_{i1}$ and $\hat{\hat{a}}_{i2}$ are abatements committed to markets 1 and 2 respectively. (3) The resulting abatement levels of the division k must yield the least cost way to satisfy the abatement targets.

The first step is to the participants in terms of $\frac{\alpha_{i1}}{\alpha_{i2}}$. Let the *k*th participant to be the one with the highest ratio such that the firm participates in market 1. There are *n*−1 possible divisions, from *k*=1 to *k*=*n*−1. For an each of these possible divisions, the first step is to find the price ratio that would support this division. For the *k*th division, it must hold that

$$(48)\quad \frac{\alpha_{k,1}}{\alpha_{k,2}} < \frac{p_1^2}{p_2^2} \text{ and } \frac{\alpha_{k+1,1}}{\alpha_{k+1,2}} > \frac{p_1^2}{p_2^2}.$$

A market equilibrium supporting a division at *k* must supply A_1^{**} and A_2^{**} credits from the firms participating in each market. It must hold that[35]

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[35] Total SM supplies in the end include the complementary by-product abatements supplied by the firms that participate in the other market, i.e., $\hat{\hat{a}}_{i1}, \hat{a}_{i2}$.

$$AS_1^{**} = \sum_{i=1}^{k} \hat{a}_{i1} + \sum_{i=k+1}^{n} \hat{\hat{a}}_{i1} = \sum_{i=1}^{k} \hat{\alpha}_{i2} p_1 + \sum_{i=k+1}^{n} \left(-\hat{\gamma}_i p_2\right),$$

$$AS_2^{**} = \sum_{i=1}^{k} \hat{a}_{i2} + \sum_{i=k+1}^{n} \hat{\hat{a}}_{i2} = \sum_{i=1}^{k} \left(-\hat{\gamma}_i p_1\right) + \sum_{i=k+1}^{n} \left(\hat{\alpha}_{i1} p_2\right)$$

(49) $\sum_{i=1}^{k} \hat{a}_{i1} = \sum_{i=1}^{k} \hat{\alpha}_{i2} p_1 \geq A_1^{**}$ and $\sum_{i=k+1}^{n} \hat{\hat{a}}_{i2} = \sum_{i=k+1}^{n} \hat{\alpha}_{i1} p_2 \geq A_2^{**}$

If the equations are rearranged in terms of p_1 and p_2, then,

(50) $p_1 \geq \dfrac{A_1^{**}}{\sum_{i=1}^{k} \hat{\alpha}_{i2}}$ and $p_2 \geq \dfrac{A_2^{**}}{\sum_{i=k+1}^{n} \hat{\alpha}_{i1}}$

We can therefore set up the starting prices as

(51) $p_1^0 = \dfrac{A_1^{**}}{\sum_{i=1}^{k} \hat{\alpha}_{i2}}$ and $p_2^0 = \dfrac{A_2^{**}}{\sum_{i=k+1}^{n} \hat{\alpha}_{i1}}$

From this starting point, we can then raise p_1 or p_2 until the following inequalities hold,

(52) $\dfrac{\alpha_{k,1}}{\alpha_{k,2}} \leq \dfrac{p_1^2}{p_2^2} = \dfrac{(p_1^0 + \Delta_1)^2}{(p_2^0 + \Delta_2)^2} \leq \dfrac{\alpha_{k+1,1}}{\alpha_{k+1,2}}$

If $\dfrac{(p_1^0)^2}{(p_2^0)^2} < \dfrac{\alpha_{k,1}}{\alpha_{k,2}}$, then p_1 is raised until $\dfrac{(p_1)^2}{(p_2^0)^2} = \dfrac{\alpha_{k,1}}{\alpha_{k,2}}$, i.e. $p_1 = p_2^0 \left(\dfrac{\alpha_{k,1}}{\alpha_{k,2}} \right)^{0.5}$ and $p_2 = p_2^0$.

If $\dfrac{(p_1^0)^2}{(p_2^0)^2} > \dfrac{\alpha_{k+1,1}}{\alpha_{k+1,2}}$, then p_2 is raised until $\dfrac{(p_1^0)^2}{(p_2)^2} = \dfrac{\alpha_{k+1,1}}{\alpha_{k+1,2}}$, i.e. $p_2 = p_1^0 \left(\dfrac{\alpha_{k+1,1}}{\alpha_{k+1,2}} \right)^{-0.5}$ and $p_1 = p_1^0$.

Once the prices that will support the k^{th} division are found, the total costs of that division are identified:

(53) $TC = \sum_{i=1}^{k} C_i^1(\hat{a}_{i1}, \hat{a}_{i2}) + \sum_{i=k+1}^{n} C_i^2(\hat{\hat{a}}_{i1}, \hat{\hat{a}}_{i2}) + \sum_{t=n+1}^{m} C_t(a_{t1}, a_{t2}) = \sum_{i=1}^{k} g_i^1(\hat{a}_{i1}, \hat{a}_{i2}) + \sum_{i=k+1}^{n} g_i^2(\hat{\hat{a}}_{i1}, \hat{\hat{a}}_{i2})$

This simplifies to[36]

$$(54)\quad TC = \sum_{i=1}^{k}\left(-\frac{\hat{\alpha}_{i2}p_1^2}{2}\right) + \sum_{i=k+1}^{n}\left(-\frac{\hat{\alpha}_{i1}p_2^2}{2}\right)$$

After finding the total cost for all possible divisions of the set of producers, the market equilibrium is the one that minimizes costs.

5.3. Simulation Analysis

In this section, we present the results of the simulation analysis that is used to evaluate the relative merits of allowing double dipping in a second-best economy in which the aggregate cap is set suboptimally. The purpose of the simulation analysis is to explore the theoretical properties of the problem in the spirit of Judd (1997). Hence, the parameter values are not chosen to reflect any particular "real-world" economic system, but are used instead to explore the general relationships of the model.

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[36] See the APPENDIX D for proof.

5.3.1. Parametric conditions of the model for simulation

We limit our analysis to sets of parameter values that yield positively sloped individual firm and social supply functions. This requires the following parametric conditions to hold:

(55)

$$\alpha_{ij} > 0,\ \gamma_i < 0, \Omega_j > 0, \theta_j > 0,\ j = 1,2$$
$$\alpha_{i1}\alpha_{i2} - \gamma_i^2 > 0$$
$$\sum_i \hat{\alpha}_{i1} \sum_i \hat{\alpha}_{i2} - (\sum_i \hat{\gamma}_i)^2 > 0 \text{ where } \hat{\alpha}_{i1} = \frac{\alpha_{i1}}{\alpha_{i1}\alpha_{i2} - \gamma_i^2},\ \hat{\alpha}_{i2} = \frac{\alpha_{i2}}{\alpha_{i1}\alpha_{i2} - \gamma_i^2},\ \hat{\gamma}_i = \frac{\gamma_i}{\alpha_{i1}\alpha_{i2} - \gamma_i^2}$$

We also limit our analysis to the concave social benefit function that limits its domain where the marginal net benefit is nonnegative.

(56) $A_j \le \dfrac{\Omega_j}{\theta_j}$ where $A_j = \{ j = 1,2 \mid A_j^*,\ A_j^{**} \}$.

However, the equation (56) is guaranteed by the positive price condition, $p_j \ge 0$ where $p_j = \{ j = 1,2 \mid p_j^*, \hat{p}_j, p_j^{MM}, p_j^{SM} \}$. These conditions ensure that the equilibrium prices are greater than zero and aggregate abatement is greater than zero.

5.3.2. Simulation methodology

We used Matlab programming language to run a simulation model. For the results presented here, we limit ourselves to the case where the number of nonpoint source firms (*i*), point source firms (*t*), pollutants (*j*) are $i=10$, $t=1$, $j=2$, respectively.

In each simulation, the parameters of benefit and cost functions ($\Omega_j, \theta_j, \alpha_{ij}, \gamma_i$) are initially chosen randomly using uniform random number generation method until the positive price conditions are met during the 50 loops of the random number generation process.[37]

The intercept parameters of marginal benefit (MB) function, Ω_j, are initially chosen between 0.1 and 10 in order to scale up magnitude so that positive prices are easily obtained without going through continually iterated loop and enough net benefits can be earned. The slope parameters of the MB function, θ_j, are chosen between 0 and 1. The parameters of the cost functions, α_{ij}, are selected between 0.2 and 3 to see when the

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[37] If positive price conditions are not satisfied until the 50 loops, negative prices could be generated and these points are differentiated in the simulation graphs, being ignored in our analysis.

single market dominates. The other cost function parameters, γ_i, are randomly chosen, but rejected until the conditions $\alpha_{i1}\alpha_{i2} - \gamma_i^2 > 0$ are satisfied.

With these initially chosen parameters, each market equilibrium, { p_j^*, a_{ij}^*, A_j^* }, { $p_j^{MM}, a_{ij}^{MM}, A_j^{**}$ }, { $p_j^{SM}, a_{ij}^{SM}, A_j^{**}$ }, was computed, and the corresponding social welfares were calculated using the social benefit and cost functions. Then, comparative static analysis was carried out by varying one parameter or a set of parameters at a time. Representative results are presented in the figures below, which indicate the qualitative properties of different types of results that might be encountered. We focus on how the social welfares of all three cases, the first best case (FB), the multiple market case (MM) and single market case (SM) in the second best case (SB), will be changing as one parameter or a set of those parameters changes. The equations that form the core of the simulation model are provided in APPENDIX E.

5.3.3. Simulation results

As we have discussed above, when a second-best cap is set on aggregate emissions, it is not known whether allowing multiple markets is efficient. If the cap is set too low, then it can be preferred to force polluters to choose one market or the other, ensuring that additional emission reductions are achieved due to the complementarity. The simulation analysis seeks to help us understand the conditions under which multiple markets might be preferred. This analysis can be thought of as simulated comparative statics analysis – holding all other parameters constant, one parameter is varied and the consequences for net benefits in the alternative institutional structures are calculated.

For notation, every index (*j*=1, 2) which follows capital letters denotes market 1 and 2. For example, MB_1 represents marginal benefit of market 1, or SM_1 and MM_2 represent the single market case in market 1 and the multiple markets case in market 2. When we want to explain an overall market, there is no index in those capital letters such as SM or MM which stand for overall single or multiple markets including market 1 and 2. Unless indicated, any other notation will be used in the same way.

Changes of the slopes of Marginal Benefit (MB) curves: θ_j

In the very simple graphical model discussed above in Figure V-4, allowing multiple markets tended to be more efficient as the marginal benefit curve became steeper. Does this effect continue in a more general setting? We begin by considering changes in the slope of one of the marginal benefit curves, θ_1. As θ_1 increases with an intercept remaining unchanged, social benefits will decrease because total benefits are integrated underneath a new MB_1 curve which is steeper than before.

Figure V-9a through Figure V-9e present the total net benefits in the economy under the first-best setting (+), and in the second best options when trading in only one market is allowed (o), and when multiple markets are allowed (*). All graphs except for Figure V-9e show that all net benefits decline monotonically as θ_1 increases. Of course, the FB case (+) always dominates since it does not have any social welfare loss. The FB graphs will not be drawn unless the FB case is needed to follow up the analysis because our main focus is on the relative performance of the MM and SM cases.

The simulation analysis shows us several things about the relative merits of the MM and SM structures. Figure V-9aa is typical of many of the simulated results; it shows that once θ_1 exceeds some level, the MM policy dominates.

Figure V-9b and Figure V-9e show a strong MM dominance over the entire range of increase in θ_1. The MM dominance pattern also holds in Figure V-9c when both slope parameters, θ_1 and θ_2, increase simultaneously and MM catches up with SM. Hence, our simulation results support our hypothesis that MM tends to be more efficient than SM as the MB curve becomes steeper. In most of our simulations the MM dominated, but this is not general as seen in Figure V-9d[38] nor necessarily reflective of conditions that might exist in a true market.

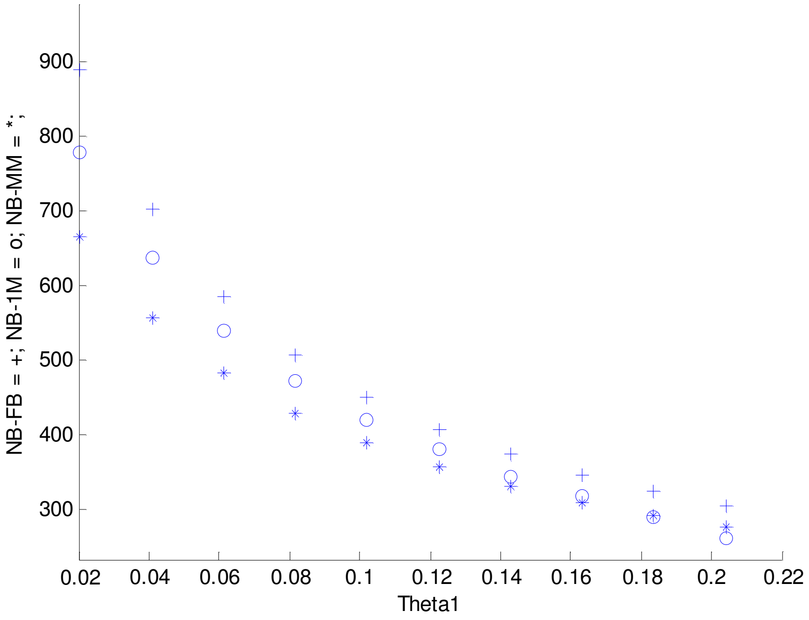

Figure V-9a. Net benefits change with a demand slope parameter changing 1

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[38] The first two points violate the positive price conditions so that they are ignored in the analysis.

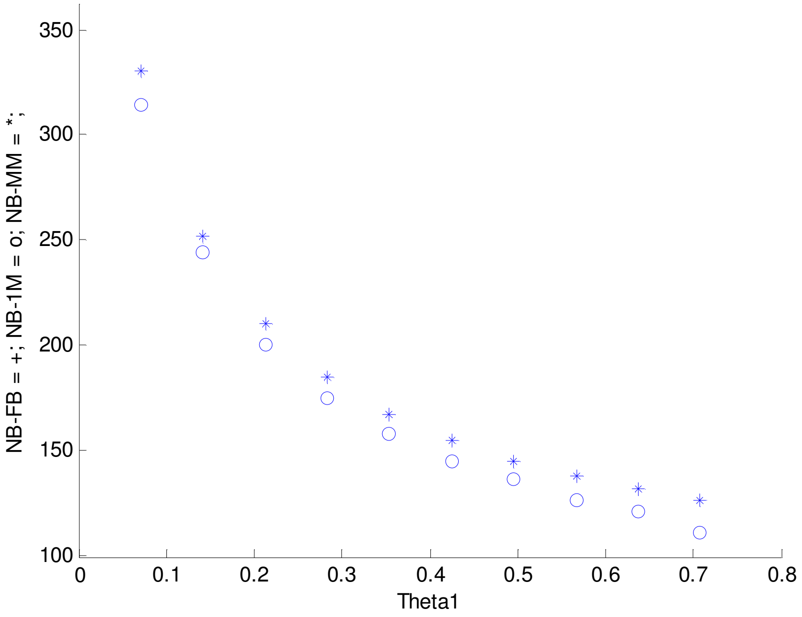

Figure V-9b. Net benefits change with a demand slope parameter changing 2

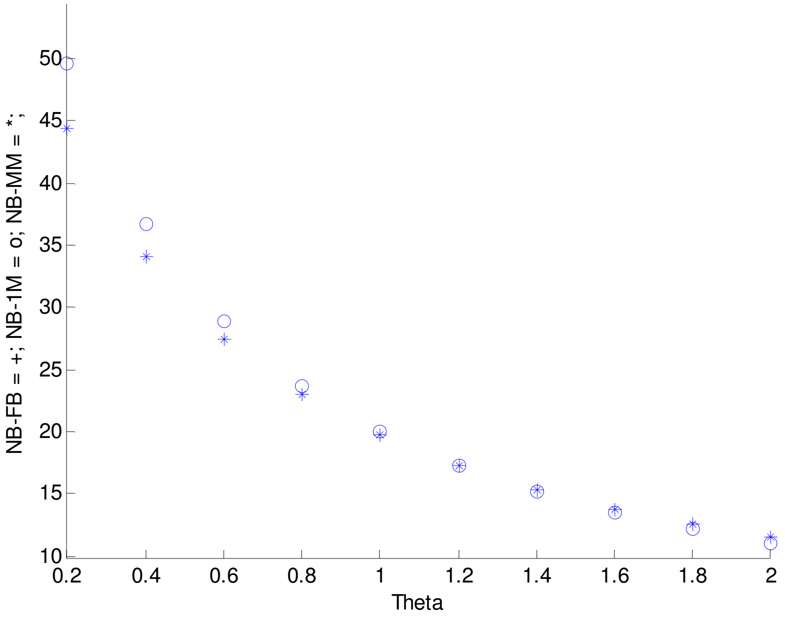

Figure V-9c. Net benefits change with demand slope parameters changing 3

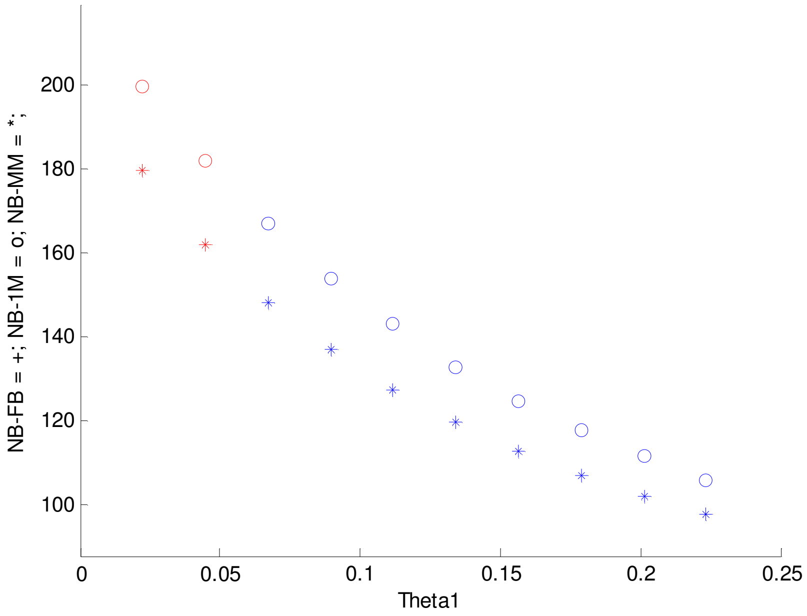

Figure V-9d. Net benefits change with a demand slope parameter changing 4

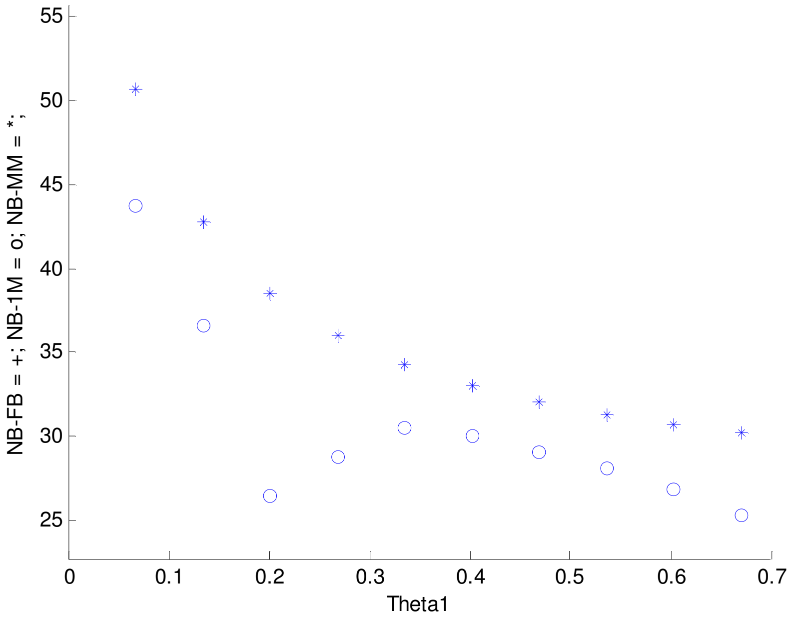

Figure V-9e. Net benefits change with a demand slope parameter changing 5

There are some anomalies to this general finding, however. Figure V-9d shows that SM (o) can dominate over a wide range even the scale of θ_1 increases. But differences between net benefits of SM and MM gradually decline as θ_1 increases. One reason this could occur is that even if MM_1 dominates in market 1, SM_2 dominance effect with the relatively steeper supply curve than MB_2 curve in market 2 is greater than MM_1 dominance effect with the relatively steeper MB_1 curve than the supply curves in market 1.[39]

In Figure V-9e, MM is dominating but it presents another exceptional case in the sense that MM overall net benefits decline gradually in a stable way but SM net benefit jumps up and down irregularly. This reflects a very special characteristic of a SM supply curve. The SM supply curve is very different from FB and MM supply curves which are continuous smooth lines. Each SM participant compares the squared market prices ratio $(p_1 / p_2)^2$ to the cost function slope parameter ratio $(\alpha_{i1} / \alpha_{i2})$ to minimize their costs and *k* firms participate in market 1 out of *n* firms. Hence, the slope of the SM

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[39] Recall that indexes 2 and 1 in SM_2 and MM_1 denote market 2 and 1. SM_2 dominance effect is a degree that the single market case in market 2 is dominant compared to the multiple market case in market 2. MM_1 dominance effect is defined likewise.

supply curve becomes flatter as one more firm participates supplying more in that market. The supply curve slopes of MM_1 and SM_1 are numerically expressed as $1/\sum_{i=1}^{n}\hat{\alpha}_{i2}$ and $1/\sum_{i=1}^{k}\hat{\alpha}_{i2}$ respectively, so that the slope of the SM_1 supply curve is always greater than those of the FB_1 and MM_1 supply curves because $\sum_{i=1}^{n}\hat{\alpha}_{i2} > \sum_{i=1}^{k}\hat{\alpha}_{i2}$. We can draw the SM supply curve (SMS) as is shown in Figure V-9f.

The dotted horizontal lines between the positively sloped segments of SMS_1 indicate that the marginal firm is indifferent between two markets on which market to enter into. Total SM supply curve ($TSMS_1$) is defined as the SM_1 supplies transacted in market 1 plus supplies of complementary abatements by the market 2 participants. If one more firm participates in market 1, one less firm participates in market 2 and the complementary abatements produced by market 2 participants will decrease. Hence, the $TSMS_1$ will get closer to SM_1 as the number of participants in market 1 increase. The initial abatement price of SM_1 is determined at the point where the vertical second-best social cap (A_1^{**}) crosses SMS_1 and then adjusted. At this price level of P_1^{SM}, $TSMS_1$ supplies include the complementary abatements produced by the market 2 participants, which determines the size of welfare loss.

Under these irregular SMS and TSMS, the slope, location and difference of each

SMS and TSMS segment are uncertain so that it is very difficult to locate it in a graphical setting and to compare its welfare loss to those of the FB and MM cases. Because of these discontinuous shifts in the supply, it is possible for the SM net benefits to jump up or down as the MB_1 curve becomes steeper and touches a steeper segment of SMS_1 and $TSMS_1$, in which participants of market 1 decrease. Dominance between SM_1 and MM_1 depends on the slope and location and difference of each SMS_1 and $TSMS_1$ segment at the market price as well as the relative slopes of the MB_1 and MM_1 supply curve. Overall dominance of SM and MM in two markets becomes more complicated when the dominance of SM_2 and MM_2 in market 2 is considered simultaneously along with that of SM_1 and MM_1.

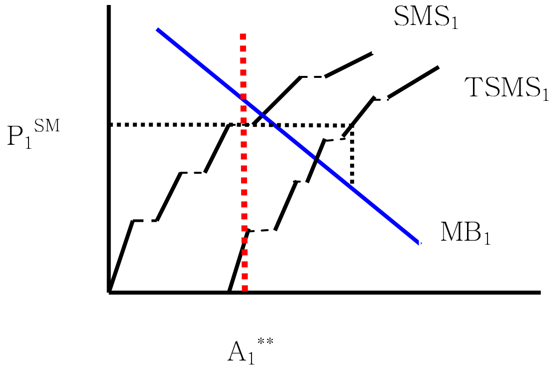

Figure V-9f. Marginal Benefit (MB) & single market supply (SMS1 & TSMS1)

Changes of the intercepts of Marginal Benefit (MB) curves: Ω_j

We now take a look at the intercept of the MB curve, Ω_j. Figures below[40] present a variety of patterns that were identified in the simulation analysis. When Ω_1 increases beginning from an initially chosen random number between 0.1 and 10, the intercept of MB_1 curve moves to the right so that net benefits of FB, MM and SM will increase. However, as the intercept parameter increases, the difference between net benefits of FB and MM *or* SM tend to increase because A_1^* increases relatively faster than A_1^{**} does due to the steeper agency's misperceived supply curve to set the second best cap than the slope of AS_1^{FB} and AS_1^{MM} and the difference between A_1^* and A_1^{**} gets larger.[41]

As we discussed above, it is not possible to judge based on theory whether the MM or SM is preferred. However, we could expect that net benefits of MM and SM will

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[40] The first point in Figure V-10c and the first four points in Figure V-10e violate the price positivity condition.

[41] The slope of agency's misperceived supply curve and those of FB and MM supply curves are $\left(\partial p / \partial AS\right) = \left(1 / \sum_i (1/\alpha_{i1})\right)$ and $\left(1 / \sum_i \hat{\alpha}_{i2}\right)$. Simple algebra can prove that the former is strictly greater than the latter under the parameter conditions we maintain.

increase and those differences may not be big since the slopes of MB and supply curves stay the same. The simulation graphs show this expectation except for Figure V-10e.

Depending on the SM supply curves, say, SMS_1 and $TSMS_1$, which correspond to increasing A_1^{**} as MB_1 curve is expanded to the right, MM dominates (Figure V-10a and Figure V-10b) or SM dominates (Figure V-10c and Figure V-10d). These figures are consistent with our expectation regardless of MM or SM dominance in the sense that the net benefits of MM and SM are being traced on the similar track. The relative performance of MM and SM is not much affected.

Figure V-10e is an exceptional case. SM net benefit is increasing and maximized, and then it begins to decrease and the differences of net benefits between MM and SM increase. This would be caused by changes of SM participants in both of market 1 and 2 during the course of choosing one market for firms to join. SM_1 participants would face a flatter SMS_1 segment and SM_2 participants would encounter a steeper SMS_2 segment when MB_1 curve is expanded and MM dominates. Hence, an increase in the intercept of the marginal benefit curve in one of the two markets can lead to a change as to which policy is preferred when the number of each market participants change.

The simulation analysis, therefore, generally indicates that for the most part, changes in the intercept of the marginal benefit curve do not affect the relative performance of the MM or SM programs. Only if the number of SM participants of market 1 and 2 changes and firms face steeper or flatter segments of their supply curves as a result do we find that the intercept changes are important to determining which policy might be preferred.

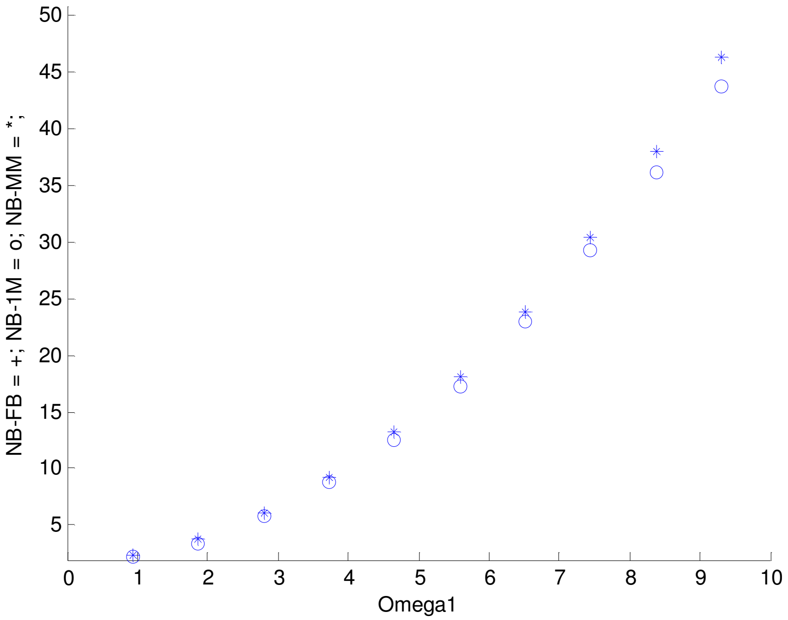

Figure V-10a. Net benefits change with a demand intercept parameter changing 1

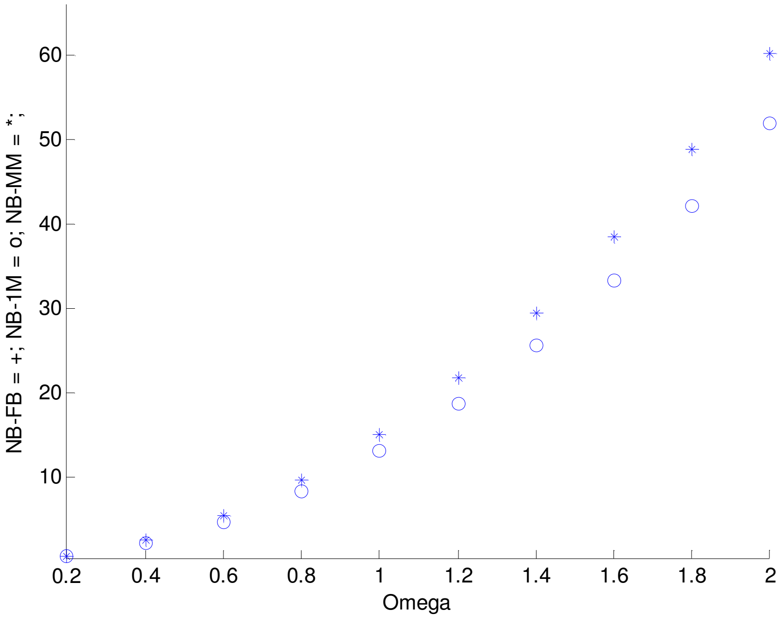

Figure V-10b. Net benefits change with demand intercept parameters changing 2

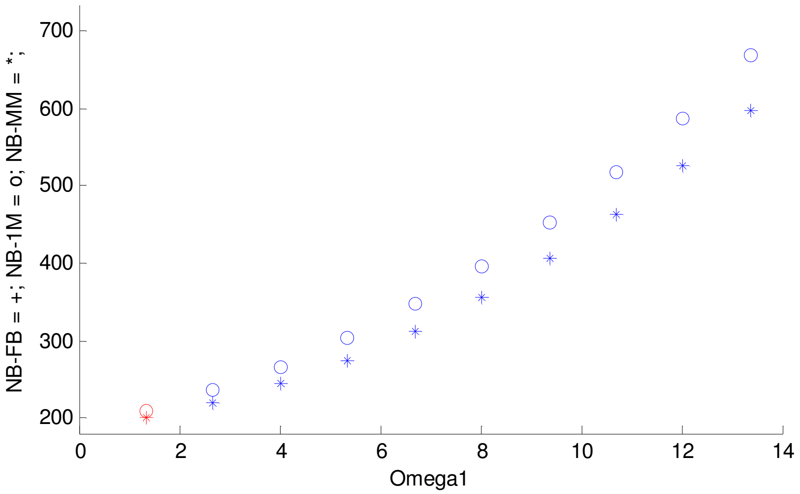

Figure V-10c. Net benefits Change with a demand intercept parameter changing 3

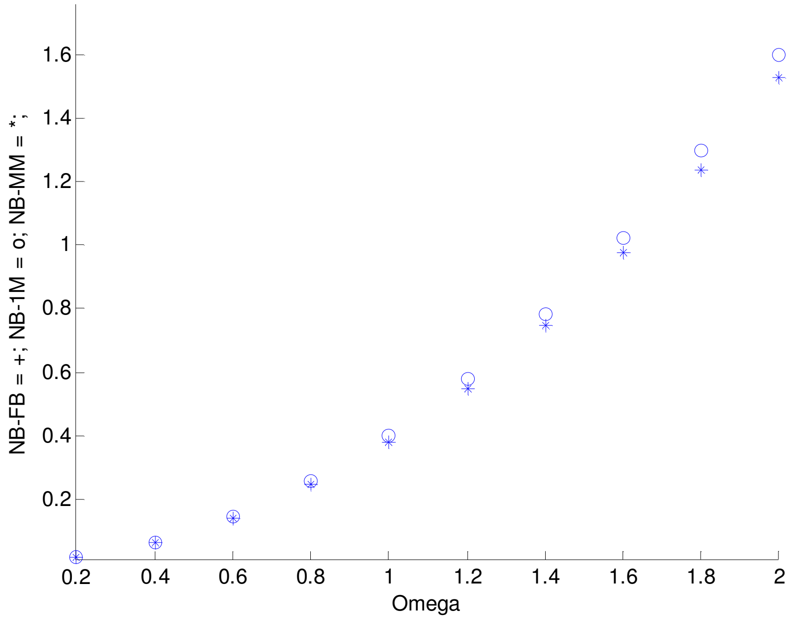

Figure V-10d. Net benefits change with demand intercept parameters changing 4

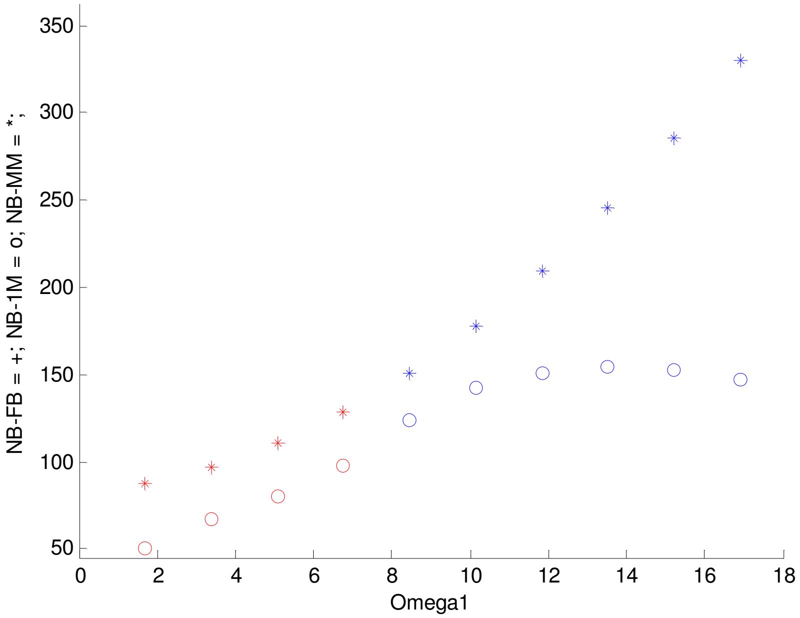

Figure V-10e. Net benefits change with a demand intercept parameter changing 5

Changes of the supply curve parameter: α_{ij}[42]

We next consider the effect of changes in α_{i2}, the supply curve parameter in market 2. Changes in the parameter affect all of the slopes and intercepts of the supply curves of FB, MM and SM in both markets.[43] The agency's misperceived supply curve of market 2 also is affected. However, the agency's misperceived supply curve of market 1 remains the same so that the second best cap, A_1^{**}, still does not change even after α_{i2} increases. These supply side changes become much more complicated than the case of the demand side where only one of the MB curve parameters in one or both market (s) changed.

In market 1, increasing α_{i2} results in decreasing $\hat{\alpha}_{i2}$ and increasing slopes of FB$_1$ and MM$_1$ supply curves.[44] The intercepts of FB$_1$ and MM$_1$ supply curves increase.[45]

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[42] The first point in each of Figure V-11a, Figure V-11b and Figure V-11c violates the positive price conditions.

[43] Note that every slope and intercept parameter of the supply curves have the α_{i2} element except for the agency's misperceived supply curve of market 1.

[44] The slopes of the supply curves in market 1 depend on the cost function coefficient of abatement 2, say $\frac{\partial p_1}{\partial A_1} = \frac{1}{\sum_i \hat{\alpha}_{i2}}$ where $\hat{\alpha}_{i2} = \frac{\alpha_{i2}}{\alpha_{i1}\alpha_{i2} - \gamma_i^2}$, and $\frac{\partial \hat{\alpha}_{i2}}{\partial \alpha_{i2}} = \frac{-\gamma_i^2}{\left(\alpha_{i1}\alpha_{i2} - \gamma_i^2\right)^2} < 0$. Thus, increase of α_{i2} leads to increasing the slope of the supply curve of market 1 steeper.

The supply curves in market 2 move in the same direction as those in market 1. The supply curves shift to the left in both markets with the slopes getting steeper and the intercepts increasing, and the FB and MM net benefits decrease. The simulation results show that the FB and MM net benefits decrease as α_{i2} increases as are expected. The net benefit of SM is also expected to decrease but the simulation does not show this in a unilateral way. Only Figure V-11a shows this continually decreasing trend of the net benefit.

This is due to the uncertainty of the SM supply curves again. The lower segments of the SM supply curve shifts less in magnitude than its corresponding upper segments do as a result of α_{i2} increase because the supply curve is drawn differently accumulated in each segment of it as the number of participants in a market increase. Further, there can be any change of indifference region or interval where participation in market 1 or 2 is identical between each positively sloped supply curve. The SM supply

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[45] The intercepts of supply curves are $\frac{p_2 \sum_i \hat{\gamma}_i}{\sum_i \hat{\alpha}_{i2}}$ and $\frac{\partial \hat{\gamma}_i}{\partial \alpha_{i2}} = \frac{-\gamma_i \alpha_{i1}}{(\alpha_{i1}\alpha_{i2} - \gamma_i^2)^2} > 0$. As α_{i2} increases, $\hat{\alpha}_{i2}$ decreases and $\hat{\gamma}_i$ increases so that the intercept increases. In other words, the supply decreases at a given price, p_1.

curves do not shift simply to the left after α_{i2} increases but can cross the previous supply curves before changes. Therefore, if SM$_1$ equilibrium is realized on the lower segment of the SM$_1$ supply curve in market 1, its net benefit may decrease or increase or even unchanged. But on the upper segment, cost increasing effect can be distinct due to the accumulated adding up effect of α_{i2} increase to the slope and intercept components.

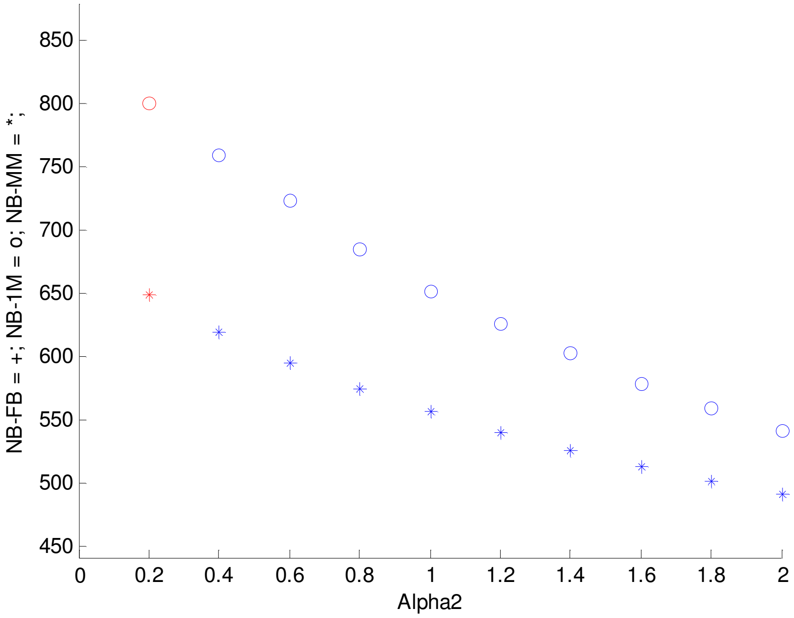

Figure V-11a. Net benefits change with a supply slope parameter changing 1

If participants in market 1 increase as α_{i2} increases for the cost function slope parameter ratio $(\alpha_{i1} / \alpha_{i2})$ decreases relative to any squared market prices ratio $(p_1 / p_2)^2$, firms participating in market 1 will face the upper segment of SM_1 supply curve and its cost increasing effect can be distinctive. But in market 2 where participants decrease, cost effect is uncertain on the lower segment but it is expected that cost will not change much compared to market 1. Hence, SM net benefit can decrease eventually in the overall markets as in Figure V-11c and Figure V-11d. Changes of SM supply curve segments in magnitude do matter as well as the slope and location and difference of each SMS and TSMS segment do. But it is still uncertain that the SM net benefit will increase or decrease. It is observed that the SM net benefits in Figure V-11b show increasing trend different from those in the other graphs. But this is the case of changes in both of α_{i1} and α_{i2} and the scale of those parameters are small compared to other simulation cases.

As for dominance between MM and SM, the simple theoretical model presented earlier suggests that as the slope of the supply curve or MC curve increases, there is a tendency for the welfare cost of the allowing multiple markets to increase and for the welfare cost of allowing participation in only a single-market to decline. Hence, as the slope of the supply curve increases, there is a tendency for SM to dominate. And this is confirmed in the numerical analysis. Every graph below except for Figure V-11d shows that SM dominates or moves to approach MM as the slopes of the supply curves get steeper when α_{i2} increases to a certain level. The advantage of SM almost catches up with that of MM in Figure V-11c, and the catch-up effect is distinctive in Figure V-11b as two parameters α_{i1} and α_{i2} change simultaneously.

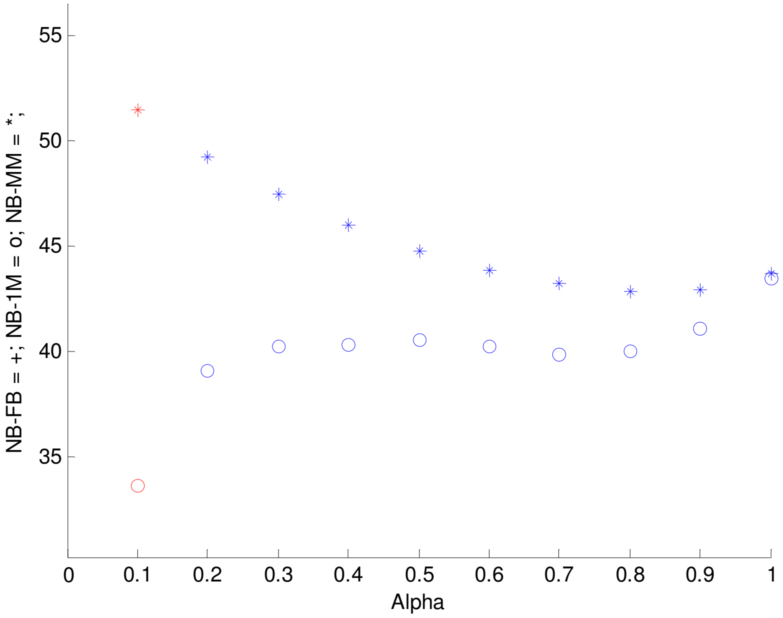

Figure V-11b. Net benefits change with supply slope parameters changing 2

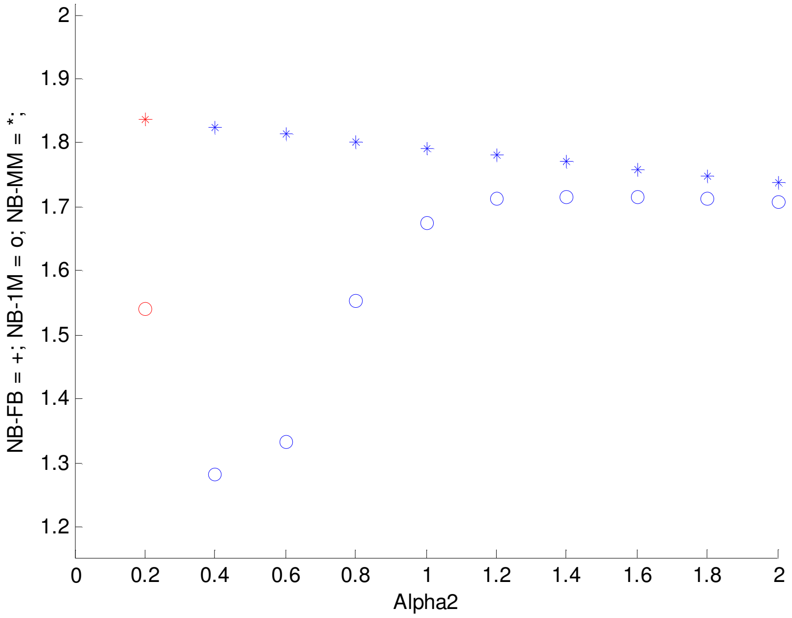

Figure V-11c. Net benefits change with a supply slope parameter changing 3

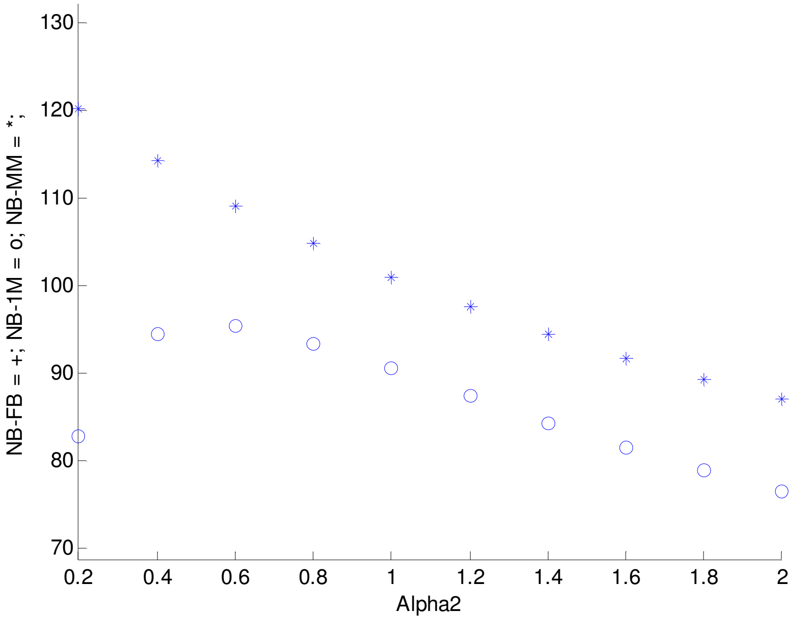

Figure V-11d. Net benefits change with a supply slope parameter changing 4

In Figure V-11e, this hypothesis could be effective over the two different regions as α_{i2} increases. The characteristic of this graph is that the SM net benefit falls discontinuously at some levels of α_{i2} due to the discontinuous nature of the SM market noted above. However, the net benefit of the SM case increases again and moves to approach the MM case. As the number of participants increase, the relative magnitude of these discontinuous shifts would decline, meaning that eventually the SM case could dominate for steeper supply curves.

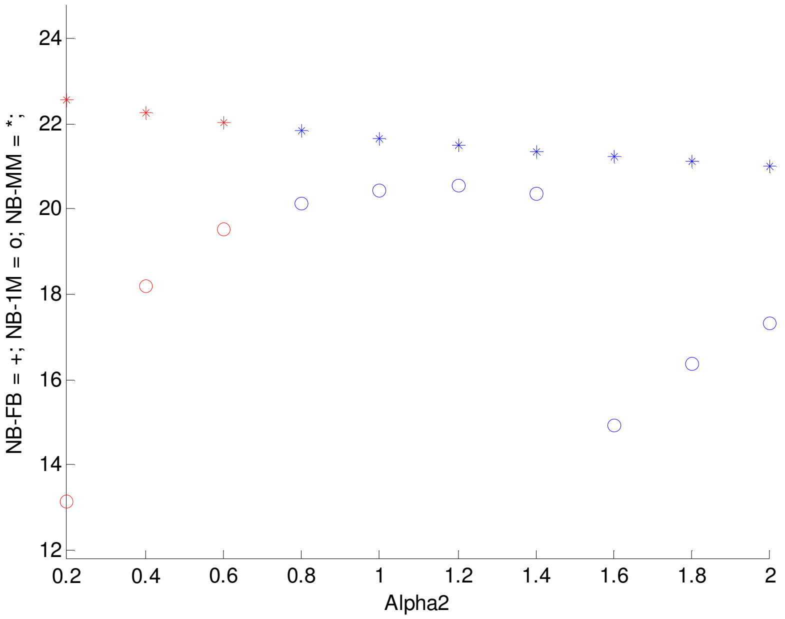

Figure V-11e. Net benefits change with a supply slope parameter changing 5

We could say that the effect of the slope change is clear in the supply side as it was in the demand side. This is confirmed in the simulation even in the case where abrupt and discontinuous SM net benefits are realized. We have seen this sensitivity of the effect of the slope change compared to that of the intercept change in the demand side case which was shown in the previous two sections: the relative performance of MM and SM was not much affected as the intercept parameter of the marginal benefit curve, Ω_j, changed. However, the effect of the slope parameter change of the marginal benefit curve, θ_j, was more distinct.

In the supply side, the intercept change will deepen the effect of the slope change in magnitude so that overall changes will be amplified unlike the demand side case where only the intercept changes. This will be true especially when firms face the discontinuous SM supply curves that have many uncertainties in their shapes.

If both slopes are changed simultaneously it holds that the SM approach becomes more attractive. In fact, in virtually every simulation in which both slopes were changed simultaneously from 10% to 200% of the randomly chosen base value, the MM case was preferred for the flat supply curves and the SM case was preferred for the steep supply curves.

Changes of the supply curve parameter: γ_i

Increase in "absolute" value of γ_i[46] decreases the slopes of supply curves and shift them outward to the right with the intercepts moving downward in both markets.[47] This is the reverse case of increase in α_{i2} which resulted in shifting the supply curves inward to the left. But the second best caps in both markets remain the same as before the parameter changes since the agency's misperceived supply curves are unchanged, and each individual firm's decision rule[48] is not affected either. In case α_{i2} increase, only the second best cap of market 1 (A_1^{**}) did not change. This unchanging characteristic of the second best caps in both markets is unique unlike the changes of any other parameter which affected the second best cap at least in one of both markets.

Net benefits of FB and MM will increase due to the cost reduction effects as the

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[46] Note that γ_i, negative numbers, are chosen to decrease in "real" value but increase in "absolute" value for comparative analysis.

[47] $\frac{\partial \hat{\alpha}_{ij}}{\partial \gamma_i} = \frac{-\alpha_{ij}(-2\gamma_i)}{(\alpha_{i1}\alpha_{i2} - \gamma_i^2)^2} < 0,\ \mathrm{j} = 1,2$ and $\frac{\partial \hat{\gamma}_i}{\partial \gamma_i} = \frac{(\alpha_{i1}\alpha_{i2} + \gamma_i^2)}{(\alpha_{i1}\alpha_{i2} - \gamma_i^2)^2} > 0$.

[48] A firm's decision is based on comparison between $\frac{\alpha_{i1}}{\alpha_{i2}}$ and $\left(\frac{p_1}{p_2}\right)^2$.

supply curves move to the right. But the simulation shows that the cost reduction effects are not big as the net benefits of FB and MM increase slowly. This implies that the first best caps are not much affected by the changes in γ_i. Net benefit changes in FB and MM as the absolute value of γ_i increases are less than those as α_{i2} increases when those simulation graphs are compared. Impact of changes in γ_i is less than that of changes in α_{i2}.

But SM net benefit shows a significant trend and several possibilities of MM and SM relationship are shown in the graphs: SM net benefit (NB) increases very slowly and MM absolutely dominates (Figure V-12a). This is the representative case of many simulations; MM dominates but net benefit differences between MM and SM decrease (Figure V-12b); SM net benefits increase fast and SM switches to dominate (Figure V-12c); MM dominates and SM net benefit decreases (Figure V-12d).

Many graphs show SM net benefit increases but it is still uncertain that SM net benefit will increase or decrease as is shown in Figure V-12d and in the case of changes in α_{i2}, implying the dynamic characteristic of the SM case. However, unlike any other parameter change that results in the slope change, the discontinuous SM net benefit trends are not found in this simulation.

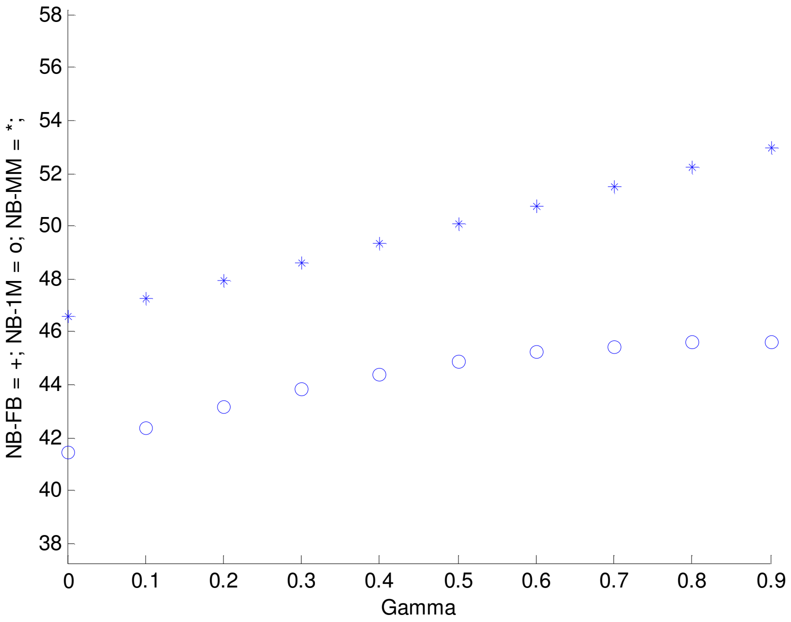

Figure V-12a. Net benefits change with a supply parameter changing 6

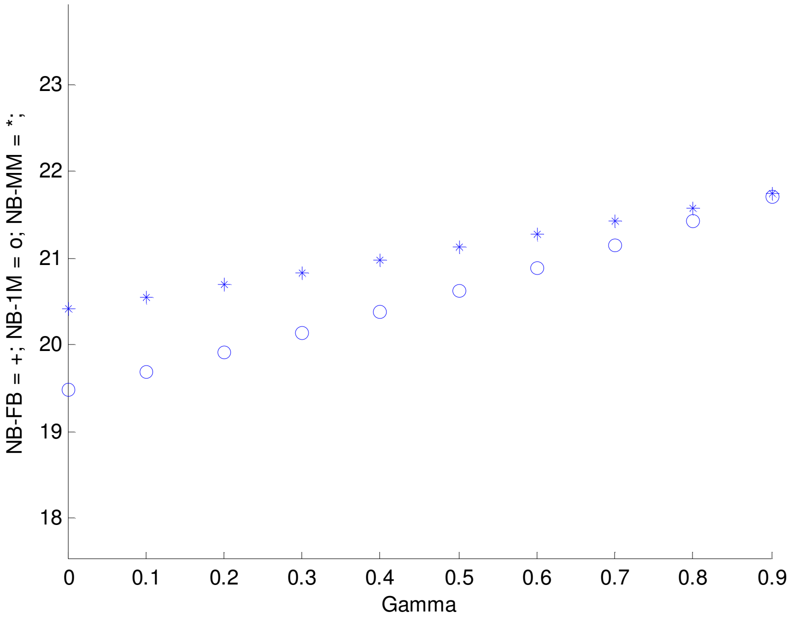

Figure V-12b. Net benefits change with a supply parameter changing 7

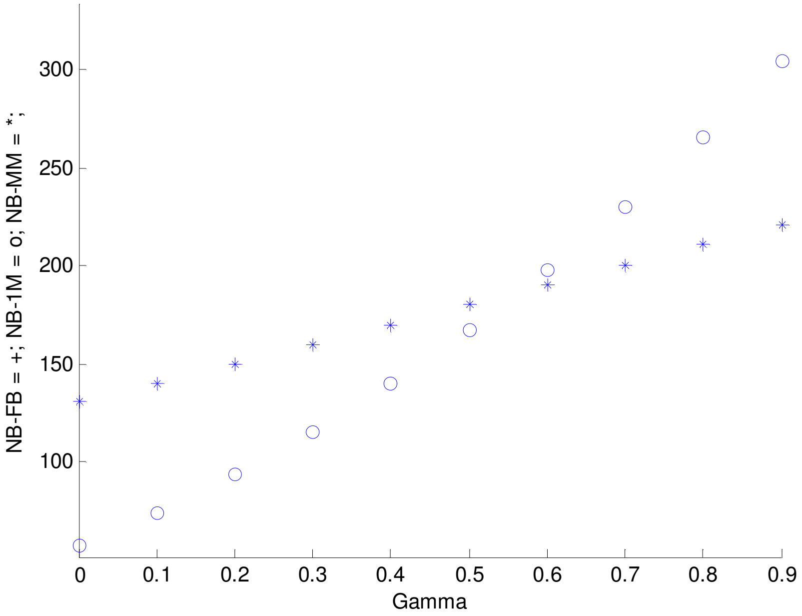

Figure V-12c. Net benefits change with a supply parameter changing 8

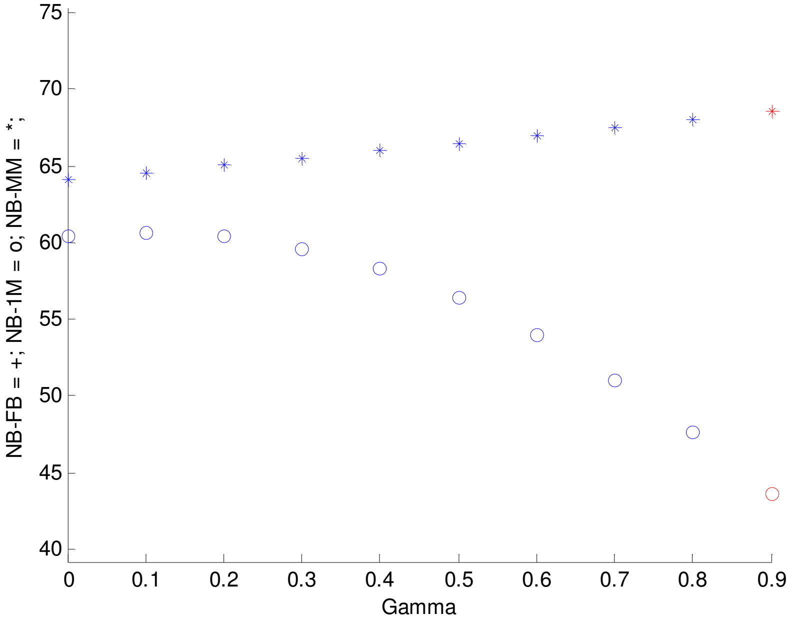

Figure V-12d. Net benefits change with a supply parameter changing 9 (*i*=20)

The SM net benefit was not discontinuous in case of the Ω_1 change but it caused only the intercept change without changing the slopes, having led to not altering the relative performance of SM and MM for most parts. Hence, not surprisingly, the slope does matter, while the intercept does not. Regarding the slope parameter changes, some characteristics could be pointed out as the absolute value of γ_i increases.

First, the change in γ_i is symmetrical and systematic in both markets in the sense that it affects the slopes and intercepts of the supply curves of both markets simultaneously, but does not affect the agency's misperceived supply curves at all in both markets. In contrast, changes in α_{i2} influenced the slopes and intercepts of the supply curves of both markets as well as just one of the agency's misperceived supply curves. The parameter θ_1 change resulted in the slope change of the MB curve in market 1 only. Second, as a result of unchanging misperceived supply curves the second best caps do not change in both markets and the first best caps don't seem to be much affected. Finally, the parameter γ_i and its change do not affect each individual firm's decision rule as is different from change in α_{i2}.

Therefore, resultant changes take place in a symmetrical and systematic way so that total effects of γ_i change seem to be rather predictable and stable in overall markets in that SM net benefit is realized as a smooth continuous curve even though we still have uncertainty that it will increase or not.

MM will dominate as the slopes of the supply curves decrease. MM dominance is also attributed to the fact that the relative cost reduction effect of MM will be greater than that of SM. The simulation analysis confirms our hypothesis in most of those figures. Some figures also suggest overall or partial MM dominance.

Figure V-12d shows another feature. The implication discussed so far comes from the result of the simulation when there are ten firms. The implication is more supported when we ran simulations with a larger number of firms. This is shown in Figure V-12d which is run with twenty firms (i=20) and the last point violates the positive price conditions. The values of the MM net benefits change very slowly under the γ_i simulations. As the total number of participating firms increase in both markets, the markets are neutralized against the effects of γ_i changes and uncertainty becomes reduced. And MM dominance becomes distinctive due to its cost reduction effect compared to SM.

Changes of the second-best cap relative to the first-best cap: $\left(A_j^{**} / A_j^{*}\right)$

Finally, we are ready to investigate the effect of changes of the relative second best cap to the first best cap ("relative cap ratio" hereinafter). Regarding the cap changes, economists and policy makers will be interested in how an isolated decision on the social cap level of any environmental abatement product without considering its joint abatement product and the resultant discrepancy between the first best and the second best cap will influence the dominance of MM or SM over the other.

For this analysis, the first best cap is set fixed, and only the second best cap increases ranging the relative cap ratio, $\left(A_j^{**} / A_j^{*}\right)$, from 0.1 to maximum 2.0 with a 0.2 unit scale interval. The first best and the second best cap coincide when the ratio is equal to 1. The possibility that the second best cap is mistakenly set up more than twice the first best cap is not assumed in this analysis.

The FB net benefits do not change since the FB cap is fixed when $\left(A_j^{**} / A_j^{*}\right)$ increases. MM net benefit is maximized when the second best cap coincides with the first best cap while SM net benefit is maximized generally between 60% and 80% of the relative cap ratio.

Every figure[49] is rather smooth and continuous as it was in the case of γ_i changes. Both cases of simulation have in common that one of the first and second best caps does not change: only the first best cap increased when the absolute value of γ_i increased with the relative (second best) cap ratio decreasing, while only the second best cap increases with the relative cap ratio increasing in the cap analysis here. The relative cap ratio is maintained stable in the sense that the ratio increases or decreases monotonically unlike any other parameter changes. Also, individual firm's decision rules do not change too in these two cases.

Every graph shows that MM moves to dominate, including an overall dominance case in Figure V-13c. MM generally dominates when the second best cap increases farther than the first best cap especially all two second best caps increase at the same time. SM sometimes gives out even negative net benefits. In the case of excessive cap, MM plays a role of hedging risks. MM induces more flexible market system that absorbs some shock of the excessive second best cap to the first best cap by composing a portfolio and diversifying those affluent abatement products in the multiple markets.

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[49] The first points in Figure V-13a and Figure V-13c violate the price positivity condition.

Reversely, SM can be advantageous when the second best cap is less than the first best cap as is very usual in case the complementary "free" abatement products are considered. It can be efficient that more abatement products should be sold in more markets. The figures show the dominance of SM when the second best cap is about 60% to 80% less than the first best cap (Figure V-13a and Figure V-13b). Particularly looking at the maximum net benefits in Figure V-13d and Figure V-13e, the SM can achieve the same net benefits as the MM with a lower cap. It is inferred that the SM approach would be safer to opt for if the second best cap is set less than the first best cap.

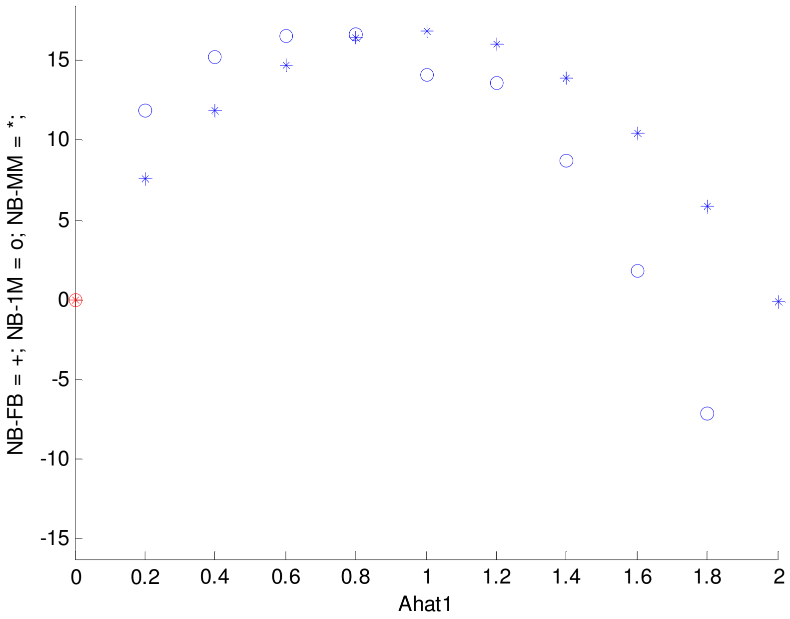

Figure V-13a. Net benefits change with a cap ratio changing 1

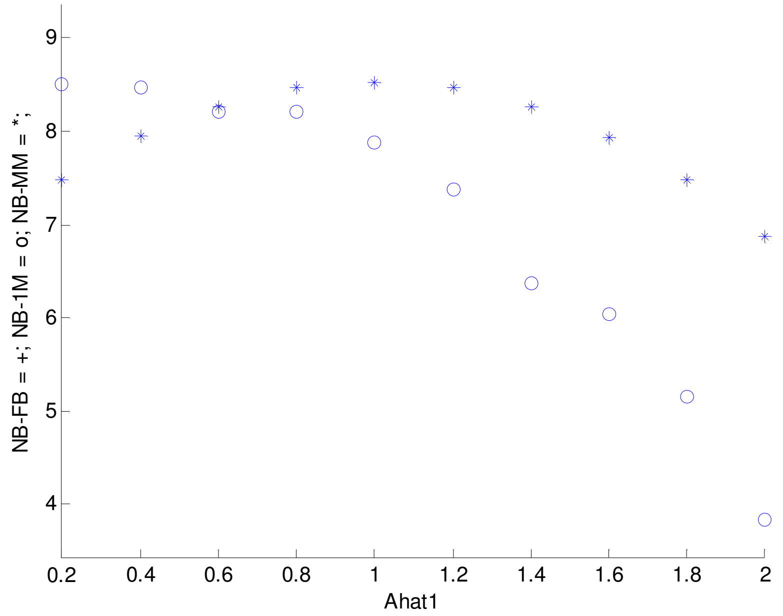

Figure V-13b. Net benefits change with a cap ratio changing 2

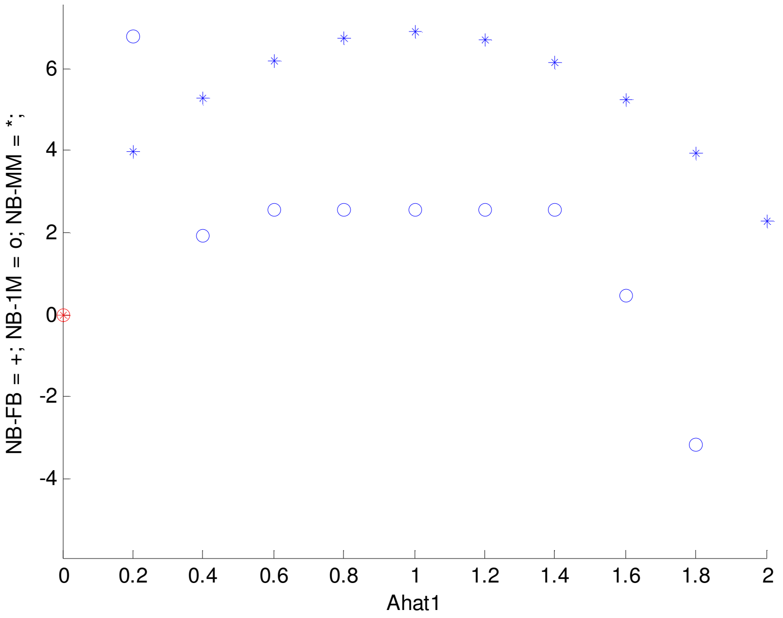

Figure V-13c. Net benefits change with a cap ratio changing 3

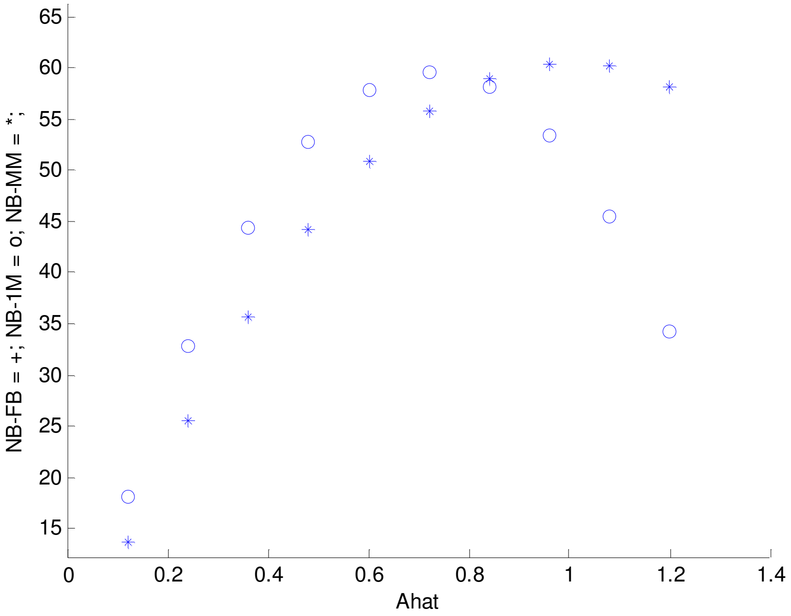

Figure V-13d. Net benefits change with cap ratios *c*hanging 4

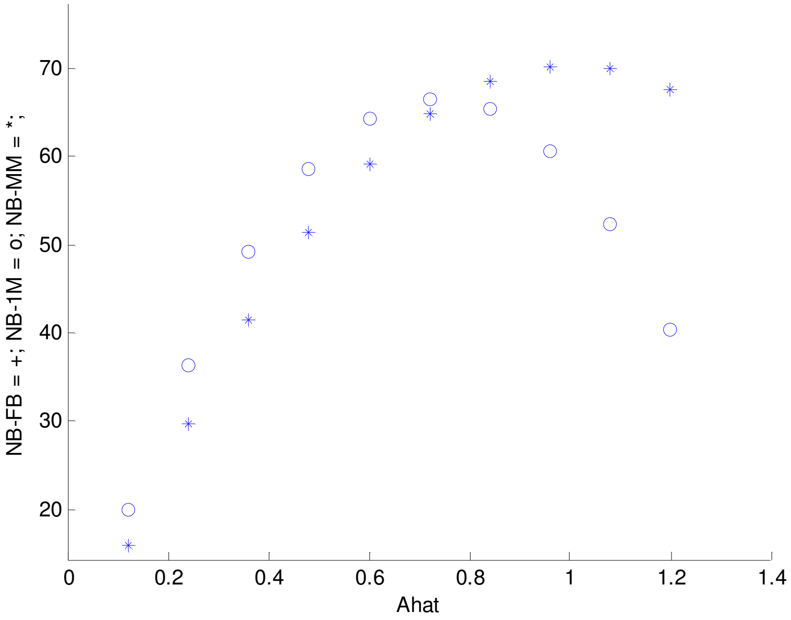

Figure V-13e. Net benefits change with cap ratios changing 5

5.4. Conclusion

We have seen that the question of whether firms should be allowed to sell credits in multiple markets is not as straightforward as might typically be assumed. If caps are set optimally, then it is clear that double-dipping provides optimal incentives and will lead to the first-best outcome (at least in the deterministic setting with a perfectly functioning market that we assume). However, policies are frequently handled in a rather piecemeal fashion; global warming goals are separate from nutrient criteria, which are separate from wetlands requirements. If caps are set in this piecemeal fashion, then to the extent that any optimization criteria is used to set the caps, it will probably be done where the marginal benefit of abatement equals its marginal cost, without taking into account how the various policies interact.

If abatement targets are set using this second-best criterion, then it is no longer automatic that allowing multiple markets is appropriate. As we show graphically, there are situations where the welfare loss can be lower without multiple markets than they are with multiple markets. It is not always efficient to allow double-dipping. In particular, we find it interesting that as the marginal benefit curve becomes flat, relative advantage of double-dipping falls.

The intuition which motivated this research still holds: the slope does matter and the simulation analysis supports this finding. We assumed that a firm does not have any legal responsibility or it has abundant initial distribution of license enough to not reduce emission. One point source firm was assumed to exist as a price taker, being so cost inefficient that it demands all abatement credits produced by the nonpoint source firms.

First what matters is not independent slopes of MB and MC or supply curves but relative slopes between MB and supply curves. When the slope parameters of the MB curve increase in absolute values and the MB curve becomes relatively steeper than supply curves, MM tends to dominate due to the welfare loss reduction caused by steeper MB curves. However, counter-examples are abundant. It is not clear that MM dominates when only one slope parameter of MB curves increases. One reason is that SM can dominate for example in market 2 with a pretty flat MB_2 and steep supply curves in market 2 and this surpasses whole other MM dominance effects in entire markets. This may happen at any time due to random number generating characteristics of the simulation. This relative slope analysis is all applied to the changes of other parameters as discussed above.

Generally, SM tends to dominate when the slope parameter of the supply curves increases, especially when their intercepts increase simultaneously with the slopes. We see that the intercept change will deepen the slope change effect in magnitude as was seen in the supply side parameter change, α_{ij}. Only an intercept change alone does not tend to much affect the relative performance of MM and SM as a whole as seen in the case of Ω_1 changes. SM eventually dominates or moves to dominate MM even when the SM net benefits fall discontinuously at some level of α_{ij}. However, it must be noted that even intercept changes can be important to determining which policy might be preferred when the number of SM participating firms change.

When the second best cap increases, MM moves to dominate as the second best cap reaches the first best cap although there is some exception. MM is better than SM in the case of excessive cap farther than the socially efficient cap level. It can be efficient that more abatements should be sold in more markets. On the contrary, SM is more advantageous or safer than MM when the cap is less than the socially efficient cap level, which will be more often the case because of positive complementary relationship between abatements. SM even achieves the same net benefits as MM does with a lower cap. Less abatements should be sold in less markets.

Second, net benefits of FB and MM always shows a consistent tendency but the net benefit of SM does not. SM supply curves, SMS and TSMS, have discontinuous and uncertain nature with segments of different slopes and locations based on the number of participating firms in that market. This discontinuity makes SM net benefit changed all of a sudden and shows some irregular net benefit pattern. As a result, the number of participating firms in the markets matter on if MM or SM dominates. Dominance between SM_1 and MM_1 depends on the slope and location and difference of each SMS_1 and $TSMS_1$ segment at the market price as well as the relative slopes of the MB_1 and MM_1 supply curve.

But the SM net benefit curves are smooth and continuous in the simulation cases when γ_i or the relative cap ratio changes: only the first best or second best cap changes and an individual firm's decision rule does not change. The changes of both caps can cause an amplified uncertainty of the markets. If comparing changes of γ_i to those of α_{ij}, the impact of γ_i changes with both of the second best cap and firm's decision rules unchanged is less than that of α_{ij} changes which affect the changes of the first and second best caps and decision rules.

With keeping these in mind, we find that the conditions for double dipping or MM from the social efficiency point of view are: (1) the abatement cap is clearly and reasonably set at the level that would be thought very close to the first best cap. This means that the environmental agency needs to know information on targeting pollutants and their technologically complementary interactions between abatements; (2) it will be safer to adopt SM if the second best cap is (perceived to be, due to the lack of complementarity information,) less than the first best cap.

Hence, we believe that it may be inappropriate to allow double dipping in the provision of greenhouse-gas credits because in diminishing this global externality, the marginal benefit of the sequestration on any one acre is likely to be essentially constant over a very large range.

The case of instream water flows in rivers and streams is another issue that deserves to be noted. They function to protect water quality and preserve recreational use value of water for water-based activities, and help to generate wetlands without additional costs. Allowing double dipping in this case is possibly more efficient as long as the marginal benefit curve for the instream water flows levels is steeper than their MC or supply curves.

The limitation of our analysis starts from the fact that the slope and location of discontinuous SM supply curves are not well identified and this made the analytical and graphical analysis pretty difficult. In the future research, more investigation on the conditions of welfare changes is needed with the simulation results. Table V-1 presents an extensive list of market-based environmental commodities.

Table V-1. Range of Environmental Credits in Use or under Consideration

Environmental goods	Currency	Regulatory Driver
Wetland	Acres	Federal & State
Stream	Linear feet	Federal & State
Buffer	Acres	State
Habitat	Species/habitat acreage	Federal & State
Forest	Acres	State
Carbon/Greenhouse Gas	Tons of CO2 emissions	State & (possibly) Federal
Nutrients	Pounds	State
Miscellaneous water quality	Pounds	Federal & State
Stormwater	Acres of pervious cover	Federal & State
Renewable energy	Renewable energy credits	State
Water rights	Acre-feet of water	State
Aquifer recharge	Acres of pervious cover	State
Development rights	Development or density units	County

Source: Based on George Kelly, Environmental Banc & Exchange. Presentation to the EPRI Environmental Sector Council, Sept. 10-12, 2003

CHAPTER VI

SUMMARY AND CONCLUSIONS

Water quantity trading refers to water markets and Interbasin Water Transfers (IBT) where water is conveyed from one set of users to another with money exchanged. Water quantity trading affects flows/inflows and their quality in the source and destination basins so that economic and environmental characteristics are at issue. This dissertation examines water quantity issues in a water trading context from wetter to dryer regions of Texas under without and with minimum requirements of freshwater inflows. We focus on welfare gain, water demand and environmental flows and complementary relationship among multiple environmental commodities.

This chapter is organized around five items: (1) Analysis and implications of implementing IBT projects; (2) Analysis of implementing minimum requirements of freshwater inflows to bays and estuaries (FWIB) and policy alternatives; (3) Conditions for efficient multiple markets; (4) Implications for environmental commodities in the presence of multiple markets; (5) Limitations and tasks for future research.

6.1. Interbasin Water Transfers (IBT): Water Quantity Issue

In Chapter II, a modeling framework TEXRIVERSIM was presented that was developed to examine the economic, hydrological and environmental effects of IBT projects across 21 Texas river basins. The model maximizes annualized expected net benefit of water use by the nonagricultural and agricultural sectors plus assigned value of freshwater inflows. It encompasses nine climate states of nature with hydrological factors such as precipitation, evaporation losses and return flows being considered. The model contains sets of constraints on agricultural land and water use, total water use by source and sector, demand curve convexity, freshwater inflows, hydrological water flow balance, reservoir and IBT capacity, etc

The model is a two stage stochastic programming with recourse: the crop mix and IBT construction decision is made in the first stage independent of the state of nature; then water availability and yields are decided in the second stage by the state of nature with water transfer and crop acres realized. In modeling this, we introduced climate-driven water demand and supply.

Chapter III reports the results of the model application. Three IBT projects were optimally chosen: Luce Bayou IBT (Trinity–San Jacinto), Cypress Basin IBT (Cypress–

Trinity), LCRA-SAWS (Colorado–San Antonio). IBT projects relocate water to increase economic use efficiency. The annualized gain of implementing these IBT projects amounts to $203 million. However, the model reveals that the agricultural sector does not materially gain from IBT. The municipal sector gain accrues 37.5% ($76 million) of the IBT gains, achieving more gains in dry states of nature where the climate-driven demand shifting factor coefficient is high. The industrial sector accommodates 62.5% ($127 million) of the gain. Implementing IBT projects reduces the freshwater inflows in seven major basins of the Gulf of Mexico, but they increase in the IBT destination basins, San Jacinto and Guadsan.

After IBT projects are implemented, water use increases in the IBT destination basins, but instream water flows and freshwater inflows decrease mainly in the IBT source basins, though positive or negative deviations exist by basin.

6.2. Recommendations on Freshwater Inflows to Bays and Estuaries (FWIB)

In Chapter IV, our analysis focused on the economic, hydrological and environmental effects of imposing minimum requirements on freshwater inflows to bays and estuaries as defined by TPWD and TWDB in the seven basins of Texas. We examined the changes in welfare gains, interactions and conflicts between water use and environmental flows according to the different freshwater inflows constraints along with the IBT implementation.

We developed simulation results for the imposition of two types of the inflow constraints. First, the inflow constraints were imposed for each state of nature (FWIB-SON). However, these constraints satisfied the recommendations only in the three basins, Guadsan, Nueces and San Jacinto. It was impossible to satisfy the constraints in the ColLavaca and Neches River basins almost in every state of nature in every month. The SanioNues and Trinity River basins could meet them on average but not in some states of nature, depending on the month.

The finding that the base set of the state of nature constraints can not be satisfied has important policy implications. Thus, we examined an alternative form of the inflow constraints (FWIB-Avg) to meet the requirements on average. There are three reasons behind this alternative constraint specification. First, the state of nature constraints are simply impossible when average constraints cannot be satisfied. Satisfaction of the average constraints is a required condition for the satisfaction of the state of nature constraints.

Second, when there are large variations of inflow levels depending on water supply levels, it is harder to meet the recommendations in some states of nature, and accordingly, the recommended inflow levels should be lowered.

Third, even if the state of nature constraints were possible, it would be costly to set the recommended inflow levels in each and every state of nature because of opportunity costs and searching costs to find the comprehensive inflow level table. And inflow levels for each and every state must be readjusted even under small changes in the model assumption, e.g., groundwater demand portion.

The FWIB recommendations could be met on average feasibly in five basins adding SanioNues and Trinity. To make the model feasible, the minimum requirements of freshwater inflow levels in the ColLavaca and Neches River basin were reduced to 1.5% and 80% of the originally recommended inflow levels, lowering the inflow levels by 98.5% and 20% of them in the two basins, respectively.

This suggests the need for policy changes by TPWD and TWDB. Several options are possible. (1) The recommended inflow levels could be lowered for the ColLavaca and Neches River basins. This merits study by ecologists. (2) The next option is extended interbasin management. In the case of ColLavaca, the FWIB recommended inflow levels are too far above the optimal levels so that freshwater inflows should be managed in the extended interbasin of ColLavaca and Colorado, and this should be implemented with the first policy option, lowering the recommended inflow levels. Freshwater inflows in Neches can be managed in the extended interbasin of Neches-Sabine if lowering the recommended levels is not possible. Extended basin-wide management of inflows are especially important when multiple inflows-out control points to bays and estuaries exist and their aggregated inflows must be comprehensively regulated, as in the case of Trinity. (3) Appropriate storage of the seasonal freshwater surpluses can make up for the shortages in conjunction with the second policy option. In the extended interbasin of ColLavaca and Colorado, the seasonal freshwater surpluses from February to May can compensate for the shortages from June to September if the seasonal storage is feasible. The strategy of seasonal management must be implemented along with yearly management to be prepared for water shortages in consecutive dry years/states of nature.

(4) Another option is to relax the recommended inflow levels based on percentage ranges as shown in the Tennant Method which suggests eight seasonally different levels of water flow recommendations. (5) The last option is to reevaluate the

economic, biological and chemical standard of the FWIB recommendations, not merely lowering the inflow levels. There should be some compromise between economics and ecology/environment when freshwater inflow levels are reevaluated and enforced.

Under the average constraints after lowering the recommended inflow levels in ColLavaca and Neches, FWIB-NB from the FWIB recommendations without the IBT projects was -$211 million. The total loss was -$8 million when FWIB-NB (-$211 million) and IBT-NB (+$203) are both considered. The welfare loss from the FWIB recommendations was greatly relived by the IBT-induced water use efficiency.

The same three IBT projects were chosen with the IBT implementation and the FWIB average constraints. The results show that the FWIB provisions decrease water use and net benefits. Overall, in terms of the total gain after the IBT implementation and FWIB average constraints, the IBT destination basins contributed to increasing water use and also freshwater inflows unlike the IBT-only scenario, while the IBT source basins contributed to decreasing instream flows. In the IBT destination basins Guadsan and San Jacinto, water use, instream flows and freshwater inflows all increased due to sufficient injection of water. The FWIB recommendations served to protect freshwater inflows: the Neches River basin has contributed to strong decrease in water use but also to increase in instream flows and freshwater inflows.

The Colorado, Lavaca, Brazos and San Jacinto River basins are interconnected with the FWIB and IBT. The FWIB recommendations reinforced the IBT gain effect more in the simultaneous FWIB average constraints and IBT scenario than in the IBT-only scenario. Water use and flows are interacting with those in the IBT and FWIB neighboring basins.

6.3. Conditions for Efficient Multiple Markets

Chapter V, presents an essay on market conditions for multiple environmental commodity markets (multiple markets or MM) to work best in a socially efficient manner when those environmental commodities are jointly produced and traded in such cases as freshwater inflows, instream flows and wet lands.

Starting and extending analytically from Montgomery (1972), we found that double dipping is efficient in the first-best economy. However, in the second-best setting, the results are mixed and double dipping may not be as socially optimal as might typically be assumed. We did the simulation analysis on this second-best setting, assuming the quadratic social benefit function and firms' cost functions with interaction terms of two jointly produced environmental commodities. We also assumed that a firm has abundant initial distribution of licenses with ten nonpoint source firms and one price-taking point source firm who demands all abatement credits.

The relative slopes of Marginal Benefit (MB) and Marginal Cost (MC) or supply curves matter on if multiple markets (MM or double dipping) or single market (SM) is preferred. When the slope parameters of MB curve increase in absolute values and the MB curve becomes relatively steeper than supply curves, MM tends to dominate due to the welfare loss reduction caused by steeper MB curves although counter-examples are abundant.

We see that the intercept change can deepen the slope change effect in magnitude. Even intercept changes can be important to determining which policy might be preferred when the number of SM participating firms change.

When the second-best cap increases, MM moves to dominate as the second-best cap reaches the first-best cap though there is some exception: more abatements should be sold in more markets. On the contrary, SM is more advantageous or safer than MM when the cap is less than the socially efficient cap level: less abatements should be sold in less markets.

Due to the discontinuous nature of SM supply curves, the number of participating firms in the markets could matter on if MM or SM dominates.

Finally, the conditions for double dipping or MM from the social efficiency point of view are: (1) the abatement cap is clearly and reasonably set up at the level that would be thought very close to the first-best cap. This means that the environmental agency should have information on the technologically complementary interactions between abatements; (2) it will be safer to adopt SM if the second-best cap is (perceived to be, due to the lack of complementarity information,) less than the first-best cap.

6.4. Implications for Environmental Commodities in Multiple Markets

The analyses of freshwater inflows and the potential for multiple markets are actually interrelated. Freshwater inflows to bays/estuaries and instream water flows in rivers/streams could become new environmental commodities that may be traded in the markets. Environmental flows function to protect water quality and preserve recreational use value of water for water-based activities, and help to generate wetlands without additional costs. There are some cases when MM is preferred when caps are suboptimally set.

First, allowing double dipping or MM in this environmental flow case is possibly more efficient if the marginal benefit of the freshwater inflows or instream flows is steep or inelastic. On the contrary, MM may not be efficient in the case of greenhouse gas credits where the marginal benefit of the sequestration on any one acre is likely to be essentially constant over a very large range. However, what matters are the relative, not absolute, slopes of demand (benefit) and supply curves matter.

Second, if we introduce the climate-driven demand shifting factor to these environmental flows and demand for the flows increases, then intercept change could deepen the efficiency of MM along with the inelastic demand curve.

Third, the second-best cap, biologically and ecologically acceptable minimum requirements for environmental flows, will generally tend to be set higher in reality than the economically optimal flow levels which will be the first-best cap. This might be due to political or bureaucratic responsibility. In case the second-best cap is set higher than the optimal flows levels, our analysis says that MM will be preferred.

It should be noted that if the IBT gain in water use (IBT-U) dominated the FWIB loss in water use (FWIB-U) as was generally seen in our analysis, then water use would increase but the optimal environmental flows provided would decrease. The caps should be adjusted as well but this will not be an easy task for environmental water agencies to accomplish, as it is a timely procedure.

6.5. Limitations and Tasks for Future Research

There are some limitations and tasks for future research in our analyses. First, the groundwater component is not introduced in our model. This will restrict comprehensive understanding on changes of welfare, water demand and (in) flows. Integration of a hydrological groundwater component into the current surface water model will be a future task.

Another issue for future research is the reexamination of the definitions of environmental flows to meet the goal of economics and environment. This would become a real issue when we enlarge our project scope and vision to cover all environmental flows, including instream flows.

One more issue is that more exact information must be gathered on IBT water in- and out-points and field-based analysis should be carried out in the geographically and IBT-FWIB interconnected river basins. The junior water rights status of water transferred needs to be incorporated in the future model for more concise understanding of water use and flows in these basins.

In the chapter regarding double dipping, the limitation of our analysis starts from the fact that the slope and location of the discontinuous single market supply curves are not well identified. This made the analytical and graphical analyses quite difficult. More investigation on the conditions of welfare changes is needed with the simulation results.

Our study is believed to be the first attempt to introduce environmental flow factors in order to evaluate comprehensive economic, hydrological and environmental effects of the FWIB and IBT implementation across Texas. We suggested new policy alternatives feasible for better use and preservation of water and for efficient environmental commodity markets.

Future research is also needed on FWIB inflow constraints addressing the infeasibility finding in chapter IV specifically looking at whether the environmental flow levels need to be redefined to accommodate drought and seasonality. This would require an interdisciplinary study involving economics, hydrology, ecology and environment factors.

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APPENDIX A

Symbol	Type	Description
AGWATERUSE	Variable	Ag water use
ARTDIVERSIONQ	Variable	Artificial variable (infeasibility)
ARTFLOWBALANCE	Variable	Artificial flow to make model feasible
COLLECTCITY	Variable	Diversions to a city from a diverters place
COLLECTINDUSTRY	Variable	Diversions to a county from a diverters place
CROPACRES	Variable	Harvested acres by crop
CROPMIX	Variable	Crop mix use
DIVERSIONQ	Variable	Amount diverted by each river location
DIVERTERUSE	Variable	Water use by diverter and by sector
ESCAPETOBAY	Variable	Water flow out of the river basins to a bay
FLOW	Variable	Flow from upstream or to downstream
INDMINDIVERTERUSE	Variable	Non stepwise industry/mining use by county
INDMINDIVERTERUSEs	Variable	Stepwise industry and mining use by county
MUNDIVERTERUSE	Variable	Non Stepwise municipal use by CITY
MUNDIVERTERUSEs	Variable	Stepwise municipal use by CITY
NETBENEFIT	Variable	Net Benefit of Water Transfer
OUTTOBAY	Variable	Escapement to the ocean
RIVERINTBBASINTRAN	Variable	Interbasin Transfer from River to River
RIVERINTBBASINTRANConstruction	Variable	Whether or not construct River IBT
STOREADD	Variable	Reservoir Storage additions
STOREWITH	Variable	Reservoir Storage withdrawals

USERINTBBASINTRAN	Variable	Interbasin Transfer from River to user
USERINTBBASINTRANConstruction	Variable	Whether or not construct USER IBT
USERINTBBASINTRANsce	Variable	Interbasin Transfer from River to user by sector
AGDIVERSIONID	Equation	All agricultural diversion identity
AGLAND	Equation	Agricultural land
AGWATERUSEBAL	Equation	Ag water use balance
CITYDIVERSIONID	Equation	Major municipal city identity
CROPBALANCE	Equation	Crop balance
DIVERSIONQMAX	Equation	Maximum diversion allowed by sector
FLOWBALANCE	Equation	Flow balance
FLOWOUTTOBAY	Equation	Outflow to bay and estuary
IBTConfigurationConstraint	Equation	Number of IBT can be built
INDCOUNTYDIVERSION	Equation	Major industrial county identity
INDCOUNTYDIVERSIONmax	Equation	Major industrial county identity
INDDIVERSIONCONVEX	Equation	Sets sum of steps equal to one by county
INDDIVERSIONID	Equation	All industrial diversion identity
MIXBALANCE	Equation	Land in mix balance
MUNDIVERSIONCONVEX	Equation	Sets sum of steps equal to one by CITY
MUNDIVERSIONID	Equation	All municipal diversion identity
MUNDIVERTERUSELIMIT	Equation	Limit on quantities without demand curves
NONCONSUSEMAX	Equation	non consumptive use balance
OBJ	Equation	Objective function
OTHERDIVERSIONIDENTITY	Equation	All other type diversion identity
QUANTITYDIVERSION	Equation	Balance on quantity diverted
RECDIVERSIONIDENTITY	Equation	All recreational diversion identity

RIVERINTBBASINTRANConstraint	Equation	Annual Capacity of RIBT
STOREBALANCE	Equation	Reservoir Storage balance
STORECAPACITY1	Equation	Reservoir Storage capacity
STORECAPACITY2	Equation	Reservoir Storage capacity
UIBTbalance	Equation	Sum of IBTs equal total IBTs
USERINTBBASINTRANConstraint	Equation	Annual Capacity of UIBT
availagland	Parameter	Available irrigated planted acres
CityDemanddata	Parameter	Parameters for Demand functions
cropdata	Parameter	Agricultural crop budget data
Evaporationloss	Parameter	Evaporation loss (%) of reservoir storage
IndMinDemanddata	Parameter	Industry/mining water use
inflow	Parameter	flows between two control points
InterBasinTranCapacity	Parameter	IBTs annual Capacity
InterBasinTranCost	Parameter	Interbasin transfer fixed/drawing cost
mixdata	Parameter	Harvested acres
Muncitydemand	Parameter	Computing demand data
Muncitydemand2	Parameter	Computing demand data for costs
newagwatercost	Parameter	Agriculture water price by county
Newwateruse	Parameter	Actual nonagricultural water use
prob	Parameter	Probability of the states
QINC	Parameter	Separable quantity increments
reservoircapacity	Parameter	Normal storage capacity of reservoirs
RFpercent	Parameter	Return flow percentage by type
upperdiversionQ	Parameter	Maximum permitted diversion
wttobay	Parameter	Weight on flow out to bay

Activemix	Set	Counties with active crop mix data
availmixdata	Set	Year when the mix data is available
City	Set	Covered municipal cities in Texas
conssector	Set	consumptive use sectors
county	Set	List of counties in Texas
Countytouse	Set	Agricultural counties with agricultural diverters
crop	Set	Crop names covered in the model
destbasin	Set	Aliased with river basins
destbasins	Set	Aliased with river basins
destplace	Set	Aliased with river location
downriver	Set	Aliased with river location
IBT	Set	interbasin transfers with data
Indminmapping	Set	Mapping of riverplace, industry/mining county
Indminmapping1	Set	Mapping of riverplace, industry/mining county
InterBasinTranName	Set	a set containing all the UIBT and RIBT names
InterBasinTranOpt	Set	Choice of IBT
interbasintranrivertoriver	Set	RIBT names (river to river)
interbasintranrivertouser	Set	UIBT names (river to user)
irrigstatus	Set	Irrigation status
isagther2	Set	Agricultural county and river basins
isagthere	Set	Agricultural county and river mapping
Mappingall6	Set	Mapping of basins, place, county/sector
Mappingall7	Set	Mapping of riverplace and sector
Mappingcity	Set	Mapping of riverplace and major cities
Mappingcity1	Set	Mapping of riverplace and major cities

month	Set	The months included in the model
mriverflowlink	Set	New river flow links between primary locations
mriverplace	Set	Major active river places with full data
nonconssector	Set	non consumptive use sectors
onriver	Set	Set telling where river points are located
reservoir	Set	River locations of reservoirs on rivers
RInterBasinTran	Set	Connection points for Inter Basin Transfer
riverbasins	Set	Basin names in Texas covered in the model
riverlocation	Set	Primary control points in each riverbasin
riverplace	Set	Aliased with river location
SAMEAS	Set	Set Element Comparison Without Checking
sector	Set	Type of water use
sector1	Set	Small type of use set
sourcebasin	Set	Aliased with river basins
sourcebasins	Set	Aliased with river basins
sourceplace	Set	Aliased with river location
state	Set	Nine states of nature
steps	Set	Restricted set of steps for testing
UInterBasinTran	Set	IBT directly diverted in destination
Upriver	Set	Aliased with river location

APPENDIX B

Assuming that the $F\ (\cdot)$ is strictly convex, the firm and planner's problems are convex programming problems so that the Kuhn-Tucker conditions are necessary and sufficient conditions for an optimum. The Lagrangian of the firm's minimization problem is

$$\text{(B.1)}\ldots L(e_{i1},\ldots e_{im},l_{i1},\ldots l_{im},u_{i1}\ldots u_{im}) = F_i(e_{i1},\ldots e_{im}) + \sum_{j=1}^{m} p_j(l_{ij} - l_{ij}^0) - \sum_{j=1}^{m} u_{ij}(l_{ij} - e_{ij})$$

Given an equilibrium price vector, p_j^*, an optimum of vector of choices and shadow prices, e_{ij}^*, l_{ij}^*, u_{ij}^*, satisfies the following first-order conditions,

$$\text{(B.2)}\ldots[F_{ij}^{'}(e_{i1}^*,\ldots,e_{im}^*) + u_{ij}^*] \geq 0,\ e_{ij}^*[F_{ij}^{'}(e_{i1}^*,\ldots,e_{im}^*) + u_{ij}^*] = 0$$

$$\text{(B.3)}\ldots(p_j^* - u_{ij}^*) \geq 0,\ \ l_{ij}^*(p_j^* - u_{ij}^*) = 0$$

$$\text{(B.4)}\ldots(l_{ij}^* - e_{ij}^*) \geq 0,\ \ u_{ij}^*(l_{ij}^* - e_{ij}^*) = 0$$

The price vector will be a market clearing if the following conditions are satisfied:

$$\text{(B.5)}\ldots\sum_{i=1}^{n}(l_{ij}^* - l_{ij}^0) \leq 0,\ \forall j\,,$$

$$\text{(B.6)}\ldots p_j^*\left[\sum_{i=1}^{n}(l_{ij}^* - l_{ij}^0)\right] = 0,\ \forall j\,.$$

The social planner's cost minimum is the vector of e_{ij}^* that solves the following problem:

(B.7) $\underset{e_{ij},\forall i,j}{Min}\sum_{i=1}^{n} F_i(e_{i1},...e_{im})$

$subject\ to \sum_{i=1}^{n} e_{ij} \le l_j^0,\ \forall j$

$e_{ij} \ge 0, \forall i, j$

The Lagrangian for this minimization problem is

$$L(e_{11},...,e_{nm},u_1,...,u_m) = \sum_{i=1}^{n} F_i(e_{i1},...,e_{im}) - \sum_{j=1}^{m} u_j (l_{ij}^0 - \sum_{i=1}^{n} e_{ij})$$

$(e_{i1}^*,...,e_{im}^*)$ for all i is a social cost minimum if and only if there exists $(u_1^{**},...,u_m^{**}) \ge 0$ such that the following Kuhn-Tucker conditions for all *i and j* are*:*

(B.8)...$[F_{ij}^{'}(e_{i1}^{**},...,e_{im}^{**}) + u_j^{**}] \ge 0,\ e_{ij}^{**}[F_{ij}^{'}(e_{i1}^{**},...,e_{im}^{**}) + u_j^{**}] = 0$

(B.9)...$l_j^0 - \sum_{i=1}^{n} e_{ij}^{**} \ge 0,\ u_j^{**}(l_j^0 - \sum_{i=1}^{n} e_{ij}^{**}) = 0$

Proof of lemma 1

Let e_{ij}^{**}, u_j^{**} be optimum choices for the planner's problem, satisfying equations (8) and (9), for some total load limit, L_j^0, *j*=1,…,*m*. Let p_j^*, e_{ij}^*, u_{ij}^*, l_{ij}^* be the satisfying the optimum conditions for the market equilibrium, equations (2) through (6).

If we substitute e_{ij}^{**}, u_j^{**} into (2) instead of e_{ij}^*, u_{ij}^*, the equation (2) becomes equivalent to equation (8) so that e_{ij}^{**}, u_j^{**} satisfy the equation (2).

Equation (3) is satisfied for all *i* and *j* if $p_j^* = u_j^{**}$, $u_{ij}^* = u_j^{**}$.

Equation (4) is also satisfied for all *i* and *j* because $l_{ij}^* = e_{ij}^{**}$, $e_{ij}^* = e_{ij}^{**}$.

Equation (5) becomes $\sum_{i=1}^{n}(h_{ij}e_{ij}^{**}-l_{ij}^{0})\leq 0$ since $l_{ij}^{*}=e_{ij}^{**}$. This is immediately equivalent to the left equation of (9) since we defined $l_{j}^{0}=\sum_{i=1}^{n}l_{ij}^{0}$.

Equation (6) is equivalent to the right equation of (9) since

$p_{j}^{*}=u_{j}^{**}$, $l_{ij}^{*}=e_{ij}^{**}$, $l_{j}^{0}=\sum_{i=1}^{n}l_{ij}^{0}$.

The social cost minimum, e_{ij}^{**}, u_{j}^{**}, satisfy the market equilibrium generated from the individual firm's optimization problem given the market price.

Since this is satisfied for an arbitrary load limit, L_{j}^{0}, it holds for any feasible limit.

Proof of lemma 2

Now, let's define the solution of (8) and (9) as $u_{j}^{**}=p_{j}^{*}, e_{ij}^{**}=e_{ij}^{*}$. If we substitute the solution p_{j}^{*}, e_{ij}^{*} into (8) and (9) instead of u_{j}^{**}, e_{ij}^{**} respectively and this solution satisfies the equation (8) and (9), then the lemma 2 is proved.

By substitution, the left side of equation (8) becomes $[F_{ij}^{'}(e_{i1}^{*},...,e_{im}^{*})+p_{j}^{*}]\geq 0$, which is shown from the left side of equation (2) because $p_{j}^{*}\geq u_{ij}^{*}$ from the left side of equation (3).

As for the right side of equation (8), if $p_{j}^{*}>u_{ij}^{*}$, then, $l_{ij}^{*}=0$ from the equation (3) and $e_{ij}^{*}=0$ from the left side of equation (4), which, in turn, satisfy the right side of equation (8) by substituting $e_{ij}^{*}=0$ instead of e_{ij}^{**}. If $p_{j}^{*}=u_{ij}^{*}$, combined with

$u_j^{**} = p_j^*$, $e_{ij}^{**} = e_{ij}^*$, the right side of equation (8) becomes equivalent to the right side of equation (2).

The left side of equation of (9) is achieved by $e_{ij}^{**} = e_{ij}^*$: Let's sum the left side of equation (4) over *i*, and add this with equation (5) after changing its sign to be positive. We can obtain $l_j^0 - \sum_{i=1}^{n} e_{ij}^* \geq 0$ with the definition of $l_j^0 = \sum_{i=1}^{n} l_{ij}^0$, which is equivalent to (9) when we replace $e_{ij}^{**} = e_{ij}^*$ in (9).

As for the right side of equation (9), if $l_{ij}^* > e_{ij}^*$, then, $u_{ij}^* = 0$ from the equation (4) and $p_j^* = 0$ from equation (3). Therefore, the right side of (9) is satisfied since $u_j^{**} = p_j^*$. If $l_{ij}^* = e_{ij}^*$, equation (9) becomes the same as (6) when $u_j^{**} = p_j^*$.

Proof of lemma 3

Equations (2) – (4) do not depend on $(l_{i1}^0,...l_{im}^0)$. Equation (5) only depends on $(l_1^0,...l_m^0)$, but not on $(l_{i1}^0,...l_{im}^0)$.

APPENDIX C

$$F_1 = -\alpha_{i1}(\bar{e}_{i1} - e_{i1}) - \gamma_i(\bar{e}_{i2} - e_{i2}) = 0$$

$$Then,\ e_{i1}{}^0 = \bar{e}_{i1} + \frac{\gamma_i}{\alpha_{i1}}(\bar{e}_{i2} - e_{i2}) \rightarrow Locus\ of\ F_1 = 0$$

$$F_2 = -\alpha_{i2}(\bar{e}_{i2} - e_{i2}) - \gamma_i(\bar{e}_{i1} - e_{i1}) = 0$$

$$\text{Then, } e_{i2} = \bar{e}_{i2} + \frac{\gamma_i}{\alpha_{i2}}(\bar{e}_{i1} - e_{i1}) \Rightarrow e_{i1}{}^1 = \bar{e}_{i1} + \frac{\alpha_{i2}}{\gamma_i}(\bar{e}_{i2} - e_{i2}) \rightarrow \text{Locus of } F_2 = 0$$

The following must be satisfied

$$e_{i1}{}^0 \geq e_{i1}{}^1 \geq 0,\ then,\ \bar{e}_{i1} + \frac{\gamma_i}{\alpha_{i1}}(\bar{e}_{i2} - e_{i2}) \geq \bar{e}_{i1} + \frac{\alpha_{i2}}{\gamma_i}(\bar{e}_{i2} - e_{i2}) \geq 0$$

For the first inequality holds,

$\rightarrow (\bar{e}_{i2} - e_{i2})(\frac{\gamma_i}{\alpha_{i1}} - \frac{\alpha_{i2}}{\gamma_i}) \geq 0$ and it must be $\frac{\gamma_i}{\alpha_{i1}} - \frac{\alpha_{i2}}{\gamma_i} \geq 0$, then $\frac{\gamma_i^2 - \alpha_{i1}\alpha_{i2}}{\alpha_{i1}\gamma_i} \geq 0$ since $\bar{e}_{i2} \geq e_{i2}$. Finally, $\gamma_i^2 - \alpha_{i1}\alpha_{i2} \leq 0$ because $\alpha_{i1} > 0,\ \gamma_i < 0$.

But if $\gamma_i^2 - \alpha_{i1}\alpha_{i2} = 0$, then $F_1 = F_2 = 0$ where the cost is minimized with the maximum emission levels that achieve a firm's profit maximization without any restriction on emission levels. We do not need to consider this here. Therefore, it is satisfied that $\gamma_i^2 - \alpha_{i1}\alpha_{i2} < 0$.

For the second inequality holds, $e_{i1}{}^1 \geq 0$

$$\bar{e}_{i1}+\frac{\alpha_{i2}}{\gamma_i}(\bar{e}_{i2}-e_{i2})\geq 0\rightarrow \bar{e}_{i1}\gamma_i+\alpha_{i2}(\bar{e}_{i2}-e_{i2})\leq 0\ \because \gamma_i<0$$

Finally, $e_{i2}\geq \bar{e}_{i2}+\dfrac{\gamma_i}{\alpha_{i2}}\bar{e}_{i1}\rightarrow -\dfrac{\gamma_i}{\alpha_{i2}}\bar{e}_{i1}\geq \bar{e}_{i2}-e_{i2}$

By symmetry, $e_{i1}\geq \bar{e}_{i1}+\dfrac{\gamma_i}{\alpha_{i1}}\bar{e}_{i2}\rightarrow -\dfrac{\gamma_i}{\alpha_{i1}}\bar{e}_{i2}\geq \bar{e}_{i1}-e_{i1}$

APPENDIX D

The firm's supply function becomes $a_{i1} = \hat{\alpha}_{i2} p_1,\ a_{i2} = -\hat{\gamma}_i p_1$ if the firm sells in market 1, and $a_{i1} = -\hat{\gamma}_i p_{2,}\ a_{i2} = \hat{\alpha}_{i1} p_2$ if the firm sells in market 2. Let's substitute these values in the cost function.

$$C_1(a_{i1}, a_{i2}, l_{i1}) = \frac{\alpha_{i1} a_{i1}^{\ 2}}{2} + \frac{\alpha_{i2} a_{i2}^{\ 2}}{2} + \gamma_i a_{i1} a_{i2} + p_1 (l_{i1} - l_{i1}^0)$$

$$C_2(a_{i1}, a_{i2}, l_{i2}) = \frac{\alpha_{i1} a_{i1}^{\ 2}}{2} + \frac{\alpha_{i2} a_{i2}^{\ 2}}{2} + \gamma_i a_{i1} a_{i2} + p_2 (l_{i2} - l_{i2}^0)$$

$$C_1(a_{i1}, a_{i2}, l_{i1}) = \frac{\alpha_{i1} a_{i1}^{\ 2}}{2} + \frac{\alpha_{i2} a_{i2}^{\ 2}}{2} + \gamma_i a_{i1} a_{i2} + p_1 \left(l_{i1} - l_{i1}^0\right)$$

$$= \frac{\alpha_{i1} \hat{\alpha}_{i2}^2 p_1^{\ 2}}{2} + \frac{\alpha_{i2} \hat{\gamma}_i^2 P_1^2}{2} + \gamma_i \left(\hat{\alpha}_{i2} p_1\right)\left(-\hat{\gamma}_i p_1\right) + p_1 \left(\bar{e}_{i1} - \hat{\alpha}_{i2} p_1 - l_{i1}^0\right) \ \textit{where } l_{i1} = \bar{e}_{i1} - a_{i1} \ \textit{at optimum}$$

$$= p_1^{\ 2} \left\{ \frac{\alpha_{i1}}{2} \left(\frac{\alpha_{i2}}{\alpha_{i1}\alpha_{i2} - \gamma_i^2} \right)^2 + \frac{\alpha_{i2}}{2} \left(\frac{\gamma_i}{\alpha_{i1}\alpha_{i2} - \gamma_i^2} \right)^2 - \frac{\alpha_{i2}}{\alpha_{i1}\alpha_{i2} - \gamma_i^2} \frac{\gamma_i^2}{\alpha_{i1}\alpha_{i2} - \gamma_i^2} - \frac{\alpha_{i2}}{\alpha_{i1}\alpha_{i2} - \gamma_i^2} \right\} + p_1 \left(\bar{e}_{i1} - l_{i1}^0\right)$$

$$= p_1^{\ 2} \frac{\alpha_{i2}}{2} \left(\frac{\alpha_{i1}\alpha_{i2}}{k^2} + \frac{\gamma_i^2}{k^2} - \frac{2\gamma_i^2}{k^2} - \frac{2}{k} \right) + p_1 \left(\bar{e}_{i1} - l_{i1}^0\right) \ \text{where } \alpha_{i1}\alpha_{i2} - \gamma_i^2 = k$$

$$= \frac{p_1^{\ 2} \alpha_{i2}}{2} \left(\frac{k}{k^2} - \frac{2}{k} \right) + p_1 \left(\bar{e}_{i1} - l_{i1}^0\right) = \frac{p_1^{\ 2} \alpha_{i2}}{2} \left(-\frac{1}{k} \right) + p_1 \left(\bar{e}_{i1} - l_{i1}^0\right)$$

If we set $\frac{\alpha_{i2}}{k} = \frac{\alpha_{i2}}{\alpha_{i1}\alpha_{i2} - \gamma_i^2} = \hat{\alpha}_{i2}$ and use the characteristics of symmetry, we obtain

$$C_1\left(a_{i1}, a_{i2}, l_{i1}\right) = p_1 \left(\bar{e}_{i1} - l_{i1}^0\right) - \frac{p_1^{\ 2} \hat{\alpha}_{i2}}{2} = -\frac{p_1^{\ 2} \hat{\alpha}_{i2}}{2}$$

$$C_2\left(a_{i1}, a_{i2}, l_{i2}\right) = p_2 \left(\bar{e}_{i2} - l_{i2}^0\right) - \frac{p_2^{\ 2} \hat{\alpha}_{i1}}{2} = -\frac{p_2^{\ 2} \hat{\alpha}_{i1}}{2}$$

where $\bar{e}_{ij} = l_{ij}^0,\ j = 1,2$

APPENDIX E

As derived in the body of the chapter, the following equations are used in the simulation model.

Cost and benefit function

$$g_i(a_{i1},a_{i2}) = \frac{\alpha_{i1}}{2}a_{i1}^2 + \frac{\alpha_{i2}}{2}a_{i2}^2 + \gamma_i a_{i1}a_{i2}$$

where $\left(\bar{e}_{ij} - e_{ij}\right) = a_{ij} \geq 0,\ e_{ij} \geq 0,\ \alpha_{i1} > 0,\ \alpha_{i2} > 0,\ \gamma_i < 0,\ i = 1,\ldots,n,\ j = 1,2$

$$B_j(A_j) = \Omega_j A_j - \frac{\theta_j}{2}A_j^2 \text{ where } \Omega_j > 0,\ \theta_j > 0,\ A_j = \sum_i a_{ij},\ j = 1,2$$

$$B(A) = \sum_j B_j\left(A_j\right)$$

The first best case

$$p_1^* = \frac{\Omega_1\theta_2\sum_i\hat{\alpha}_{i1} + \Omega_2\theta_1\sum_i\hat{\gamma}_i + \Omega_1}{\theta_1\theta_2\{\sum_i\hat{\alpha}_{i1}\sum_i\hat{\alpha}_{i2} - (\sum_i\hat{\gamma}_i)^2\} + \theta_1\sum_i\hat{\alpha}_{i2} + \theta_2\sum_i\hat{\alpha}_{i1} + 1}$$

$$p_2^* = \frac{\Omega_2 + \theta_2\sum_i\hat{\gamma}_i p_1^*}{1 + \theta_2\sum_i\hat{\alpha}_{i1}}$$

$$a_{i1}^* = \frac{\alpha_{i2}p_1^* - \gamma_i p_2^*}{\alpha_{i1}\alpha_{i2} - \gamma_i^2} = \hat{\alpha}_{i2}p_1^* - \hat{\gamma}_i p_2^*$$

$$a_{i2}^* = \frac{\alpha_{i1}p_2^* - \gamma_i p_1^*}{\alpha_{i1}\alpha_{i2} - \gamma_i^2} = \hat{\alpha}_{i1}p_2^* - \hat{\gamma}_i p_1^*$$

$$A_1^* = AD_1^* = \frac{\Omega_1 - p_1^*}{\theta_1} = AS_1^* = p_1^*\sum_i\hat{\alpha}_{i2} - p_2^*\sum_i\hat{\gamma}_i$$

$$A_2^* = AD_2^* = \frac{\Omega_2 - p_2^*}{\theta_2} = AS_2^* = p_2^*\sum_i\hat{\alpha}_{i1} - p_1^*\sum_i\hat{\gamma}_i$$

The second best case

Abatement cap of the second best case

$$A_1^{**} = AD_1^{**} = \frac{\Omega_1 - \hat{p}_1}{\theta_1} = AS_1^{**}(\gamma_i = 0) = \sum_i \hat{a}_{i1} = \sum_i \frac{\hat{p}_1}{\alpha_{i1}} \text{ where } \hat{p}_1 = \frac{\Omega_1}{1 + \theta_1 \sum_i \frac{1}{\alpha_{i1}}}$$

$$A_2^{**} = AD_2^{**} = \frac{\Omega_2 - \hat{p}_2}{\theta_2} = AS_2^{**}(\gamma_i = 0) = \sum_i \hat{a}_{i2} = \sum_i \frac{\hat{p}_2}{\alpha_{i2}} \text{ where } \hat{p}_2 = \frac{\Omega_2}{1 + \theta_2 \sum_i \frac{1}{\alpha_{i2}}}$$

Multiple market (MM) in the second best case

$$p_1^{MM} = \frac{\sum_i \hat{\alpha}_{i1} A_1^{**} + \sum_i \hat{\gamma}_i A_2^{**}}{\sum_i \hat{\alpha}_{i1} \sum_i \hat{\alpha}_{i2} - (\sum_i \hat{\gamma}_i)^2}$$

$$p_2^{MM} = \frac{\sum_i \hat{\alpha}_{i2} A_2^{**} + \sum_i \hat{\gamma}_i A_1^{**}}{\sum_i \hat{\alpha}_{i1} \sum_i \hat{\alpha}_{i2} - (\sum_i \hat{\gamma}_i)^2}$$

$$a_{i1}^{MM} = \frac{\alpha_{i2} p_1^{MM} - \gamma_i p_2^{MM}}{\alpha_{i1}\alpha_{i2} - \gamma_i^2} = \hat{\alpha}_{i2} p_1^{MM} - \hat{\gamma}_i p_2^{MM}$$

$$a_{i2}^{MM} = \frac{\alpha_{i1} p_2^{MM} - \gamma_i p_1^{MM}}{\alpha_{i1}\alpha_{i2} - \gamma_i^2} = \hat{\alpha}_{i1} p_2^{MM} - \hat{\gamma}_i p_1^{MM}$$

$$AS_1^{MM} = \sum_i a_{i1}^{MM} = p_1^{MM} \sum_i \hat{\alpha}_{i2} - p_2^{MM} \sum_i \hat{\gamma}_i$$

$$AS_2^{MM} = \sum_i a_{i2}^{MM} = p_2^{MM} \sum_i \hat{\alpha}_{i1} - p_1^{MM} \sum_i \hat{\gamma}_i$$

Single market (SM) in the second best case

Prices are set up at the interval $\frac{\alpha_{k,1}}{\alpha_{k,2}} \le \frac{p_1^{2\,SM}}{p_2^{2\,SM}} = \frac{(p_1^{0\,SM} + \Delta_1)^2}{(p_2^{0\,SM} + \Delta_2)^2} \le \frac{\alpha_{k+1,1}}{\alpha_{k+1,2}}$

Abatements of a non-point source firm *i* (=*1…n*) under the condition that $l_{i2}^0 \ge \hat{e}_{i2}$, $l_{i1}^0 \ge \hat{e}_{i1}$ are

$\hat{a}_{i1}^{SM} = \hat{\alpha}_{i2} p_1^{SM}$, $\hat{a}_{i2}^{SM} = -\hat{\gamma}_i p_1^{SM}$ If a firm participates in market 1

$\hat{\hat{a}}_{i1}^{SM} = -\hat{\gamma}_i p_2^{SM}$, $\hat{\hat{a}}_{i2}^{SM} = \hat{\alpha}_{i1} p_2^{SM}$ If a firm participates in market 2

Abatements of a point source firm *t* (=*n+1…m*) are

$$a_{t1}^{SM} = a_{t2}^{SM} = 0$$

Aggregate supplies or Total SM Supplies (TSMS_j) are comprised of market supplies for the abatement *j* in the market *j* (SMS_j) plus complementary byproduct abatements for the abatement *j* in the other market.

$$AS_1^{SM} = \sum_{i=1}^{k} \hat{a}_{i1}^{SM} + \sum_{i=k+1}^{n} \hat{\hat{a}}_{i1}^{SM} = \sum_{i=1}^{k} \hat{\alpha}_{i2} p_1^{SM} + \sum_{i=k+1}^{n} \left(-\hat{\gamma}_i p_2^{SM}\right)$$

$$AS_2^{SM} = \sum_{i=1}^{k} \hat{a}_{i2}^{SM} + \sum_{i=k+1}^{n} \hat{\hat{a}}_{i2}^{SM} = \sum_{i=1}^{k} \left(-\hat{\gamma}_i p_1^{SM}\right) + \sum_{i=k+1}^{n} \hat{\alpha}_{i1} p_2^{SM}$$

VITA

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