# An Approach to Hydro-Economic Modeling Using Partial Equilibrium Optimization

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# Table of Contents


Table of Contents ........ 2
Part 1 – The Hydro-Economic Approach to Water Resources Management ........ 4
Why Use Hydro-Economic Modeling for Water Resources Planning? ........ 4
Basics of Hydro-Economic Models ........ 5
Water Economic Valuation ........ 7
Elements of Partial Equilibrium Modeling ........ 9
Part 2 - Methodology and Application ........ 9
Step 1 –Developing Marginal Cost Curves for Water Supply ........ 10
Canal Irrigation Supply Costs ........ 12
Groundwater and Drain Water Irrigation Supply Costs ........ 14
Flood Control Storage Supply Costs ........ 18
Instream Flow Supply Costs ........ 19
Step 2 – Determining the Water Flux Relationships ........ 21
Step 3 - Developing Marginal Price Curves for Water Demand ........ 23
Irrigation Water Demand Prices ........ 24
Flood Control Storage Marginal Demand Prices ........ 26
Instream Flow Marginal Demand Prices ........ 30
Step 4 – Solving the Integrated Problem ........ 33
Simplified PE Model Applications ........ 35
Example 1: PE Modeling using Mixed Complementary Programming ........ 36
Example 2: Managing Hydrologic Externalities in the Lower Boise Basin ........ 39
Example 3: Managing Rival and Non-Rival Water Demands in the Henry's Fork Basin ........ 43
References ........ 45
Appendix A IDEP Demand Function Calculator ........ 50
Appendix B GAMS PE Model Code with Hydrologic Externalities ........ 58
Appendix C GAMS PE Model Data for Hydrologic Externalities ........ 65
Appendix D GAMS PE Model Code with Rival and Non-Rival Demands ........ 68
Appendix E GAMS PE Model Data for Rival and Non-Rival Demands ........ 80

# Figures

Figure 1: Basin-wide hydro-economic modeling, modular components .......................... 6
Figure 2: A block rate supply-cost function ........................................................................ 7
Figure 3: A requirements demand function and a constant elasticity demand function.... 8
Figure 4: Canal diversion supply cost for natural flow and storage water at the river point of diversion. .......................................................................................................................... 13
Figure 5: Fitted DTW response to Boise Project canal seepage, for five groundwater pumping rates. ................................................................................................................. 16
Figure 6: Fitted drain return flow response to Boise Project canal seepage, for five groundwater pumping rates................................................................................................ 16
Figure 7: Upward shifts in groundwater irrigator's supply cost due to reduction in Boise Project canal seepage. ........................................................................................................ 17
Figure 8: Rightward shift in drain irrigator's supply constraint due to reduction in Boise Project canal seepage and groundwater pumping. The influence of groundwater pumping on the drain constraint is indicated by the right to left shift in symbols of the same color. ........................................................................................................................................ 18
Figure 9: New reservoir storage marginal supply-cost function..................................... 19
Figure 10: Horizontal summation of water demand quantities for two rival irrigated crops. .............................................................................................................................. 25
Figure 11: Marginal water demand-price data for high value and low value crops in a groundwater irrigated zone. ............................................................................................. 26
Figure 12: Marginal water demand-price data for high value and low value crops in drain flow irrigated zone. ............................................................................................................ 26
Figure 13: Annually expected Boise basin flood damage as a function of unregulated flow at Glenwood Bridge................................................................................................ 27
Figure 14: Utility function for Boise basin flood storage. ............................................... 28
Figure 15: Marginal utility (demand-price) function for Boise basin flood storage........ 29
Figure 16: Shifts in the marginal utility function for flood control storage due to increased flood probability. ............................................................................................. 30
Figure 17: Vertical summation of water demand-prices for two non-rival eco-services 31
Figure 18: Vertical summation of Island Park and St Anthony reach demand-prices for instream flow. ................................................................................................................. 33
Figure 19: PE model equilibrium solution with non-binding supply constraint............... 38
Figure 20: PE model equilibrium solution with binding supply constraint. .................... 39
Figure 21: Schematic of three node PE model with a hydrologic externality. ................ 39
Figure 22: Schematic of four node PE model with rival and non-rival water demands.. 44

# Part 1 – The Hydro-Economic Approach to Water Resources Management

## *Why Use Hydro-Economic Modeling for Water Resources Planning?*

> ***"Managing water as an economic good is an important way of achieving efficient and equitable use, and encouraging conservation and protection of water resources."*** *- U.N. Dublin Statement on Water and Sustainable Development, 1992*[1]

Conventional, economics-based water planning approaches often fail to adequately evaluate the economic efficacy of water projects by ignoring the dynamic relationship that exists between water supply and demand. More specifically, under the conventional approach to water management, which can be referred to as the supply management approach, the value of water is based upon the amount of compensation necessary to recover distribution costs (O&M, infrastructure, construction, etc.) with water demand forecasts assumed to be static and not affected by the cost of the supplied water (Howitt and Lund, 1999). The demand management approach, on the other hand assumes that the costs associated with developing and delivering water supplies is invariant, and focuses on the value of water relative to the amount of water demand and controlling factors such as regulation, conservation, and availability of infrastructure. By ignoring how the demand for water changes as a result of changes in price and ignoring the change in cost associated with supplying greater amounts of water (referred to as the price/cost elasticity), both of these conventional approaches to water management fall short in their ability to adequately inform the development of effective water management strategies.

Hydro-economic analysis presents an alternative to the Demand Management and Supply Management approaches. This type of analysis utilizes economic concepts to understand how the supply and demand for water are affected by changes in the cost of developing and delivering water supplies and how the demand for these water supplies is based on the value that can be derived from the water by the water users (ie crop value). This approach moves away from a static view with a fixed and invariant water demand, to a view where the demand for water is related to the economic concept of "value". Use

[1] Quoted in J.J. Harou et al. 2009

of an economic approach in water management and planning, particularly under conditions where water is a scarce resource, enhances the ability to develop management alternatives that are based on an efficient and equitable use of water, thereby reducing wasteful practices at both the individual and institutional scale (Harou et al., 2009).

Given that the value of water changes with both quantity and type of use, understanding the economic costs and benefits associated with meeting the demand for water resources allows for a more effective comparison of water management alternatives. Hydro-economic analysis provides a framework for incorporating multiple-, and often competing-, objectives (ie water supply, flood control, hydropower, recreation, ecosystem requirements, etc) into a single analysis. By translatingthe value of each objective (or hydro-service) into its respective economic benefit, hydro-economic analysis allows for a direct evaluation of the economic efficacy of competing water management alternatives. Such an approach allows for a more holistic evaluation of water resource management actions, resulting in the development of more effective and sustainable water management strategies, and in turn reducing the likelihood of undesirable outcomes or unsustainable plan.

## *Basics of Hydro-Economic Models*

Hydro-economic modeling can be traced back to the use of water demand curves developed in the 1960s and 1970s by Jacob Bear and others (1964, 1966, 1967, and 1970) for optimization of water resource systems in arid regions of Israel and the south-western United States. Researchers since then have used different names to refer to applications and extensions of this integrated systems approach to hydrologic, engineering, and economic water modeling including: hydrologic–economic (Gisser and Mercado,1972), hydroeconomic (Noel and Howitt, 1982), institutional (Booker and Young, 1994), demand and supply (Griffin, 2006) analysis approaches, among others.

Hydro-economic models have the ability to represent physical, environmental, and economic aspects of basin-scale water resource systems in an integrated framework that accounts for the value of water in terms of the services or benefits it generates for users (Harou et al, 2009; Brouwer and Hofkes, 2008). There are two basic forms for hydro-economic models. The more holistic configuration combines hydrology and economic optimization into a single model, while the modular configuration (illustrated in Figure 1) involves a transfer of supply and demand information from an independent hydrologic model to an economic optimization model. For basin-scale studies, the modular approach is generally preferred because it allows for more robust and realistic representation of basin hydrology and more efficient optimization of a basin-wide network of water supply and demand nodes (Brouwer and Hofkes, 2008).

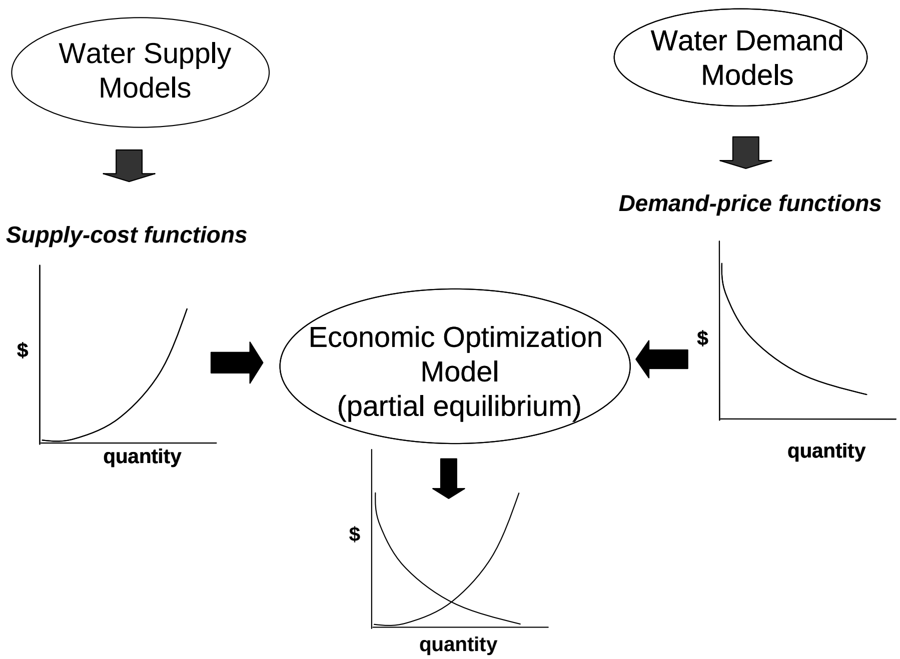



**Figure 1: Basin-wide hydro-economic modeling, modular components**

Most hydro-economic models share basic elements including spatial representation of hydrologic flows and water supply infrastructure, supply costs and constraints, economic demands, and operating rules affecting water allocations. Basin-wide hydro-economic model application involves five basic steps:

1. Develop a basin-wide network consisting of nodes (representing locations where water can be supplied or demanded) and links (representing the conveyance system that is responsible for delivering water from supply nodes to demand nodes).
2. Develop relationships that describe the marginal cost for supplying water from each supply node, the marginal benefits accrued through the use of water by each

demand node, the cost of conveying water between each water supply node and each demand node, and the loss of water through each part of the conveyance system.

3. Calibrate the parameters for the basin-wide model relative to available hydrologic and water-budget data in the basin.
4. Develop alternative water infrastructure and management scenarios and predict changes in the physical and cost relationships between water supplies, demands, conveyance costs, and conveyance losses.
5. Perform a Cost Benefit Analysis (CBA) comparing the various water infrastructure and management scenarios to determine the most cost effective water management scenario(s).

## *Water Economic Valuation*

The economic valuation of water can occur from a supply or demand perspective and produces a supply-cost function or a demand-price function. For water suppliers, the economic value of water is determined by the fixed costs of infrastructure and the operating costs associated with supplying water to users. When calculated by engineering economists, a water supply-cost curve is often simplified into a block rate structure (illustrated in Figure 2) with price steps reflecting the increasing capital and operating costs associated with the addition of new supplies.

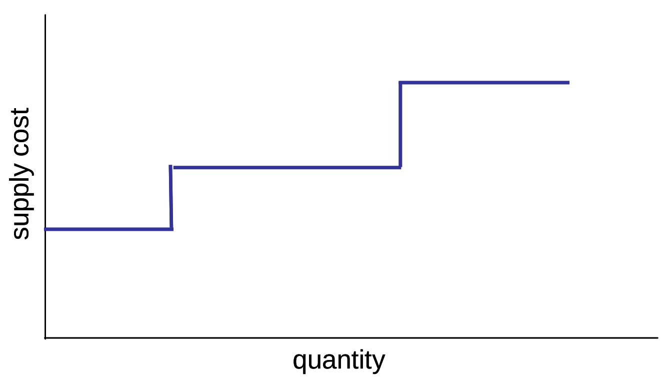



**Figure 2: A block rate supply-cost function**

From the demand perspective, water is an input into a production process (such as irrigation, hydropower generation, or recreation) and water demand is therefore derived from the demand for the final product produced.  Price elasticity is also an important component in the valuation of water from the demand perspective and represents the variation inwillingness-to-pay for water with respect to varying quantity of water provided.

Demand price elasticity varies with type of water use (agricultural, municipal, industrial, recreational etc.) and with hydrologic condition (e.g. dry year, normal year, wet year, etc).  A steeply sloping demand curve implies a water use that is more price responsive (has low price-elasticity) and a valuation that is more sensitive to water availability.  Meanwhile, a demand curve that is gently sloped implies a water use that is less price responsive (high price-elasticity) and a valuation that is less sensitive to availability. .Figure 3a illustrates a situation where the demand for water is inelastic, in other words there is no change in the demand for water with respect to price.  Such a relationship would represent a situation where there is a “requirement” to provide a specified amount of water to meet the demand, no matter what the cost.  Figure 3b illustrates a situation where the demand for water is elastic, in other wordsthe demand for water does change with respect to its price.

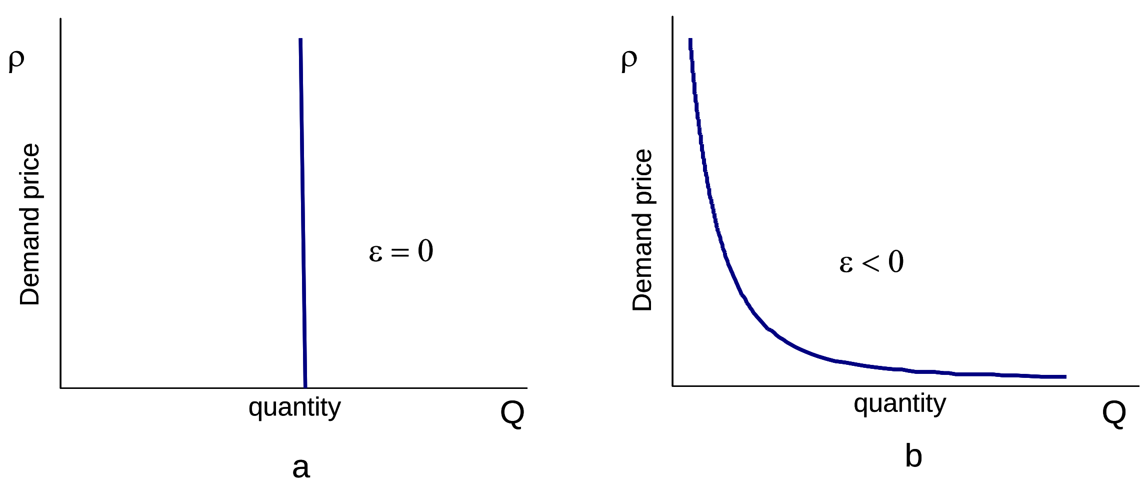



**Figure 3:  A requirements demand function and a constant elasticity demand function.**

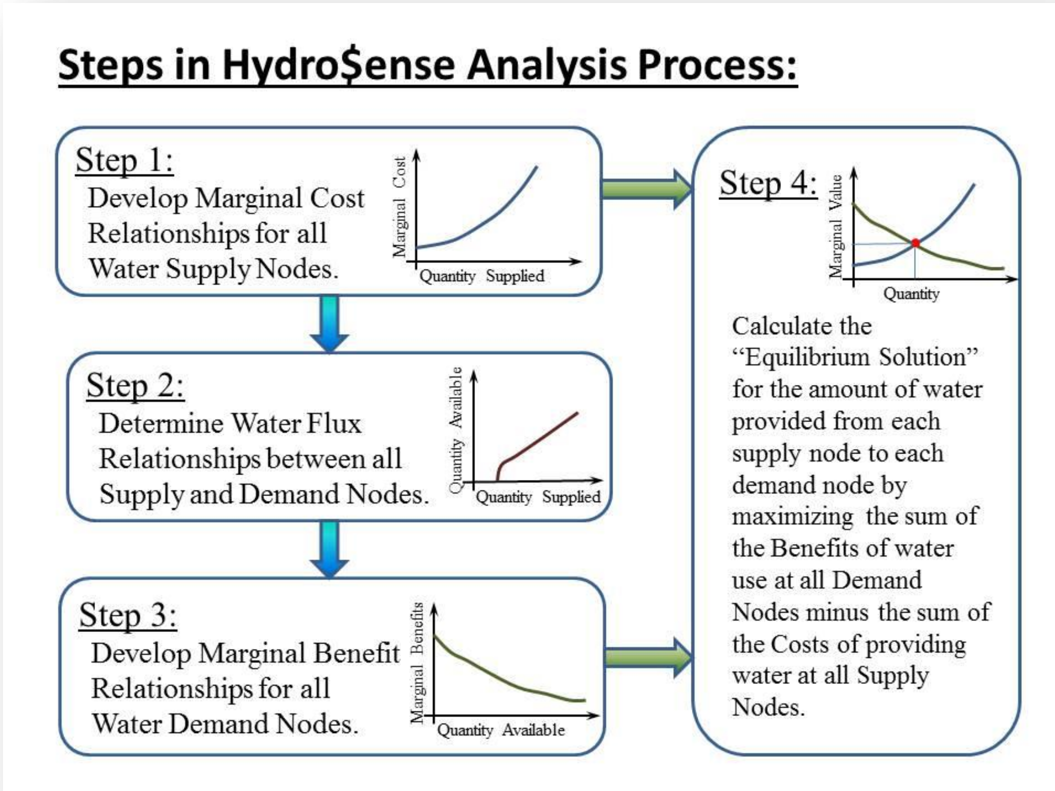
### *Elements of Partial Equilibrium Modeling*

The mathematical goal in hydro-economic modeling is to determine the point where a market equilibrium exists between the marginal costs of supplying water and the marginal benefits that can be accrued by the use of the water at demand nodes to produce other economic goods (e.g. crops, ecosystem services, hydropower, etc.). This equilibrium is referred to as a Partial Equilibrium (PE) and is the point where the maximum economic net benefit can be accrued by optimally distributing water between the supply nodes and demand nodes. The concept of marginality, which expresses the supply-cost or demand-price associated with one additional unit of water (at the margin),is central in PE modeling. The microeconomic equi-marginal principle states that in an optimal allocation of water, each water user derives the same value (or utility) from the last unit of water allocated (Harou et al, 2009).

PE modeling is not equivalent to advocating water marketing, nor does it assume all water resources are private goods. Constraints on private allocations, and on demands for public goods such as river system eco-services, are readily included in hydro-economic models.

## Part 2 - Methodology and Application

Generally speaking, hydro-economic modeling follows a four step process (illustrated in Figure 4). The first three steps define the water supply, demand, and delivery relationships as mathematical functions for input into a PE solver. The fourth step involves using a PE solver to find the equilibrium solution given the mathematical functions developed in the first three steps. There is essentially no limit to the number or form of the mathematical functions used in the PE model. The only requirement is that they define relationships in terms of price (or cost) and quantity alone. These steps are described in more detail below, and provide examples of their application.

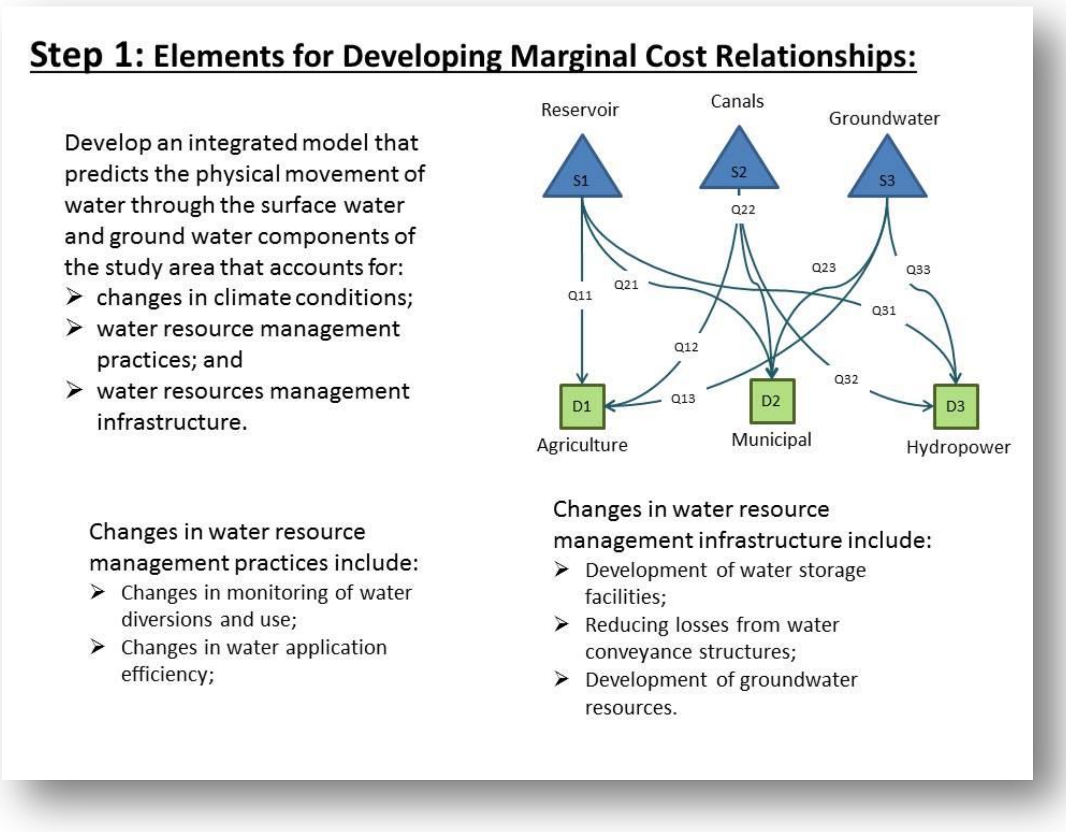



### *Step 1 –Developing Marginal Cost Curves for Water Supply*

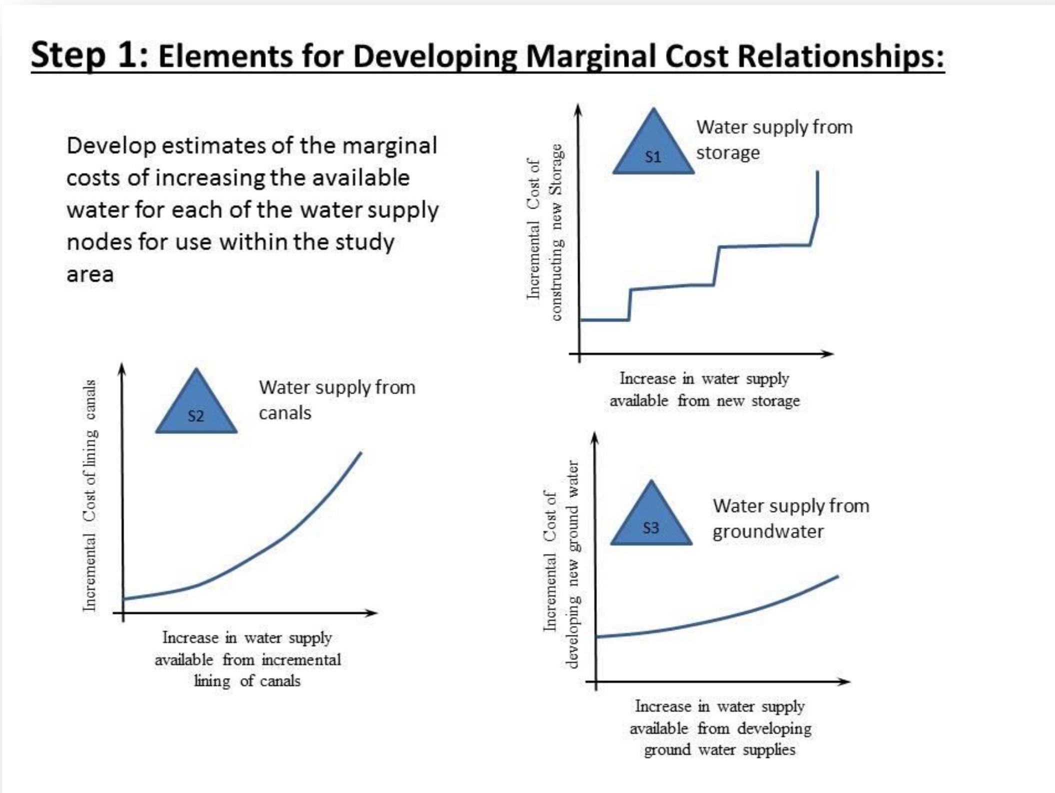
Water valuation from the supply perspective results in a supply-cost curve that represents the unit change in price for a unit change in quantity supplied, taking into account the costs and constraints associated with:

- development of the water supply infrastructure, such as the construction of groundwater wells, the building of water storage facilities, and the development of water conveyance structures;
- operation of the infrastructure, such as the energy and maintenance required to operate pumps, and the maintenance required to ensure the efficient and safe operation of conveyance systems such as canal and pipe system;
- and regulatory considerations associated with water rights administration and environmental legislation and policies.

The purpose of this step is to define the cost of supplying water to each demand node with mathematical functions which can then be input into the partial equilibrium optimization model. In cases where a demand node has multiple supply sources, a separate function can be developed to represent the cost of delivering water from each source. As stated previously, there is essentially no limit to the number or form of these mathematical functions as long they calculate cost in terms of a quantity supplied (e.g. y = f(x), where y is cost and x is a quantity of water). Figure 5 provides a schematic representation of the analysis elements that must be completed in this step.




The form of the supply-price function will depend upon the nature of the diversion and the supply and the factors influencing the cost to deliver water from the supply to the diversion. It is up to the modeler to identify the level of detail required for a particular study and which factors should be considered in the development of these supply-cost functions. Figure 6 depicts the general shape of the marginal cost curves that would be expected d for various types of water supplies within a study area. The following sections provide a more detailed discussion of the development of supply-cost functions for various types of supplies, namely: canal irrigation (surface water) supply, groundwater and drain water irrigation supply, flood control storage supply, and instream flow supply.




## Canal Irrigation Supply Costs

Water supply costs for canal irrigators typically have a stepped block-rate structure. The lowest step typically represents the cost associated with the delivery of natural flows that simply pass through reservoirs (determined by water rights associated with the demand). Higher steps typically reflect the added cost of water delivery from reservoir storage (determined by operation and maintenance of existing infrastructure and/or repayment costs for the construction of new facilities). Figure 6 shows an example of the block-rate cost structure for irrigation water delivered to the head (river point of diversion) of four different canal systems within the Boise Project. The quantity of natural flow and storage water available for delivery to each canal system is constrained by the water rights and storage account space owned by each system. In this example, supply costs range from $2.60 to $7.20 per acre-foot (AF) for natural flow (reflecting the various canal system O&M costs), while the delivery of storage water adds an additional $1.60/ per AF (reflecting reservoir O&M costs).

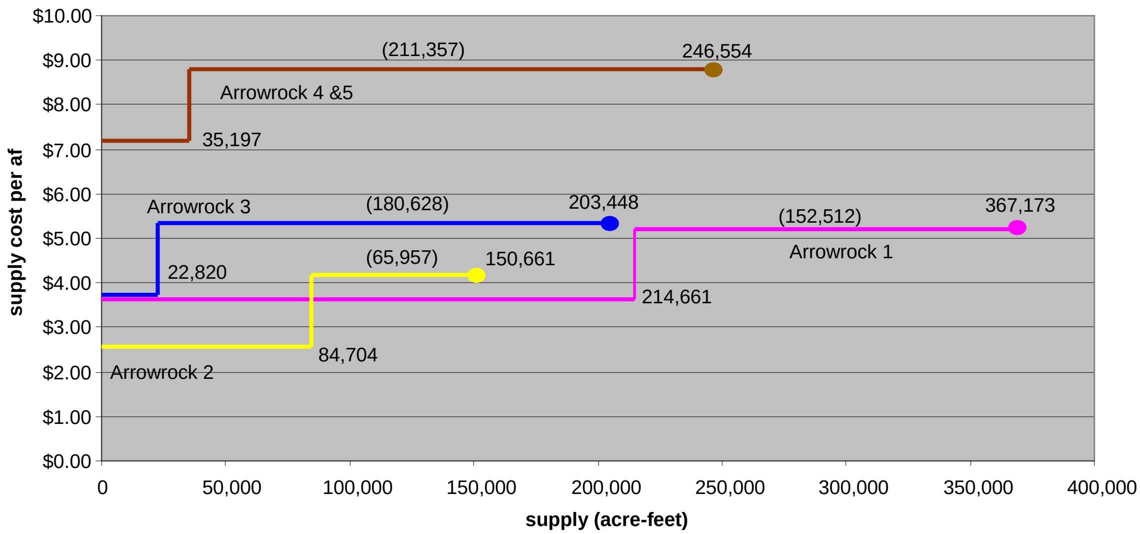



**Figure 4: Canal diversion supply cost for natural flow and storage water at the river point of diversion.**

Conveyance losses associated with delivery of irrigation water to end users (at farm head-gates further down the canal) should also be considered in the supply-price function and are dependent upon the characteristics of the canal infrastructure and basin hydrology. The effective supply cost, or the cost to deliver water to a particular farm head-gate, will often be higher than the cost to deliver water to the head of the canal system due to conveyance losses that occur between the head of the canal and the farm head-gate. There are two options to account for conveyance losses in a PE model. Given a conveyance cost that can be represented by the following equation:

***Conveyance cost = river point of diversion supply cost · % seepage loss***

The cost to deliver the water to the farm head-gate could be computed as

***effective supply cost = river point of diversion supply cost · (1+ % seepage loss).***

Alternatively, the amount of water made available to the demand nodes can be adjusted to account for the loss of water through the conveyance system, such that

***Available water for Demand = Water from Supply Node – Conveyance Losses***

## Groundwater and Drain Water Irrigation Supply Costs

Supply costs for groundwater and drain water irrigators can often largely be determined by pump operating costs. For both groundwater and drain water irrigators, supply-cost curves (representing the unit change in cost per unit change in diversion or pumping rate) can be estimated from power costs, pump characteristics (efficiency, etc.), and pumping lift. For drain water irrigators, pumping lift is fixed and supply cost is a function of pumping rate alone. However, for groundwater irrigators, pumping lift is not only dependent upon the general depth to groundwater (DTW), but is also influenced directly by pumping rate.

Taking this into account and incorporating any costs associated with the delivery of irrigation water from the well-head to the field (which are likely fixed costs), the marginal supply-cost function for groundwater irrigators can be expressed as

$$\textit{groundwater supply cost} = G_1 + G_2 \cdot \textit{pumping lift}, \qquad (3)$$

Where $G_1$ is the cost of delivering one AF of irrigation water from the well head to the field and $G_2$ is the cost of lifting one AF of water one foot in the well bore. For drain water irrigators, where water supply costs depend only on the fixed costs associated with pumping and delivering one AF of water from the drain to the field, the marginal supply cost function can be expressed as a constant rate

$$\textit{drain water supply cost} = G_1, \qquad (4)$$

regardless of how much water is diverted from the drain.

While the cost of diversion (per AF) may be constant for drain water diverters, these entities have no control over the availability of drain return flow, which is subject to other factors such as canal seepage and groundwater pumping rates. Similarly, groundwater irrigators have little control over changes in depth to groundwater and the associated changes in cost of diversion. In situations where groundwater elevations and drain water return flows are influenced by canal seepage, decreases in canal seepage will result in increased depth to groundwater (and therefore increased pumping lift) and decreased drain return flow availability. In such cases the cost of diversion is dependent on (or constrained by) groundwater processes in addition to the quantity of diversion and the use of groundwater models to generate response functions can help reduce the function into terms of diversion quantity alone (as is necessary for input into the PE trading model).

The groundwater and drain flow response functions for various locations can be estimated by performing a series of hydrologic modeling runs with incremental changes in a particular stressor of interest (e.g. groundwater pumping rate or canal seepage rate). The output from these model runs provides a series of points along a curve that relate the depth to groundwater (or drain flow response) to incremental changes in the stressor. Where more than one stressor must be considered, the entire series of model runs can be repeated for each incremental change in the additional stressor. The data points provided by the multiple model runs can then be used to fit analytic response functions that define depth to groundwater or drain flow response in terms of the particular stressor.

Figures 5 and 6 illustrate an example where the groundwater and drain flow responses to canal seepage and groundwater pumping rates were evaluated using a series of model runs. As can be seen in Figure 5, decreases in canal seepage result in increasing depths to groundwater, which in turn increase the cost of using groundwater as a water supply. Figure 6 illustrates the reduction in drain flows that occurs as a result of decreases in canal seepage, thereby making less drain flow water available for use within the study area In this example the response function for pumping lift (Equation 1) at a particular location has a non-linear form representing the nature of a shallow aquifer that transitions from confined to unconfined as canal seepage is reduced:

$$\boldsymbol{pumping\ lift} = \boldsymbol{C_1 e^{(C_2 * canal\ seepage + C_3 * groundwater\ pumpage\ rate)}} \qquad (1)$$

Meanwhile, the response function for drain flow is assumed to have the form:

$$\boldsymbol{drain\ flow} = \boldsymbol{D_1 \cdot e^{(D_2 \cdot canal\ seepage)} + D_3 \cdot groundwater\ pumping\ rate).} \qquad (2)$$

Values for the coefficients $\boldsymbol{C_1, C_2}$ ***and*** $\boldsymbol{C_3}$ and $\boldsymbol{D_1, D_2}$ ***and*** $\boldsymbol{D_3}$ can be obtained using a non-linear least squares regression procedure.

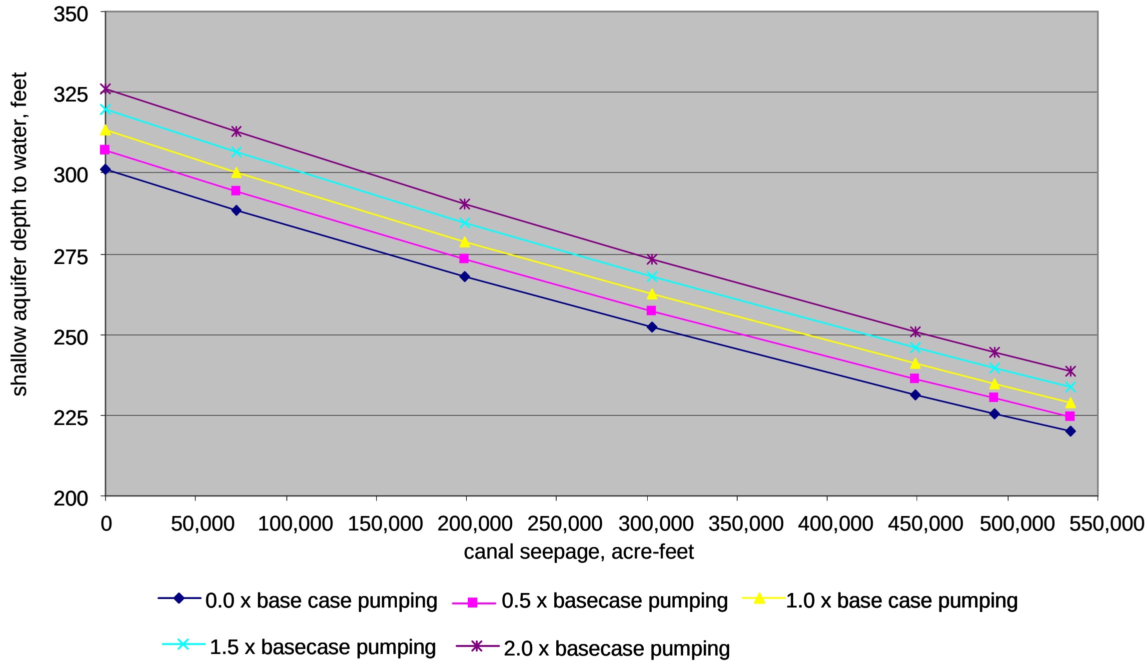



**Figure 5**: **Fitted DTW response to Boise Project canal seepage, for five groundwater pumping rates.**

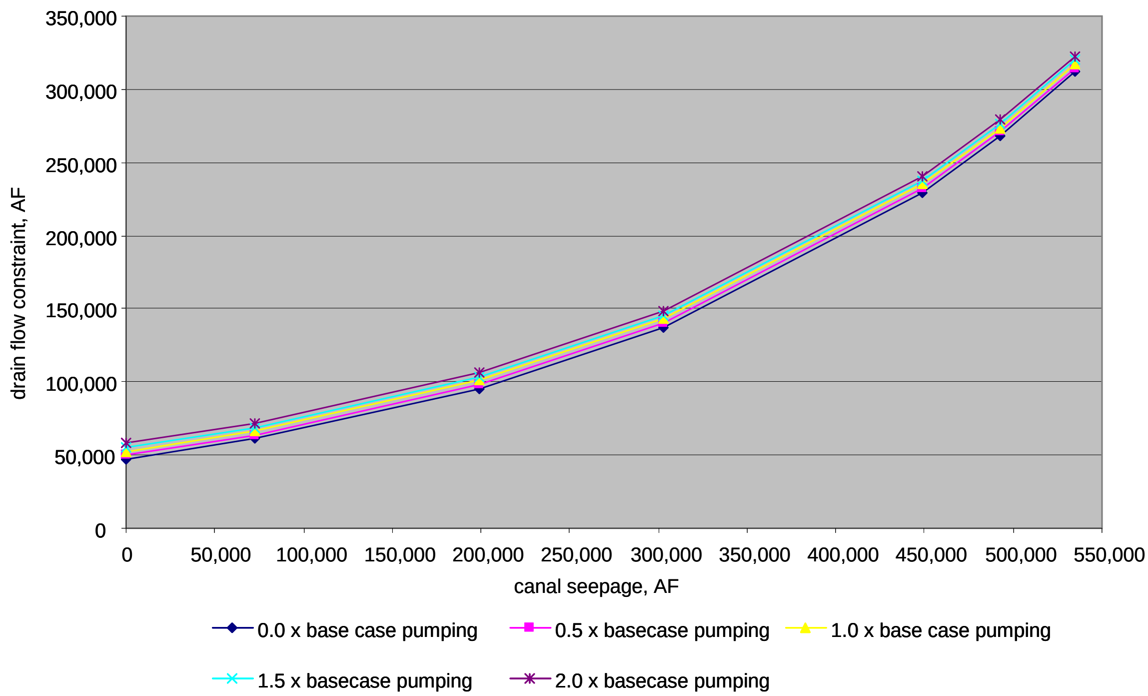



**Figure 6: Fitted drain return flow response to Boise Project canal seepage, for five groundwater pumping rates.**

Taken together, the relationships represented by Equations 1 and 2, and the response functions represented by Equations 3 and 4, can be used to generate supply-cost functions that are defined in terms of diversion rate alone. Figure 7 shows the marginal supply cost for groundwater in one particular groundwater response zone as a function of pumping rate and canal seepage rate. Figure 8 shows the marginal supply cost functions for drain water in one particular drain water response zone. Since the cost per AF is fixed for drain water irrigators, canal seepage and ground water pumping affects only the quantity of drain water available and not the supply-cost. In the example of varying canal seepage, multiple PE model runs will be required, one for each canal seepage rate. The results from the multiple PE model runs can then be compared to one another to evaluate the impact of canal seepage on the system.

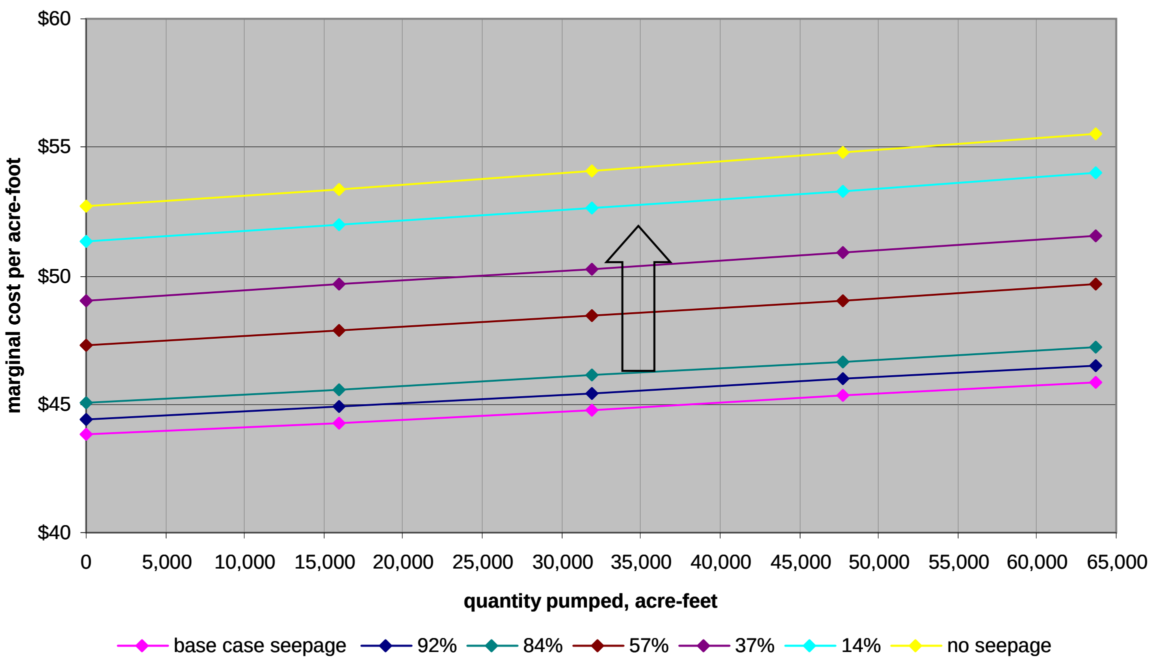



**Figure 7: Upward shifts in groundwater irrigator's supply cost due to reduction in Boise Project canal seepage.**

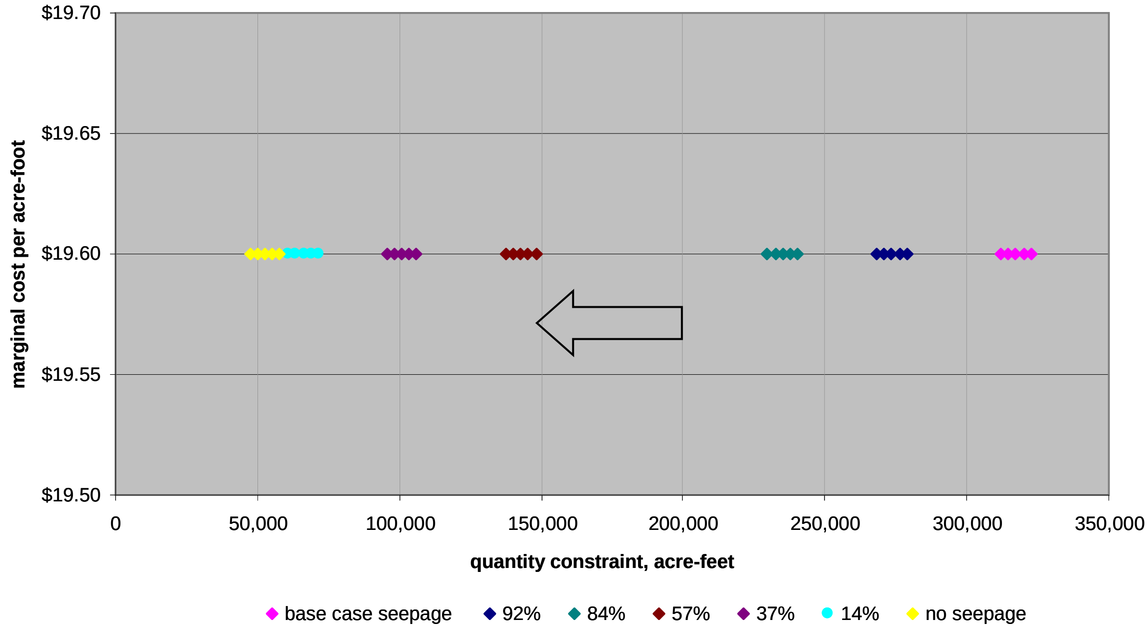



**Figure 8: Rightward shift in drain irrigator's supply constraint due to reduction in Boise Project canal seepage and groundwater pumping. The influence of groundwater pumping on the drain constraint is indicated by the right to left shift in symbols of the same color.**

## Flood Control Storage Supply Costs

Supply costs for new flood control storage typically take on a form that is analogous to the stepped block-rate structure shown previously in the section on calculating supply costs for canal irrigation. The lowest step represents the supply cost of current flood control storage and subsequent steps represent the supply costs associated with delivery of new reservoir storage for additional flood control. The supply-cost functions associated with new reservoir storage will likely vary between individual reservoir storage options.

For example, based on the options for new reservoir storage outlined in the Army Corp of Engineers Boise Basin Water Storage feasibility study (USACOE, 2010), construction of a larger dam at Arrowrock reservoir would provide 317,000 AF of new storage at an estimated construction cost of $2,700/AF, and a new Twin Springs dam and reservoir would provide 304,000 AF of new storage at an estimated construction cost of $3,600/AF. Assuming that a new dam and a new reservoir would have 100-year life spans, the annualized per AF reservoir construction costs would be $27/AF/year for additional Arrowrock reservoir storage and $37/AF/year for new Twin Springs reservoir storage.

The resulting flood storage supply-cost function, illustrated in Figure 9, incorporates existing flood control storage (assumed by USACOE to be 987,000 AF) and possible future flood control storage options. The curve starts at $1.60/AF/year, representing the cost of existing flood control storage (assumed to be equivalent to the current O&M charge for irrigation storage and assumed by USACOE to total approximately 987,000 AF). The cost of supply then rises to $28.60/AF/year with the construction of a new Arrowrock dam and then to $38.60/AF/year with the addition of Twin Springs reservoir. Note that the shape of this curve is dependent upon the order in which the new storage projects are added. This particular curve assumes that the least expensive option, in terms of annualized cost, would be implemented first. Other factors may influence this order.

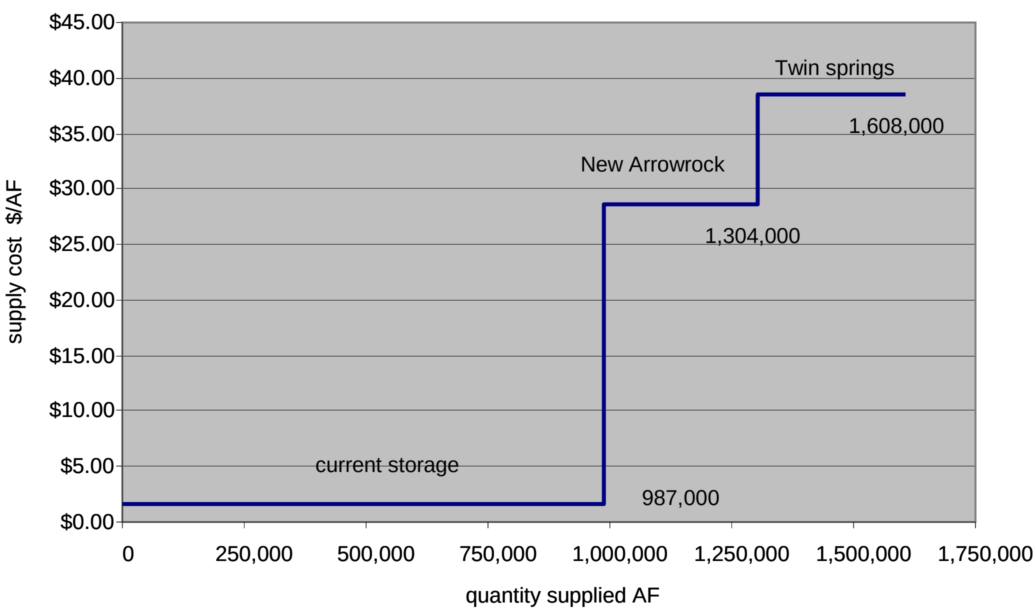


**Figure 9: New reservoir storage marginal supply-cost function.**

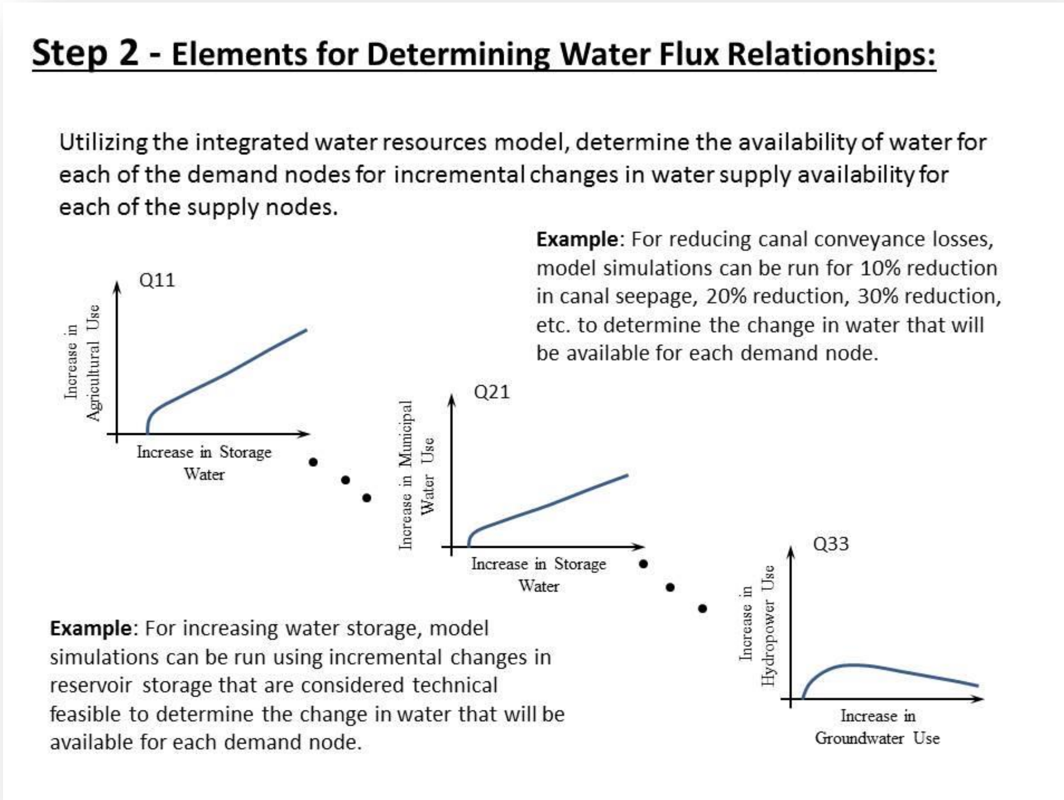
## Instream Flow Supply Costs

The meaning of the term "instream flow" has evolved over the years, but usually describes the quantity of water set aside to sustain river ecology and river eco-services. An instream flow regime may be a single-value minimum flow recommendation, but more often it describes a range of natural flow conditions that vary according to the time of year, the river reach, and the type of eco-services provided (fisheries, recreation etc).

In situations where instream flow demands can be used by downstream ) irrigation and/or hydropower demands (defined as a non-rival demand), the supply cost of instream flows is borne by these entities. In situations where instream flow demands cannot be used by other consumptive uses (rival demands), supply costs may be derived from water acquisition costs (e.g. rental pool rates); or if instream flows are "requirements" through Reclamation O&M, the costs borne by Reclamation (a federal agency) are passed along to the public through taxes.

In the Henrys Fork (HF) river basin, nearly all instream flows are non-rival with irrigation demands of the Freemont Madison Irrigation District (FMID) (Van Kirk et al, 2011), thus instream flow supply costs are borne mainly by HF irrigation entities. Depending on canal O&M costs, the resulting FMID supply cost for irrigation water ranges from $0.29/AF to $0.59/AF for natural flow and an additional $3.00/AF for water released from Island Park storage.

### *Step 2 – Determining the Water Flux Relationships*



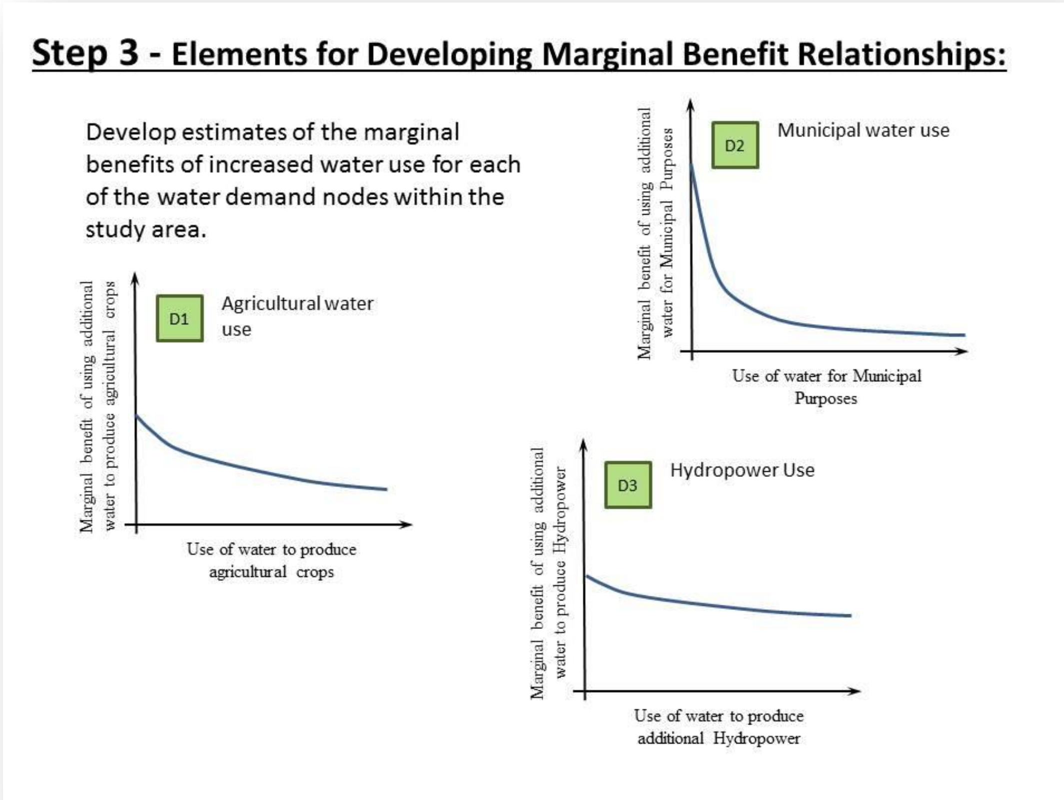

In order to link the marginal cost associated with providing water from the supply nodes to the benefits associated with utilizing water at the demand nodes, a model (or mathematical relationships) must be developed to simulate the movement of water between all of the supply and demand nodes within the study area. The model used to complete this step can be as simple as a water budget, to something as complex as a physically-based model that simulates the behavior of water movement throughout the study area. The type of model developed will depend on the available resources, hydrologic data, and modeling expertise associated with the project, as well as the types of simulations that are needed to develop the relationships to complete the PE economic optimization analysis.

Once developed, the model is used to determine the relationships between the extraction of water from a supply node and the amount of water delivered to a demand node within the study area. These relationships must be determined for the conveyance of water between each supply and demand node and for each water management scenario being considered. For example, if the potential water management scenario being considered is the lining of canals within the Boise Project area, simulations would be performed to determine the reduction in canal seepage that would be associated with lining a certain percentage of the canals. The simulation model developed in Schmidt et al. (2013) was used to determine the reduction in canal seepage, and hence the increase in water available to the demand nodes relying on delivery of water through the canal system and the impacts on depth to groundwater and drain flow, for a range of canal lining options within the Boise Project Study Area (see Figures 5, 6, 7 and 8). The results of each of these simulations was then used to determine changes to the marginal costs associated with providing water from each supply node, and the amount of water that can be delivered to each demand node.

In terms of the changes to the marginal cost relationships, it was assumed in the study that there would be no changes to the natural inflow to the reservoirs and storage supply node costs. However, by lining a portion of the canal, the marginal cost relationships for the ground water supplies are changed. The marginal costs for groundwater change as a result of increased depth to groundwater and the associated increase in pumping cost for ground water users (see Figure 5). Supply constraints for the drain water were also altered by canal lining. While the marginal costs for drainage water do not change, the availability of drain water is lowered due to the reduction in seepage losses in the canal that occur when the canal is lined (see Figures 6 and 8).

This analysis must be performed for each water management scenario under consideration. Such scenarios might include canal lining, increasing on-farm irrigation efficiency, or the development of new storage facilities. Examples of the types of analyses that must be performed can be found in the study by Schmidt et al. (2013), which evaluated how changes in water management conditions would impact water use in the Boise River Basin from a hydro-economic perspective.

*Step 3 - Developing Marginal Price Curves for Water Demand*




Step 3 in the hydro-economic analysis procedure requires the development of relationships representing the marginal benefits associated with increased use of water for each water demand in the study area. Two broad approaches are available to model water demand (Kindler and Russell, 1984) and develop demand functions: inductive techniques, which rely on econometric- or statistical-analysis of observed data to estimate price-response and deductive methods which can be viewed as more of a modeling approach using production functions and mathematical programming.

The inductive method is commonly used for determining hydropower and instream flow water demands. Demand prices for hydropower flows are often calculated using alternative-cost techniques, where the cost of hydropower is compared to the next less expensive alternative (Gibbons, 1986; Booker and Young, 1994). Demand prices for instream flows (discussed in more detail later in this chapter) can be calculated based on recreation travel costs or user surveys.

Deductive methods are more commonly used for determining agricultural water demand (Tsur et al., 2004; Young, 2005). Irrigation demand prices are typically developed using deductive modeling approaches the employ the use of crop production models, commodity prices and crop acreages to determine the relationship between the amount of irrigation water used and the value of the crop produced (Martin et al., 1984).

**Irrigation Water Demand Prices**

Demand-price relationships can be developed using the *Irrigation Water Demand from Evapotranspiration Production Function* (IDEP) calculator (IWRRI, 2008). This calculator (described in greater detail in Appendix B) uses commodity prices and the evapotranspiration (ET) production function of Martin and Supalla (1989) to derive static, short-term demand for irrigation water for a particular crop. This is accomplished by transforming the ET production function into an irrigation water production function through the use of an exponent related to crop irrigation efficiency. The IDEP calculator can derive these exponents for up to six crops using basin-specific production and agronomic inputs. The calculator assumes that market mechanisms have already maximized crop acreages and the mix of crops and therefore all existing constraints on crop distribution are assumed to be fully reflected in the status-quo allocation of crops to lands. The IDEP calculator also assumes that limited water supplies will be optimally delivered when most needed and does not consider seasonal demand for irrigation water (only full-season volume delivered).

Water demand for a mix of crops is calculated by horizontally summing the demands of individual crops at every marginal price, thus ensuring crops are allocated water on an equal-marginal basis (Figure 10). Although crop mix is fixed in the horizontal summation, lower value crops may drop out of production at higher prices. The IDEP summation of marginal water demand quantities for high value cash crops and for low value field crops plots as a series of steps, indicating the price points at which different crop lands are taken in or out of production as the price of irrigation water decreases or increases.

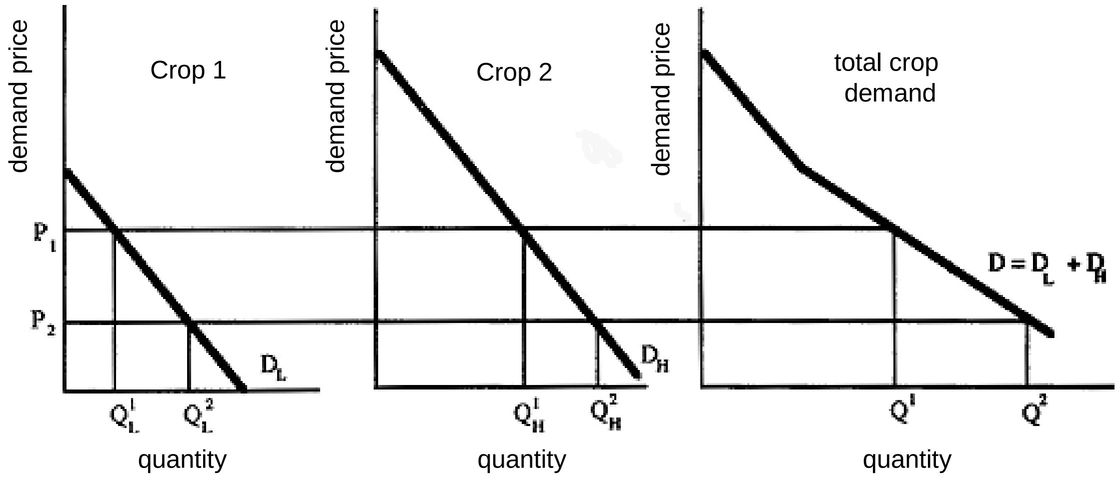



**Figure 10: Horizontal summation of water demand quantities for two rival irrigated crops.**

These plots of IDEP price and quantity data can be translated into demand-price functions for high value and low value crop irrigation is accomplished by performing a regression analysis and fitting the data to analytic functions of the form

$$\textit{demand price} = B_0 \cdot (1 - B_1 \cdot \textit{demand quantity}^{B_2}) \qquad (5)$$

Where $B_0$, $B_1$, and $B_2$ are calibrated parameters estimated using a least squares regression analysis approach. Figures 11 and 12 illustrate the example where fitted irrigation water demand-price functions were developed using the IDEP calculator for a groundwater irrigated zone and a drain water irrigated zone based on given crop distributions, acreages and irrigation efficiencies.

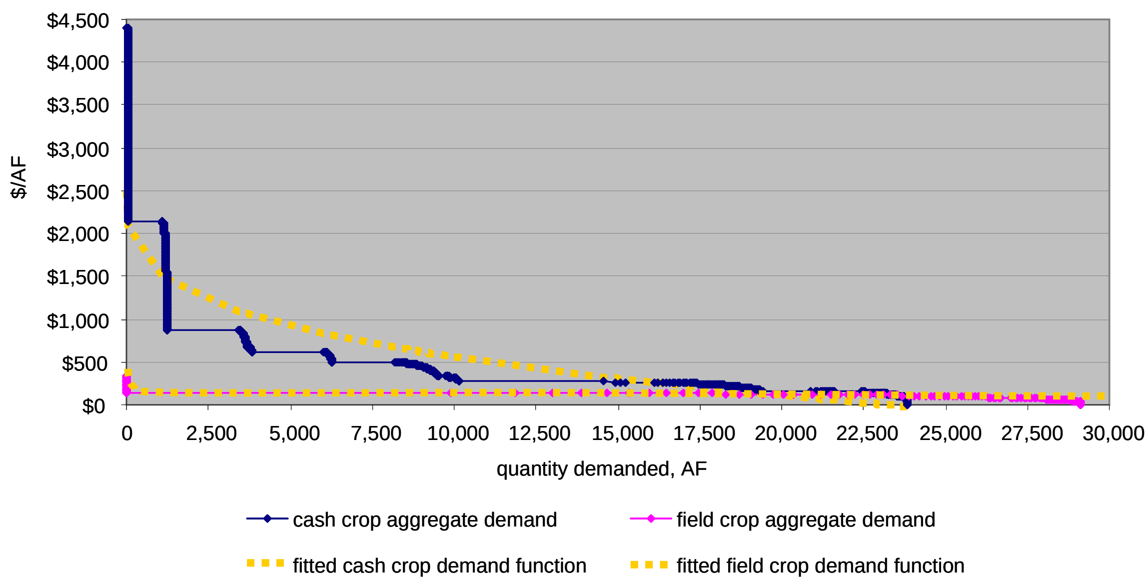


**Figure 11: Marginal water demand-price data for high value and low value crops in a groundwater irrigated zone.**

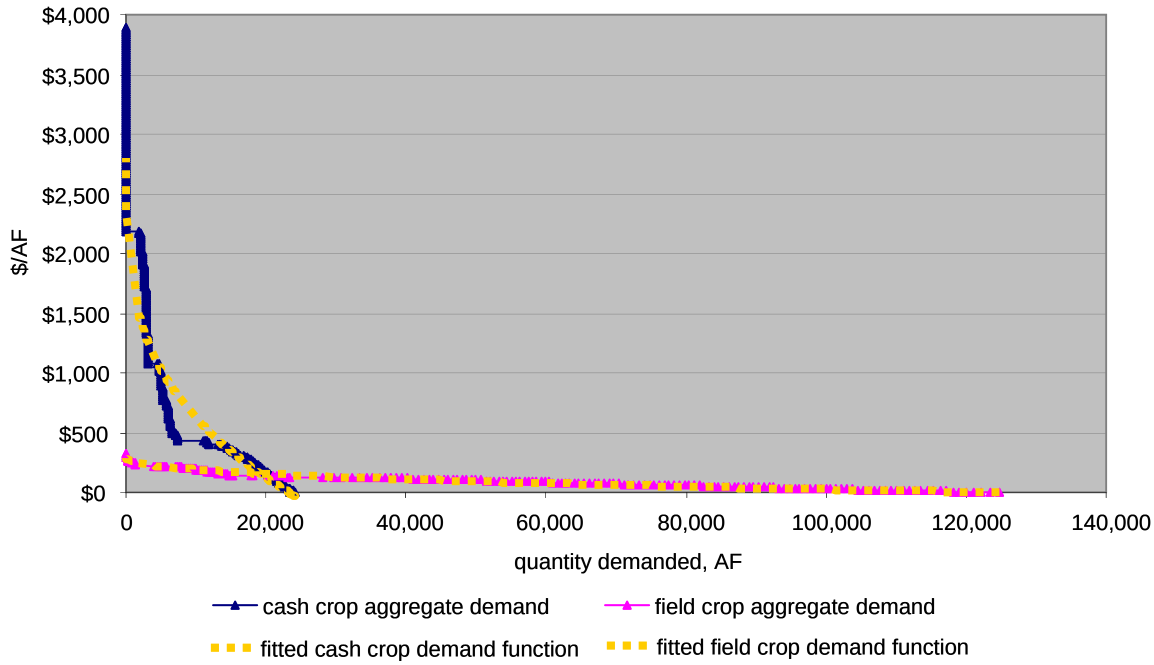



**Figure 12: Marginal water demand-price data for high value and low value crops in drain flow irrigated zone.**

## Flood Control Storage Marginal Demand Prices

The demand price estimation for flood control storage depends on a variety of factors including the recurrence interval for flood flows, the expected duration of peak flood flows, and the expected flood damages within a 100 year or 500 year flood plain (IWRRI, 2013). Considered together, this information enables the formulation of demand-price curves, defined in terms of storage volume, that can then be incorporated into a PE optimization model.

A recent Corp of Engineers (USACOE) Lower Boise River Reconnaissance Study (USACOE, 1995) used a frequency-curve averaging technique to estimate the recurrence interval of various unregulated flow in the Lower Boise River. The same study estimated damages within the 500 year flood plain of the Boise River as a function of unregulated flow. Annually expected damage due to flooding was obtained by multiplying the exceedence probability of flood flow by the damage (cost) associated with those flood flows. Figure 13 shows the relationship between flood flow and annually expected damage after applying a multiplier of 2.5 to account for population growth and inflation since 1994.

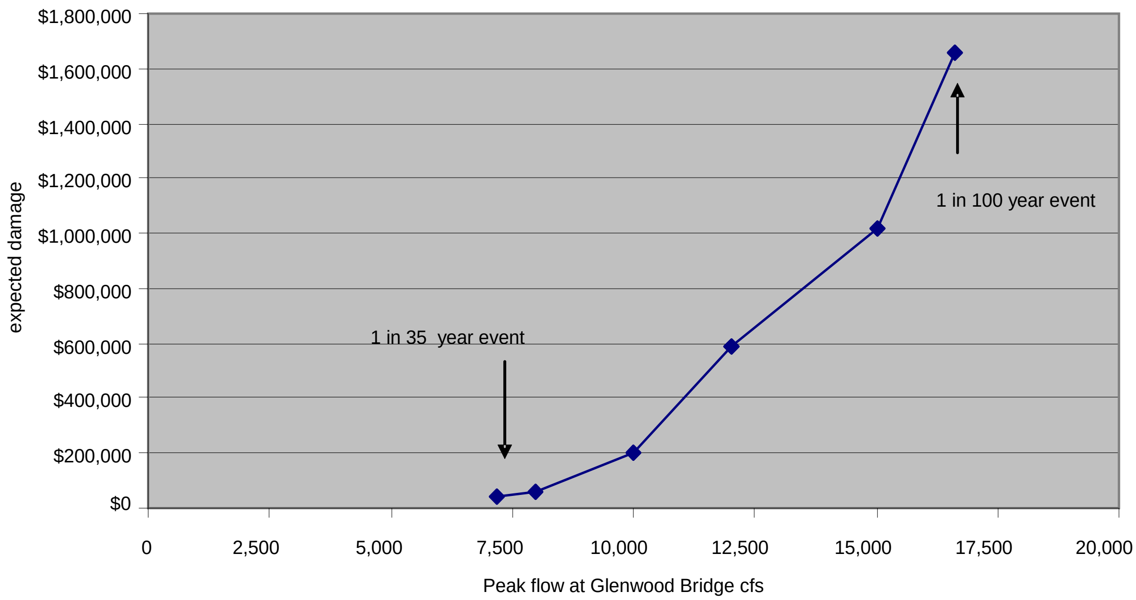



**Figure 13: Annually expected Boise basin flood damage as a function of unregulated flow at Glenwood Bridge**

A separate USACOE Boise River water storage feasibility study (USACOE, 2010) calculated that, for adequate flood control, 60 days of storage would be required for each 1-cfs of peak flow. Such information defines the relationship between peak unregulated flow and required reservoir storage space and allows the expected damage to be translated from terms of flow into terms of reservoir storage as is shown in Figure 14. The reduction in annually expected flood damage with increasing flood storage space can then be represented by a fitted utility curve that has the form of a power function

$$\textit{flood storage utility} = F_1 \cdot (1 - F_2 \cdot \textit{storage}^{F_3})\,, \qquad (6)$$

where $F_1$ is the expected damage in the absence of all flood storage, and $F_2$ and $F_3$ are parameters which define the reduction in damage that results from the availability of flood storage. For the Boise River, the fitted flood storage utility function for the 60 day storage equivalent of unregulated flows of 16,600 cfs (a one in 100 year event) is,

$$\textit{flood storage utility} = 10^7 \cdot (1 - .030754 \cdot \textit{storage}^{0.23972})\,. \qquad (7)$$

The fitted Boise basin utility function (Figure 14) is downward sloping because of the inverse relationship between downstream flood flows and the availability of flood storage space. In other words, increasing storage would correspond to a decrease in downstream flood flows and therefore a decrease in damages.

A backward extension of the utility curve produces an estimate of the utility of existing flood storage space. For example, in the absence of all flood storage, the annually expected damage due to flooding is estimated to be about $7.9 million. Assuming currently available flood storage is 987,000 AF, annually expected flood damage is reduced to about $1.6 million. The annual utility of current storage (i.e. the reduction in annually expected damages due to flooding) is therefore about $6.3 million.

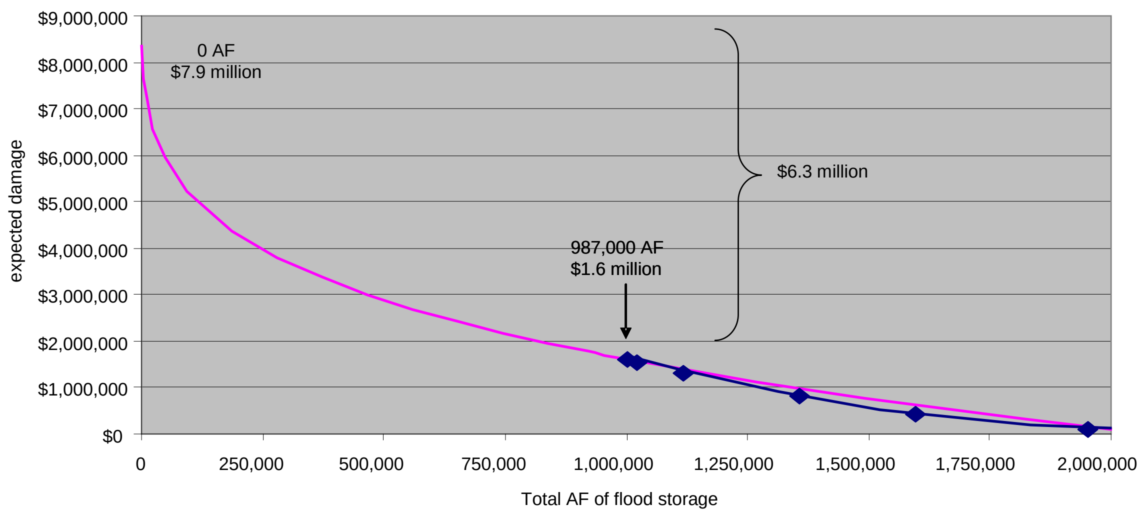



**Figure 14: Utility function for Boise basin flood storage.**

The marginal utility of flood control storage is defined as the reduction in annually expected flood damage resulting from the availability of each additional AF of flood storage space.[2] The flood storage marginal utility function, which is the derivative of (6), is then

$$\textbf{\textit{flood storage marginal utility}} = -F_2 \cdot F_3 \textbf{\textit{storage}}^{(F_3 - 1)}, \qquad (8)$$

and the fitted Boise basin marginal utility function is,

$$\textbf{\textit{flood storage marginal utility}} = -.030754 \cdot (0.23972)\, \textbf{\textit{storage}}^{-0.76021} \,. \qquad (9)$$

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[2].Defining marginal utility in terms of an AF of flood control storage space is equivalent to defining marginal utility in terms of an AF of regulated flood release made to create an AF of storage space.

Equation 9 yields a demand price for each additional AF of flood storage (Figure 15). For example, given 5,000 AF of available flood storage, the demand price for one additional AF is $112.00, and given the currently available quantity of storage (987,000 AF) the demand price of one additional AF is $3.63. The marginal utility of flood storage decreases as storage space increases due to the fact that each additional AF reduces the annual expected damage from flooding..

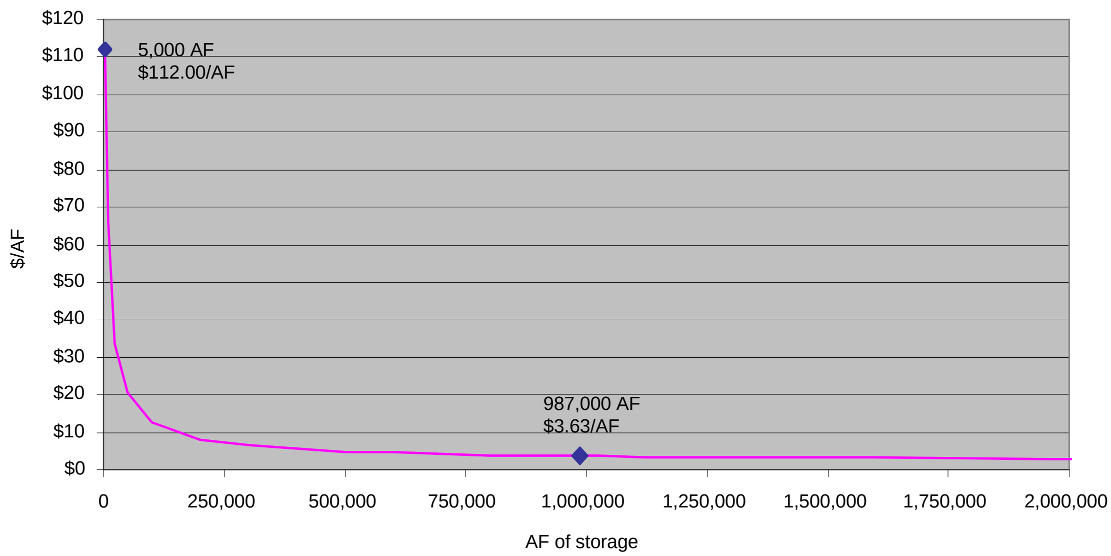


**Figure 15: Marginal utility (demand-price) function for Boise basin flood storage.**

Current allocation of Boise River/reservoir system flood control storage space is based on rule curve operations. Rule curve requirements for flood control and irrigation storage are determined by runoff forecasts, carryover from the previous year, and snowpack (USBR, 2008). Rule-curve operations provide assurances that Boise River flows do not reach flood stage and that reservoirs refill to meet subsequent irrigation demand (USACOE, 1985). Assuming accurate forecasting, reservoir rule curve operations mean that demands for irrigation and flood control allocations of existing reservoir storage are mostly non-rival.

An increase in flood probability increases the marginal utility of flood control storage which is represented by an outward shift in the marginal demand-price function for flood storage. Shifts in demand representing 5-, 10-, and 20-fold increases in flood flow probability (Figure 16) approximate recent projections of increased flood potential in the Boise basin due to climate change (WCRP, 2012). Outward shifts in the marginal demand-price function translate toan increased willingness-to- pay for flood control storage, making flood control increasingly rival with irrigation. This increased willingness-to-pay applies not only to new rival storage, but to existing storage as well.

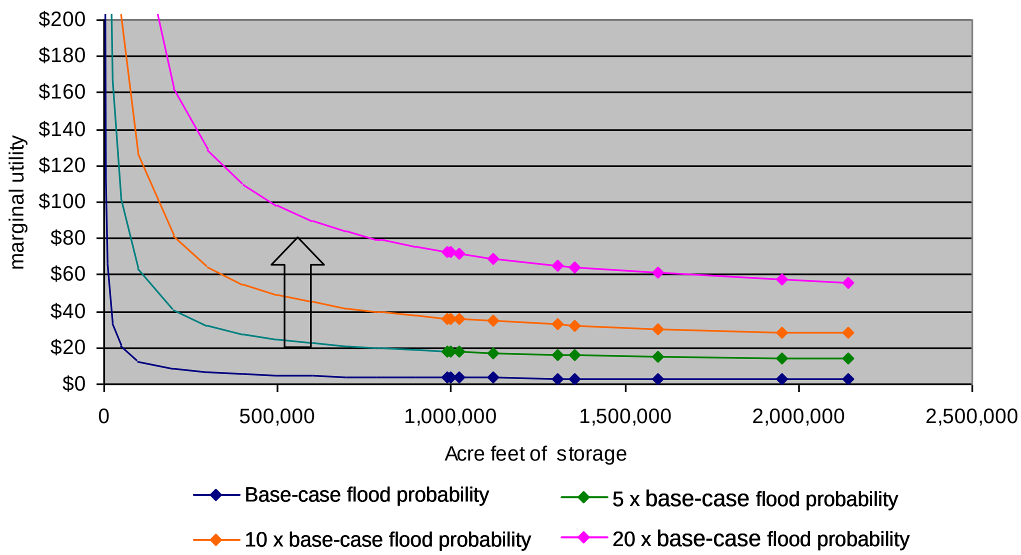


**Figure 16: Shifts in the marginal utility function for flood control storage due to increased flood probability.**

## Instream Flow Marginal Demand Prices

Demand for instream flows can be inferred from the willingness to pay for these hydro-services as public goods, with different individuals and groups expressing differing values for these flows Estimation of the value of the benefits associated with instream flows cannot be estimated directly, and thus must be derived through either implicit analysis methods (e.g. travel cost or hedonic pricing analyses), or surveys of users of instream flow ecoservices which can include fishermen, boaters and wildlife viewers (Young, 2005 and Loomis, 2006). Because eco-service public goods tend to be non-consumptive, and thus non-competitive, the total demand-price is obtained by summing the individual demand prices (i.e. willingness-to-pay for fisheries, boating recreation, wildlife viewing etc.), which is necessary to accurately value the public goods, and for accurate CBA of water projects that affect river system eco-services (Figure 17). Nevertheless, since no one can be excluded from using public goods, their value is prone to under valuing (the free-rider effect) and, as a consequence, public goods are likely to be under produced (Nicholson and Snyder, 2008).

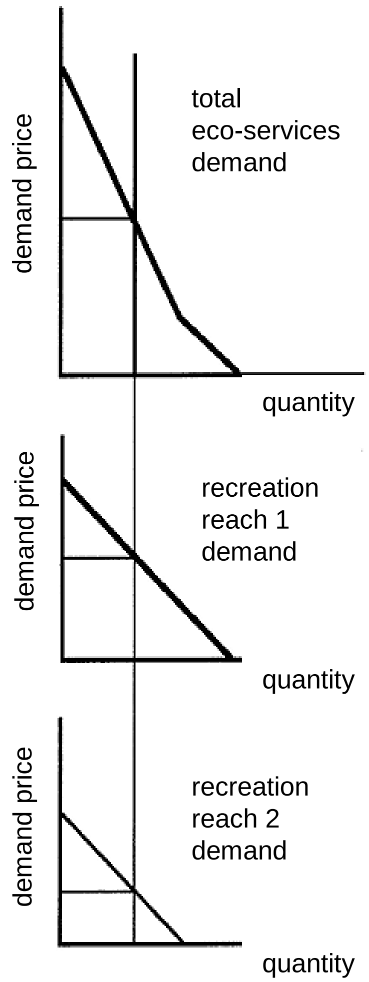


**Figure 17: Vertical summation of water demand-prices for two non-rival eco-services**

The main eco-service generated by instream flows in the Henrys Fork basin is trout fishing. Two reaches of the Henrys Fork attract recreational anglers, the upper reach, located just below Island Park dam; and the lower reach, located just above St Anthony. Empirically derived equations (Van Kirk, 2012) describe fishable trout populations in both reaches as a function of instream flow. The marginal increase in trout population per AF of instream flow is obtained by calculating the derivatives of these equations. For the upper reach the marginal increase in the fishable trout population is given by

$$\frac{dN_i\left(\textit{Island Park utility)}\right)}{dx}=8.5603\cdot 0.5276\cdot\sum_{j=0}^{4}0.4^j\left(x_{i-j-1}\right)^{0.5276-1.0} \qquad (10)$$

where $N_i$ is the fishable trout population in year $i$ , and $x_{i-j-1}$ is instream flow (in AF) during three months following spawning (Dec, Jan, & Feb) for each of the previous five years. For the lower reach, which has a different spawning habitat, the marginal increase in fishable trout is,

$$\frac{dN_i\left(\textit{St Anthony utility}\right)}{dx}=4.109\cdot 0.5276\cdot\sum_{j=0}^{4}0.4^j\left(x_{i-j-1}\right)^{0.5276-1.0} \qquad (11)$$

Inductive methods of valuation (revealed and stated preferences) indicate that Henrys Fork angler’s willingness-to-pay to catch one additional Cutthroat trout averages about $22.45 (Loomis, 2005). Marginal demand-price functions for instream flows to sustain this trout species is then obtained by multiplying (8) and (9) by this valuation of catching a single trout. For the upper reach this equates to

$$\textit{Island Park instream flow marginal utility}=\$22.45\cdot\frac{dN_i(\textit{IslandPark utility})}{dx}\ , \qquad (12)$$

and for the lower reach to

$$\textit{St Anthony instream flow marginal utility}=\$22.45\cdot\frac{dN_i(\textit{St Anthony utility})}{dx}\ . \qquad (13)$$

The specific source of water supply determines whether the demands for instream flows in the two reaches are rival or non-rival with irrigation. If the source of supply is a storage release for irrigation that flows through the upper reach but is diverted before reaching the lower reach, irrigation demand is non-rival with instream flow demand in the upper reach, but rival with instream flow demand in the lower reach. If the source of supply is irrigation return flow that enters the river below the upper reach but above the lower reach, irrigation demand is non-rival with instream flow demand in the lower reach but rival with instream flow demand in the upper reach. If storage water is being released for operational purposes, or for downstream aquifer recharge, then the instream flow demands in both reaches are non-rival. Only when instream demands are non-rival is the total willingness-to-pay for instream flow equal to the vertical sum of the two marginal demand prices (Figure 18).

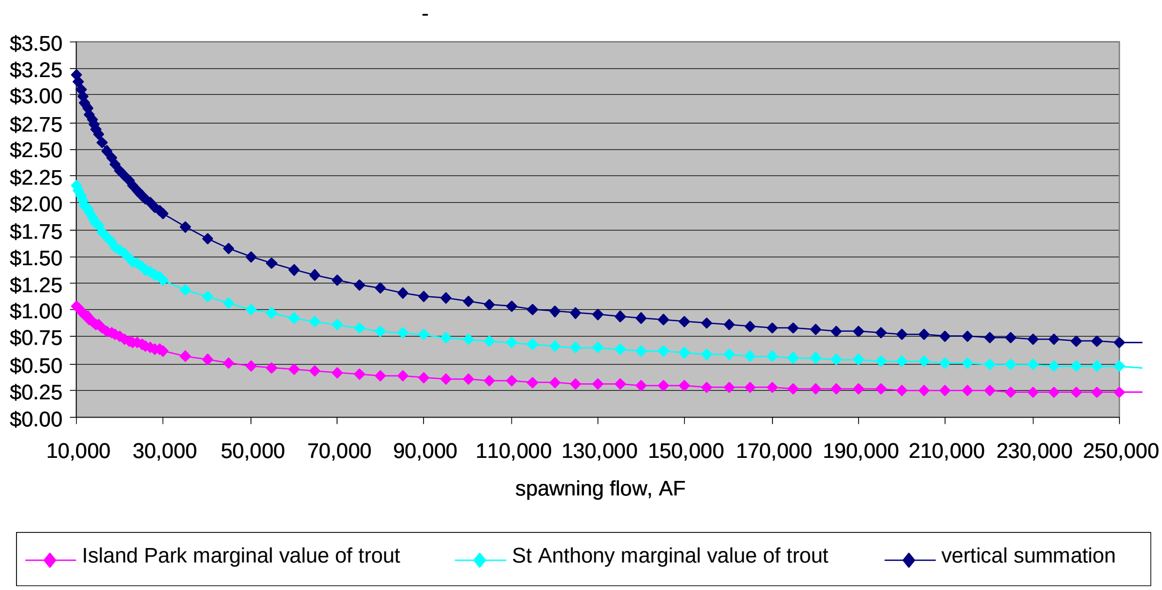


**Figure 18: Vertical summation of Island Park and St Anthony reach demand-prices for instream flow.**

## *Step 4 – Solving the Integrated Problem*

Once the marginal cost relationships have been developed for all of the water supply nodes (Step 1), the simulation of the conveyance of water between all of the supply and demand nodes has been developed (Step 2), and the marginal benefit relationships have been developed for all of the water demand nodes (Step 3), the Partial-Equlibrium, or optimal solution (Step 4), is defined as the point where the amount of water delivered from each supply node to each demand node maximizes the Consumer Surplus plus the Producer Surplus (CSPS). This can be represented mathematically as:

$$maximize\ OF[q(i,j)]$$

$$s.t.\ q(i,j) < flow\ availability\ and\ limits$$

$$q(i,j) < minimum\ flow\ requirements$$

$$\sum q(i,j) = Q_S - Q_L - Q_D$$

In which

$q(i,j) =$ *the amount of water provide from supply node j to demand node i;*

$\sum q(i,j) = Q_S - Q_L - Q_D =$ *the water balance constraint, where:*

$Q_S =$ *the amount of water provided by the supply nodes;*

$Q_L =$ *the amount of water lost through conveyance from supply to demand nodes;*

$Q_D =$ *the amount of water used by the demand nodes;*

$OF = \text{ the Objective Function, defined as:}$

$$OF[q(i,j)] = \sum_i B[q(i,j)] - \sum_j C[q(i,j)] - \sum_i \sum_j T_c \; [q(i,j)]; where:$$

$B[q(i,j)] =$ *the total benefits derived from using all water delivered to demand node i;*

$C[q(i,j)] =$ *the total costs associated with providing water from supply node i;*

$T_c[q(i,j)] =$ *the total cost of conveying water from supply node j to demand node i;*

The fully developed Partial-Equilibrium Optimization problem can be solved utilizing a number of tools. For simple problems, the optimization utilities available in commercial spreadsheet analysis tools (e.g. Excel©) can be used to determine the allocation of water between supply and demand nodes that maximizes the objective function described above. For more complex problems, the solution of the PE Optimization problem may require specialized computer software that is specifically designed to solve optimization problems. One class of software that can be used are generic modeling systems, such as the GAMS© model, which links equations written in algebraic notation to commercial solvers that implement linear, integer, or non-linear optimization. These systems are flexible, transparent, self-documenting, and provide a simple link between model formulation and the solver solution. These characteristics have resulted in the early and widespread use of generic modeling systems by both economists and engineers in implementing hydro-economic models.

Another option is to develop computer software that is designed to specifically solve the PE Optimization problem for hydro-economic models. One example of this was the development of the Hydro$ense tool, a simple optimization solver written in the C# language that was designed to solve the PE Optimization problem. In brief, the Hydro$ense solver employs a Gradient Descent search method that utilizes numerical approximations of the first and second derivatives of the Objective Function with respect to the decision variables. The solution proceeds by developing an initial guess for the optimal decision variables which is then used to estimate the first and second derivatives of the Objective Function with respect to the array of decision variables. The decision variables are then updated by solving the linear system of equations as:

$$\{dv^i\} = \{dv^{i-1}\} - \left[\frac{\Delta^2 OF}{\Delta dv^2}\right]^{-1} \left\{\frac{\Delta \mathrm{OF}}{\Delta dv}\right\}$$

Where:

$dv^i$ = the updated array of the estimated optimal decision variables for iteration i of the solution;

$\Delta dv =$ the incremental change in the decision variable used to calculate the numerical estimates of the first and second derivatives of the Objective Function. This value is set to 0.01 within the Hydro$ense program.

$\left\{\frac{\Delta \mathrm{OF}}{\Delta dv}\right\}$ = the numerical estimates of the first derivative of the Objective Function (OF) with respect to the estimate of the optimal decision variables at iteration i-1; and

$\left[\frac{\Delta^2 OF}{\Delta dv^2}\right]^{-1}$ = the inverse of the matrix containing the numerical estimates of the second derivatives of the Objective Function (OF) with respect to the estimate of the optimal decision variables at iteration i-1.

At the end of each iteration, the updated optimal solution is checked to make sure that all of the problem constraints are met. If an updated decision variable falls outside of its constraint, the decision variable is set to equal its constraint limit and is then used in the optimal set of decision variables for the next iteration in the solution.

To aid in converging towards a stable solution, an adjustment to the diagonal values of the matrix (representing the second derivatives of the Objective Function with respect to the decision variables) is performed utilizing a Marquardt adjustment, defined as:

$$1 - e^{\{i-500)*\Delta dv}$$

The optimization solver will iterate towards the optimal solution using the procedure described above until the change in the values of the Objective Function and decision variables meet a user defined convergence tolerance, or the user defined maximum number of iterations is reached.

### *Simplified PE Model Applications*

PE modeling of water policy alternatives using an economic objective function that is subject to physical and management constraints provides insights regarding benefits and efficiencies that are essential for Cost Benefit Analysis. To demonstrate this, one qualitative example explaining the use of PE modeling using the GAMS© program is provided, along with two simplified PE models that are solved using the

GAMS© modeling program. The first model provides a conceptual understanding of the hydro-economic PE modeling using a mixed complementary programming approach. The second model evaluates three alternatives for managing hydrologic externalities resulting from irrigation and canal seepage. The third model evaluates two alternatives for managing rival and non-rival water demands for instream flow public goods. The models are highly simplified representations of the Lower Boise basin and the Henrys Fork basin water management and planning alternatives, and the results presented here are for illustration purposes only.

Appendix B contains the annotated GAMS code for the simplified PE model with hydrologic externalities, and Appendix C contains the GAMS data file for this application. Appendix D contains the annotated code for the simplified PE model with rival and non-rival instream flow demands, and appendix E contains the GAMS data file for this application. The changes necessary for each application are described in the code along with the changes described in the Appendix C and E data files.. Text annotations are indicated by a * in the first column [3].

**Example 1: PE Modeling using Mixed Complementary Programming**

When Takayama and Judge (1971) published their book, numerical optimization techniques were well understood, but mixed complementary programming (MCP) was in its infancy. With the advent of GAMS (Brooke et al. 1988) and accompanying solvers, it is now possible to formulate PE problems as complementary slackness equations in a mixed complementary problem and solve them directly. Five sets of complementary slackness[4] equations, provided in Appendix B, define economic equilibrium conditions in the presence of hydrologic externalities:

- Equation 1 states that, at equilibrium, if the quantity of surface water demanded is greater than zero, demand price must equal marginal benefit from irrigation;

[3] Although the current GAMS model does not incorporate a graphical user-interface a utility exists for developing GAMS model GUIs. (http://www.gams.com/dd/docs/tools/ask.pdf) .

[4] The $\perp$ operand denotes complementary slackness. Thus $x \perp f(y)$ means $x \geq 0$, $f(y) \geq 0$ and $xf(y)=0$ .

- Equation 2 states that, at equilibrium, if the quantity of groundwater supplied is greater than zero, supply price must equal marginal cost at equilibrium plus the externality marginal cost;
- Equation 3 states that, at equilibrium, if the quantity of surface water traded is greater than zero, the sum of supply price and transportation cost (i.e. cost of surface water seepage losses) must equal demand price;
- Equation 4 states that, at equilibrium, if the demand price is greater than zero, quantity of water demanded must equal the sum of all deliveries from supply nodes less seepage losses;

And equation 5 states that, at equilibrium, if supply price is greater than zero, quantity of water delivered must equal quantity of water produced at each supply node.

By solving these equations together, the PE model solution describes an allocation of water quantities and prices that is Pareto efficient, meaning that no other water allocation can provide further gain in total benefit without simultaneously creating an equivalent loss. PE models are capable of representing both aggregate Pareto efficiency, which maximizes the net benefits of a system irrespective of the allocation of water between demand nodes, and neutral Pareto efficiency , which incorporates social preferences in the efficiency objective (e.g. the valuation of public goods such as river system eco-services). .

Figure 19 illustrates the PE model Pareto optimal equilibrium solution for a single water supply and demand node with a non-binding supply constraint (i.e. the supply is more than sufficient to satisfy the demand, with the optimal solution occurring where the supply and demand cost curves intersect). Consumer surplus (or net benefit) is defined as the difference between what the demand nodes are willing to pay (characterized by the demand function) and what they are required to pay (i.e. the equilibrium price generated in the PE model solution) for a particular quantity of water.

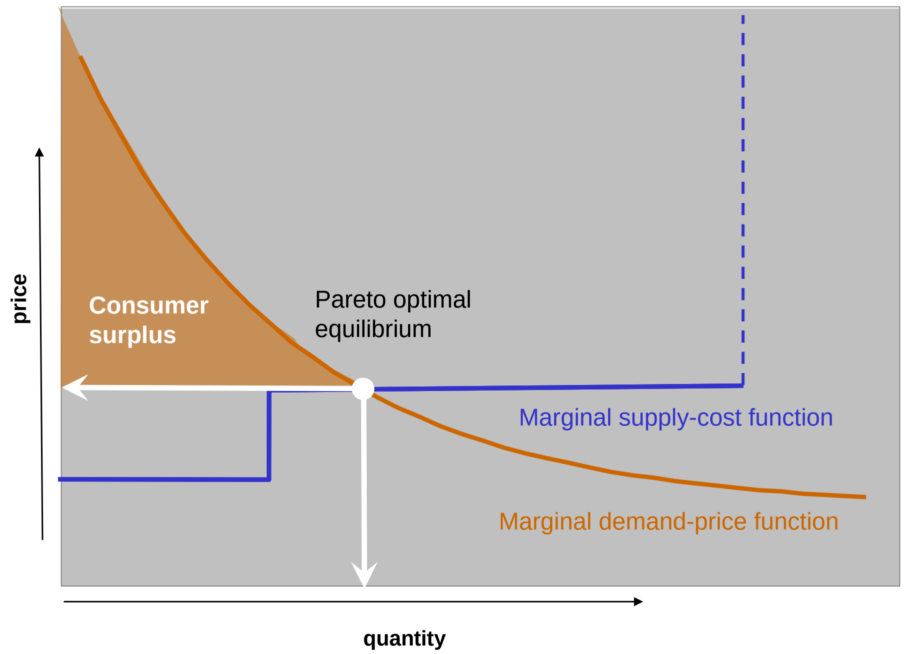


**Figure 19: PE model equilibrium solution with non-binding supply constraint.**

Figure 20 illustrates the PE model solution for a single water supply and demand node that is not Pareto optimal because of a binding supply constraint (i.e. the supply is not sufficient to satisfy demand and the supply and demand cost curves do not intersect). Relative to the equilibrium solution in Figure 19, consumer surplus (net benefit) is reduced due to the binding constraint. When a supply constraint is binding, the PE model calculates the constraint cost (or shadow price), which in the illustration is the willingness-to-pay for one more AF of water in order to relax the binding constraint. Constraint costs are important model results that can reveal the marginal value of eliminating infrastructure bottlenecks such as new reservoir storage for irrigation or flood control. Shadow prices can also reveal the opportunity cost to society resulting from restricted public goods such as instream flows.

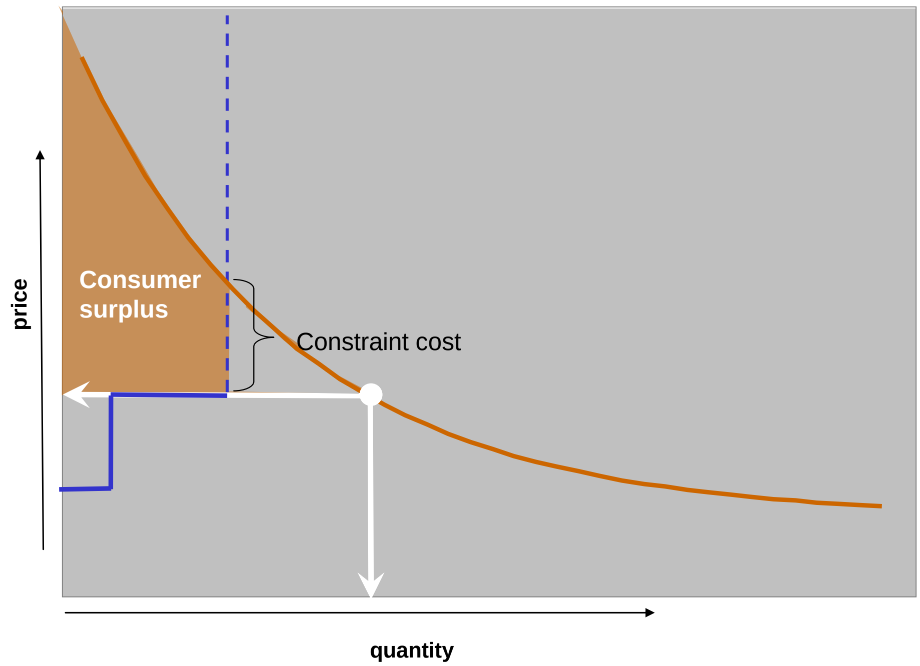


**Figure 20: PE model equilibrium solution with binding supply constraint.**

### Example 2: Managing Hydrologic Externalities in the Lower Boise Basin

The PE model application incorporating hydrologic externalities is demonstrated using a much simplified model comprised of just three nodes, a reservoir supply node and two irrigation demand nodes representing a canal user and a groundwater pumper (Figure 21).

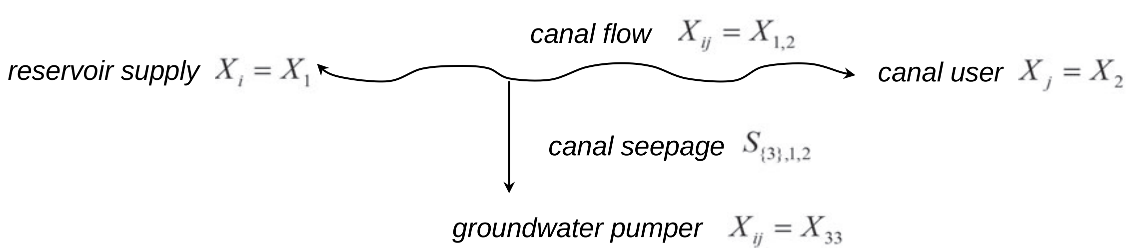


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**Figure 21: Schematic of three node PE model with a hydrologic externality.**

Jointness-of-production occurs as a result of canal seepage losses which hydrologically link the canal irrigator's reservoir supply to the groundwater irrigator's aquifer supply. A hydrologic externality arises due to the fact that the canal seepage contribution to the groundwater supply is un-priced. In this example, three alternatives for dealing with the hydrologic externality are modeled. They include eliminating the externality (eliminating seepage), pricing the externality, or a tax/subsidy scheme whereby negative externalities are taxed and positive externalities are subsidized (Taylor et al., 2014).

<u>Base-case Scenario</u>

The base-case is the "without" scenario, as is required in a "with-versus-without" CBA. In the base-case, the aquifer is connected to the leaky canal for some portion of the canal length. The groundwater pumper receives a positive externality of reduced pumping lift due to a decrease in depth to groundwater caused by canal seepage and pumping inflicts a negative externality upon canal users by inducing additional seepage.

In the surface water market, node $S_1$ supplies 3,097 AF priced at $15/AF, of which 2,130 AF reaches node $X_2$, who is willing-to-pay $21.65/AF for the water delivered at the canal end. Node $X_2$ makes a payment to node $S_1$ in the amount of $46,406 ($15/AF × 3,097 AF), which includes $14,505 ($15/AF × (3,097 AF - 2,130 AF) for water not received, but lost to canal seepage. In the groundwater market, node $X_{3,3}$ pumps 1,283 AF (286 AF of induce seepage, plus 681 AF of passive seepage, plus 316 AF from sources other than seepage) for which he pays $30.65/AF in pumping costs. The node $X_{3,3}$ pumper thus makes a payment to the node $S_3$ supplier (i.e., the power company) in the amount of $39,325 ($30.65/AF × 1,283 AF). The total base-case surplus (benefit) totals $164,087, where $90,900 is node $X_2$ consumer surplus, $64,242 is node $X_3$ consumer surplus, and $8,946 is node $S_3$ producer surplus. The horizontal supply function of node $S_1$ yields no producer surplus because the supply cost is a single block rate, thus there is no marginal increase in the cost with an increasing amount of water supplied from node $S_1$.

<u>Pigouvian Tax/Subsidy Scenario</u>

In a competitive equilibrium, the welfare of two agents depends only on consequences of their own choices. An externality creates an asymmetry between social and private prices, while internalization of the externality forces both agents to account for the consequences of their actions on the other's welfare by aligning prices. Absent this internalization (as in the base-case), the canal water user responds only to the supply cost of the canal company and the “shrinkage” cost of seepage. In the base-case, the groundwater pumper responds only to changes in the cost of pumping, while the reduction in costs that the pumper receives from canal seepage is ignored, as is the increased cost borne by the canal diverter for pumping-induced seepage.

A Pigouvian tax/subsidy internalizes the externality by aligning marginal supply prices of canal diverters and groundwater pumpers. The price alignment creates a “signal” to decrease production of the negative externality (pumping induced seepage) and increase production of the positive externality (canal diversions that create seepage). To internalize the hydrologic externality, the canal water supply function is redefined as the marginal cost at node $S_1$, plus the negative externality of seepage in the conveyance of water from node $S_1$ to node $X_2$, plus a Pigouvian subsidy (represented by $\beta$), plus feedback from the pumping tax. The Pigouvian subsidy equals the reduction in marginal cost provided by canal seepage to the node $X_3$ groundwater pumper. Similarly, the groundwater supply function is redefined as the cost of pumping at node $X_3$, plus a Pigouvian tax (represented by $\alpha$) that is equal to the marginal cost of pumping-induced canal seepage for the canal diverter at node $X_2$, plus feedback from the pumping tax (which creates a signal that reduces pumping).

Internalization of the externality through a Pigouvian tax/subsidy increases the welfare of both the groundwater pumper and canal diverter. The tax/subsidy causes a downward shift in the supply-cost curves for the canal irrigators (the supply cost at the end of the canal). This is due to the canal irrigator's marginal supply cost at the end of the canal shifting downward because the Pigouvian subsidy reduces the cost associated with canal seepage. The resulting feedback also causes a downward shift in the supply-cost curves for the groundwater irrigators. This occurs as a result of the feedback from the Pigouvian tax which reduces groundwater pumping and pumping-induced canal seepage. In this scenario, the equilibrium price of groundwater fell from $30.65/AF in the base-case to $25.72/AF and equilibrium pumping increased from 1,283 AF in the base-case to 1,306 AF. In a with-versus-without CBAcomparison, benefit in the groundwater market increases by 10% and benefit in the surface water market increases by 34%, while total irrigator benefit increases by 21% relative to the base-case.

Eliminating Seepage

In this scenario, the hydrologic externality is eliminated through lining of the leaky canals. When the canals are lined, the cost of seepage is no longer imposed upon the canal diverter and the quantity of water supplied at node $X_1$ equals the quantity demanded at node $X_2$. Absent canal seepage, pumping costs in this scenario increase from $30.65 (base-case scenario) to $95.24/AF due to increased depth to groundwater, which in turn results in a decrease in groundwater pumping. The consumer surplus of the surface water market increases by 16% as a result of the increased canal efficiency, but is offset by a 64% decrease in consumer and producer surplus in the groundwater market. With-versus-without CBA comparison reveals a 67% decline in total surplus as a result of canal lining. Note that, in this example, construction costs are ignored and the sole beneficiary of canal lining is the short run increase in irrigation intensity of the existing crop mix and acreage of the canal water user.

Aquifer Recharge Payment

In contrast to the external Pigouvian tax/subsidy scenario, payments for aquifer recharge are internal, that is the groundwater irrigator pays to receive the benefit of aquifer recharge from surface water. The canal diversion is priced via a payment from node $X_3$ to node $X_2$ that matches the decrease in total pumping cost that is attributable to canal seepage.

The marginal cost of pumping with respect to diversion is calculated by integrating the groundwater pumpers' marginal cost function with respect to pumping yield and then differentiating with respect to canal diversion. This produces a function that represents the cost of groundwater pumping, plus the cost of the water that seeps from the canal into the groundwater, priced as if it were a canal diversion. By definition, groundwater pumpers maximize their benefits by paying the canal diverter this amount for each acre-foot of water diverted down the canal.

Table 2 summarizes the equilibrium results from the aquifer recharge scenario along with the results from the other scenarios discussed here. In the groundwater market, the transfer payment from node $X_3$ to node $X_2$ increases the marginal cost for node $X_3$ to

$51.68 per/AF, relative to the base-case scenario cost of $30.65 per AF. As a consequence, groundwater pumping decreases relative to the base-case from 1,283 AF to 1,124 AF. In the surface water market, the transfer payment reduces node $X_2$ marginal cost relative to the base-case from $21.65 per AF to $9.79 per AF, and as a result, the quantity of water delivered from node $X_1$ to node $X_2$ increases and the total payment made by node $X_3$ increases to $29,445. Consumer surplus increases by 30% in the surface water market (node $X_2$) and decreases by 40% in the groundwater market (node $X_3$). Although the managed recharge scenario does not penalize pumping-induced seepage, the CBA total surplus from this scenario exceeds that of the base-case. In contrast to the tax/subsidy remedy, which corrects both sides of the reciprocal externality, the recharge payment sustains only the positive externality of seepage.

**Example 3: Managing Rival and Non-Rival Water Demands in the Henry's Fork Basin**

The PE model application with rival and non-rival demands for instream flow public goods is demonstrated using a model comprised of just four nodes, a reservoir supply node an irrigation demand node, and two spatially distributed demands nodes for instream flow to support fisheries (Figure 22). The application consists of three scenarios:

- The base-case scenario calculates instream flow allocations and benefits assuming the two instream flow demands and irrigation demand are all rival.
- The second scenario assumes the two instream flows are non-rival with one another in meeting fisheries demands, but rival with irrigation demand.
- The third scenario assumes that the two non-rival instream flow demands are also non-rival with specific irrigation demands (i.e. irrigation water storage releases made during winter months as part of reservoir operations or for aquifer recharge).

In the base-case scenario, the net benefit is determined by summation of the instream flow demand quantities (along the horizontal axis) for the two reaches. In the second, the net benefit is determined by summation of instream flow demand prices (along the vertical axis), as these flow demands are not in competition with each other. In the third scenario, the net benefit is determined by the summation of instream flow for fisheries and irrigation demand prices (along the vertical axis), as the flows for fisheries and irrigation are not in competition with one another. Once again, the base-case is the "without" scenario, as required for conducting a with-versus-without CBA.

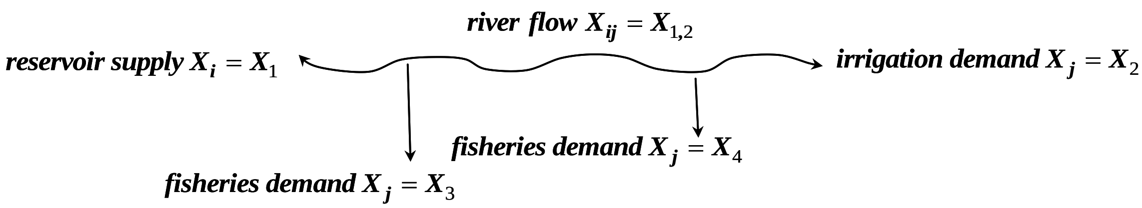


**Figure 22: Schematic of four node PE model with rival and non-rival water demands.**

Results from the base-case PE model scenario (which assumes that the sources of supply for instream flows in both reaches will result in rival instream flow demand conditions) generates the lowest total surplus for fisheries ($5,539). The second PE model scenario (which assumes sources of supply for the two HF reaches result in non-rival instream flow demand conditions) generates a total surplus for fisheries that is greater than the base-case by a factor of four ($21,104). Finally, the third PE model scenario (which assumes that instream flow demands are non-rival with specific irrigation demands) generates total fisheries surplus that is nearly two orders of magnitude greater than the base-case (all rival) scenario ($584,178).

Of the three scenarios, the third scenario is the closest to approximating the actual management of instream flows for fisheries in the Henrys Fork (HFAG/JPC, 2005). The difference between the total benefits for scenario 3 and scenario 2 ($584,178-$21,104) is therefore closest to representing the value of instream flows to Henrys Fork fisheries that can be derived from the use of Henrys Fork reservoir storage being managed for both irrigation and fisheries.

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# *Appendix A IDEP Demand Function Calculator*

The underlying production function developed by Martin and others (Evaluation of Irrigation Planning Decisions. Journal of Irrigation and Drainage Engineering. Vol. 115, No. 1, February 1989, 58-77) is expressed in equation (1) with altered notation:

$$Y = Y_d - (Y_m - Y_d)\left(1 - \frac{I}{I_m}\right)^{1/B} \qquad (1)$$

where

| | | |
|---|---|---|
| Y | = | crop yield (yield units/area) |
| $Y_m$ | = | crop yield at full irrigation (same units as Y) |
| $Y_d$ | = | non-irrigated (dry land) crop yield (same units as Y) |
| I | = | irrigation depth (length) |
| $I_m$ | = | irrigation depth at full irrigation (same units as I) |
| $ET_m$ | = | evapotranspiration at Ym (same units as I) |
| $ET_d$ | = | evapotranspiration at Yd (same units as I) |
| B | = | $(ET_m - ET_d)/I_m$ (unitless) [1] |

For the spreadsheet tool, "$I_m$" is assumed to include any leaching requirement. [2]

Substituting "a" for (1/B), equation (1) can be rearranged as:

$$Y = Y_m - (Y_m - Y_d)\left(1 - \frac{I}{I_m}\right)^{a} \qquad (2)$$

Multiplying yield by irrigated area (A) and commodity price [3] (Pc) gives the gross revenue (R):

$$R = APY_m - AP(Y_m - Y_d)\left(1 - \frac{I}{I_m}\right)^{a} \qquad (3)$$

The derivative of revenue with respect to irrigation depth (I) is:

$$\frac{dR}{dI} = \left(\frac{1}{I_m}\right) aAP(Y_m - Y_d)\left(1 - \frac{I}{I_m}\right)^{(a-1)} \qquad (4)$$

The derivative "dR/dI" is the marginal production value of water [4] and may be considered the willingness-to-pay for irrigation water, or the water-depth demand price "Pwd." Solving equation (4) for irrigation depth, the depth of irrigation water demanded as a function of price is:

$$I = I_m - I_m\left(\frac{I_m B P_{wd}}{AP_c(Y_m - Y_d)}\right)^{\left(1/(a-1)\right)} \qquad (5)$$

Equation (5) gives a relationship between depth of irrigation demanded and price per depth of irrigation. The units of Pwd (price per water depth) are (currency units/length). We need price in terms of water volume, and irrigation in terms of volume. Pwv (price per water volume) has units (currency/length^3), so Pwd = Pwv times area (currency/length^3 x length^2 = currency/length). Substituting Pwv * A for Pwd, and multiplying all of equation (5) times depth to obtain volume, gives equation (6), the volume of irrigation demanded as a function of the price per volume:

$$V = AI_m - AI_m \left(\frac{I_m B P_{wv}}{P_c(Y_m - Y_d)}\right)^{\left(1/(a-1)\right)} \qquad (6)$$

This equation will give a nonsensical result of negative volumes of water at high prices; therefore, the spreadsheet uses equation (7) which includes a conditional test:

$$V = Max\left(0, AI_m - AI_m \left(\frac{I_m B P_{wv}}{P_c(Y_m - Y_d)}\right)^{\left(1/(a-1)\right)}\right) \qquad (7)$$

If the contemplated use of the composite demand function can accommodate multiple conditional tests, then the composite demand for the farm or region in question is simply the horizontal summation of all individual crop demands:

$$V = \sum Max\left(0, A_i I_{mi} - A_i I_{mi} \left(\frac{I_{mi} B P_{wv}}{P_{ci}(Y_{mi} - Y_{di})}\right)^{\left(1/(a-1)\right)}\right) \qquad (8)$$

Where subscript "i" denotes an individual crop, with its unique acreage and other parameters.

For uses where the contemplated use of the demand function cannot accommodate conditional statements for each component of the summation, the spreadsheet tool offers an opportunity to manually calibrate two approximations of the composite demand function:

$$V = b_0 + \frac{b_1}{(P_{wv} - b_3)} + b_2(P_{wv} - b_3) \qquad (9)$$

$$V = b_4(P_{wv} + b_5)^{b_6} + b_7 \qquad (10)$$

where

$b_j$ = empirical parameter.

Values from the crop worksheet may also be used in regression equations to estimate demand equations. All these approximations will give nonsensical results beyond the price-axis and quantity-axis intercepts. Therefore, if any of the equations are to be used in further computer processing, steps must be taken to limit calculations to an appropriate reasonable range of values.

End Notes

[1] Parameter "B" is closely related to irrigation efficiency at full irrigation depth, depending on the particular definition of efficiency.

[2] See leaching requirement worksheet for assumptions regarding leaching requirements.

[3] "Pc" is the net price after deducting per-unit harvest costs such as hay twine or drying.

[4] This derivative depends on the important assumptions that commodity prices are perfectly competitive (i.e. independent of local production quantity) and that allocation of crop acres is fully constrained by considerations besides water supply.

EXPLORATION OF PRODUCTION FUNCTION EQUATION

Not all the parameters of equation (1) are physically or conceptually independent. In the spreadsheet tool, the following parameters are variables that the user may input:

| | |
|---|---|
| $I_m$ | Irrigation depth at full yield |
| $ET_m$ | Evapotranspiration depth at full yield |
| $Y_m$ | Yield at full irrigation |
| $Y_d$ | Dryland Yield |
| $P_c$ | Price of commodity (net of per-unit harvest costs) |

Guidance worksheets aid in selecting these parameters. The remaining parameters are calculated by the spreadsheet:

$$ET_d = \left(\frac{Y_d}{Y_m}\right) ET_m \quad (11) \qquad B = \frac{(ET_m - ET_d)}{I_m} \quad (12)$$

$$a = {}^{1}/_{B} \quad \text{no italics} \quad (13)$$

$$K = {}^{1}/_{I_m} \quad \text{no italics} \quad (14)$$

The calculation of ETd depends on an assumption that the yield/evapotranspiration relationship is approximately linear with an intercept near zero (see FAO56 and FAO33). Martin and others (1989) defined the calculation of B.

Figure 1 shows the relationship between the yield curves generated by equation (1) using three pairs of values for the interrelated parameters Im and B. The other parameters are:

$ET_m$ = 2 feet
$Y_m$ = 5 tons
$Y_d$ = 1 ton

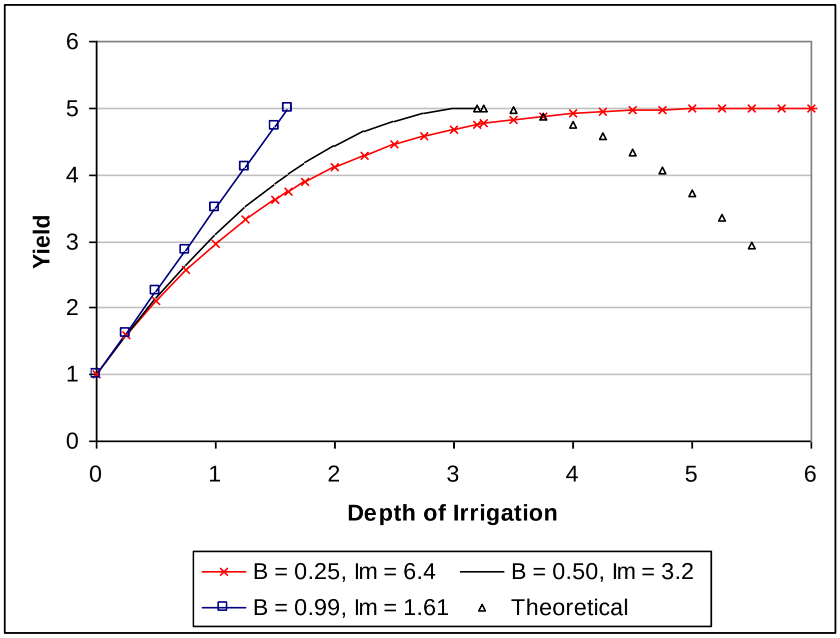


Figure 1. Yield/Irrigation relationship from production function equation.

In theory, the yield would begin to decline at application depths beyond "full" irrigation, as illustrated by the "theoretical" curve in Figure 1. However, except when parameter "1/B" happens to be an even integer, equation (1) gives a spreadsheet error when depth of irrigation is greater than or equal to full-yield irrigation. This is not a serious limitation; for most economic studies, this range of the production function is not of interest, since rational producers will not enter this region.

ECONOMIC DEMAND FOR IRRIGATION WATER

The production value and hence willingness-to-pay (i.e. demand price) are derived from the slope of the production function. The B = 0.99 curve illustrates that at very high irrigation efficiency, the slope is nearly constant, up to full production. The low-efficiency curve shows a marked decline in slope as depth of irrigation increases. These characteristics affect the calculation of production value of various depths of irrigation water (using equation (7)), as shown in Figure 2. The figure is consistent with expectations from examining Figure 1. A commodity price of $100/ton unit was used, with 100 acres of crop.

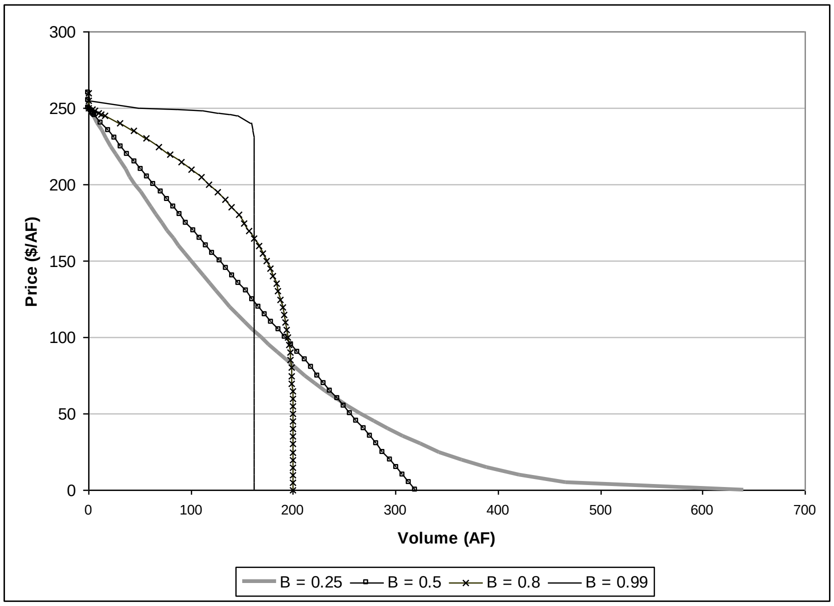


Figure 2. Demand for irrigation water at different values of B.

At first glance, Figure 2 may not match intuitive expectations. However, comparison of the high-efficiency curves with the low- efficiency curves actually makes sense. For instance, at $200/acre foot, the 80%-efficiency user is able to profitably utilize up to 118 acre feet, but the low-efficiency user cannot extract as much economic value and therefore is only willing to use 46 acre feet. Once the price drops to $100/acre foot, the 80%-efficiency user purchases an essentially full supply, so that any further price reduction does not entice meaningful further purchases. However, the low efficiency user can still extract some marginal benefit of additional water even up to 600 acre feet, if the price is low enough.
The price intercept of individual demand curves is defined by the value of the crop. These curves represent the same crop; they all have very similar price intercepts because physically, at very low application depths, nearly all of the water is used for crop production (irrigation efficiency begins to approach 100% for any application method). In the production-function equation, this characteristic is achieved by entering (1/B) as an exponent. The quantity intercept is defined by the crop acreage. In Figure 3, both curves have identical parameters, except that one curve is for 100 acres and the other is for 200 acres.

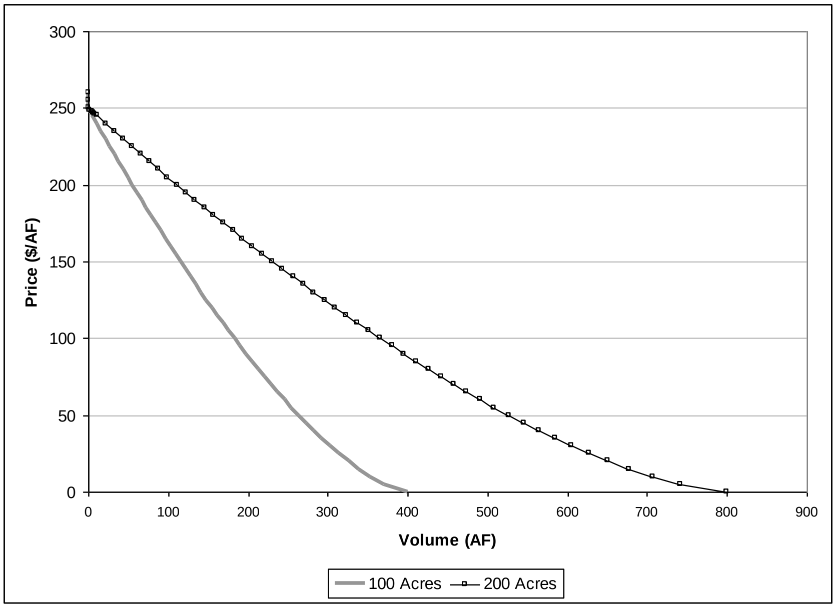

Figure 3. Demand curves for identical crops on different size parcels.

EXPLORATION OF HORIZONTAL SUMMATION

The standard construction of aggregate demand is to horizontally sum individual demands. The summation process can produce a convex-to-the origin aggregate demand curve even when individual demand curves may be knee shaped, as shown in Figure 4. One can imagine that if this were an aggregation of hundreds or thousands of individual demand curves, the aggregate demand could indeed become a smooth curve.

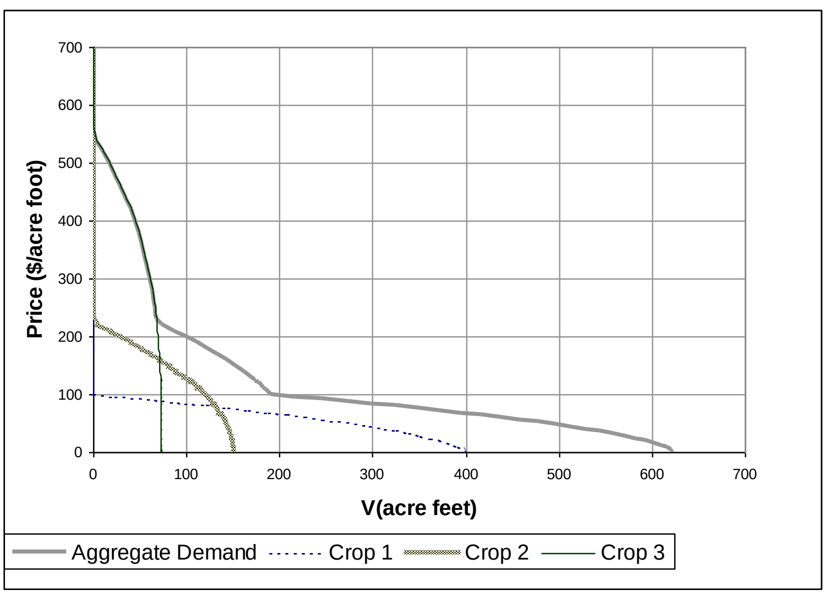

Figure 4. Aggregate demand by horizontal summation.

DERIVATION OF EQUATIONS WITH INDEPENDENT VARIABLES

Equation (6) from above is repeated:

$$V = AI_m - AI_m \left(\frac{I_m B P_{wv}}{P_c (Y_m - Y_d)}\right)^{\left(1/(a-1)\right)} \quad (6)$$

Equation (6) is defined using readily-available input data, but these data are not independent. Therefore, marginal analyses using partial derivatives of equation (6), or iterative exploration by varying one input value at a time will not be valid. To derive equations of only independent exogenous variables, the following simplifications and assumptions are relied upon:

1. The relationship between yield and evapotranspiration is linear (this is implicit in the form of equation (6)). This leads to the following relationships:

$$Y_m = K_1 \, ET_m \quad (15)$$

$$Y_d = K_1 \, ET_d \quad (16)$$

Where $K_1$ is a crop-specific yield coefficient.

2. ET at the dry-land yield equals effective precipitation (Re). This leads to two additional relationships:

$$ET_d = Re \quad (17)$$

$$Y_d = K_1 \, Re \quad (18)$$

3. The relationship that defines B is a function of irrigation system, crop agronomy and management. It will be essentially unaffected by the range of climate changes for which these simplifications are appropriate. This leads to:

$$I_m = a(ET_m - Re) \quad (19)$$

Note that if effective precipitation exceeds ETm, Im will be negative. This is simply an indication that irrigation is not required; the magnitude of Im is the depth by which effective rainfall could decrease without affecting yield (assuming appropriate temporal distribution of rainfall).

Substituting these simplifications into equation (6) gives equation (20):

$$V = Aa(ET_m - R) - Aa(ET_m - R)\left(\frac{P_{WV}}{P_c K_1}\right)^{\left(1/(a-1)\right)} \quad (20)$$

Implicit in these simplifications is an assumption that (K1) and (a) are independent of climate change. If one further assumes that (Pc) is independent of (Pwv) and climate, the following rates of change can be derived from equation (20):

$$\frac{\partial V}{\partial P_{wv}} = \frac{-1}{(a-1)} Aa\left(ET_m - Re\right)\left(\frac{1}{P_c K_1}\right)^{\left(1/(a-1)\right)} P_{wv}^{\left(1/(a-1)^{-1}\right)} \tag{21}$$

$$\frac{\partial V}{\partial ET_m} = Aa - Aa\left(\frac{P_{WV}}{P_c K_1}\right)^{\left(1/(a-1)\right)} \tag{22}$$

$$\frac{\partial V}{\partial Re} = -Aa - Aa\left(\frac{P_{WV}}{P_c K_1}\right)^{\left(1/(a-1)\right)} \tag{23}$$

$$\frac{\partial V}{\partial P_c} = \frac{1}{a-1} Aa(ET_m - Re)\left(\frac{P_{wv}}{K_1}\right)^{\left(1/(a-1)\right)} P_c^{\left(-1/(a-1)^{-1}\right)} \tag{24}$$

## *Appendix B  GAMS PE Model Code with Hydrologic Externalities*

```
$ONTEXT

Partial Spatial Equilibrium Water Distribution Model

Version 14.0


Active model parameters in this file represent base-case scenario
conditions

$OFFTEXT
* set path to data set
$SETGLOBAL PROGPATH "C:\watermodel\Denver_folder\"
$INCLUDE "%PROGPATH%base_data_final.gms"
$SETGLOBAL TEXTNAME test

* allow empty data sets to be initialized
$ONEMPTY

* choose solvers: PATH is mixed complementary program solver
*                 MINOS is non-linear programming optimization solver
* The MINOS NLP solution is used here as a check on PATH MCP solution
OPTION MCP = PATH;
OPTION NLP = MINOS;

*print formatting
OPTION LIMCOL = 3, LIMROW = 3;

* QS3LIMIT is a constraint on gw pumping = quantity pumped in the
managed recharge (direct payment) scenario.
* Also used as a water right constraint.
SCALAR QS3LIMIT
   /
*   1124.
   99999999.0
   /
;
* list all variables in the model
VARIABLES

* node 1 is canal diverter at river point of diversion
* node 2 is canal diverter at head gate
* node 3 is groundwater pumper
*   WELFARE is the maximized NLP value of objective function

   QD2              quantity demanded at node 2
   QD3              quantity demanded at node 3
   QS1              quantity supplied at node 1
   QS3              quantity supplied at node 3
   X12              quantity transported from node 1 to node 2
   X33              quantity transported from node 3 to node 3
   RHOS1            supply price at node 1
   RHOS3            supply price at node 3
   RHOD2            demand price at node 2
```

```
   RHOD3            demand price at node 3
   BETA             marginal benefits received from seepage at node 3
   ALPHA            marginal cost with respect to QS3 of induced
seepage
   RHOCON           price of constraint
;

POSITIVE VARIABLES QD2,QD3,QS1,QS2,X12,x33,RHOD2,RHOD3,RHOS1,RHOS3,
RHOCON;

* list of all equations in the model
EQUATIONS
   EQ1C
   EQ2C
   EQ3C
   EQ4C
   EQ5C
   EQ6C
   EQ7C
   EQ8C
   EQ9C
   EQ10C
   ALPHACALC
   BETACALC
   QCONSTR


;
* Marginal demand-price functions for canal diveters,node 2. All demand
prices are GE 0.
EQ1C..
* Marginal demand-price function, P=f(Q), NOT compatible with IDEP
demand calculator coefficients.
*   RHOD2 - B20*(1-(B21*QD2)**B22) =G= 0

* Inverse of marginal demand-price function, Q=f(P), Compatible with
IDEP demand calculator coefficients.
   RHOD2-(1/B21*(-(QD2-B20)/B20)**(1/B22)) =G= 0
;

* Marginal demand-price functions for gw pumpers, node 3. All demand
prices are GE 0.
EQ2C..
* Marginal value function  P=f(Q), NOT compatible with IDEP demand
calculator coefficients.
*   RHOD3 - B30*(1-(B31*QD3)**B32) =G= 0

* inverse of marginal demand-price function, Q=f(P) Compatible with
IDEP demand calculator coefficients.
   RHOD3-(1/B31*(-(QD3-B30)/B30)**(1/B32)) =G= 0
;

* Canal supply price at river (node 1) is ge 0.
EQ3C..
     A10 - RHOS1 =G= 0
;
```

```
***********************Pigouvian Tax-Subsidy insertion
***************************************
*       Supply-cost functions with and without Pigouvian tax on gw
pumpers and
*       Pigouvian subsidy to canal diverters are inserted here.

*    ALPHA is the pigouvian tax that groundwater pumpers pay for the
damage done to canal diverters.
*    ALPHA is added to the per AF supply cost of groundwater pumping
RHOS3.

EQ4C..
*    Groundwater supply-cost function with pigouvian tax
*    Groundwater supply cost (RHOS3) GE Groundwater supply cost with
seepage (function)
*    + tax paid by gw pumpers to the state (ALPHA) + pumping constraint
cost (RHOCON)if any.

*    A30 + A31*[A32*EXP(A33*QS3-A34*X12)] + ALPHA - RHOS3 + RHOCON =G=
0
*
*    Groundwater supply-cost function without pigouvian tax.

     A30 + A31*[A32*EXP(A33*QS3-A34*X12)]- RHOS3 + RHOCON =G= 0
;

* BETA is the subsidy that canal diverters get for the seepage benefit
provided to gw pumpers
* NOTE: THE CALCULATION OF BETA ASSUMES THAT THE CANAL IS UNLINED. BETA
WILL BE NON ZERO EVEN WHEN THE CANAL IS LINED.

EQ5C..
*  Canal demand-price at node 2 (end of canal) with pigouvian subsidy.
*  Demand-price at the end of the canal GE canal supply-cost at the
head of the canal(RHOS1) + cost of canal seepage - subsidy from state

*      RHOS1 - RHOD2 + RHOD2*(C0*C1*EXP(-C1*X12) + C2*(1-EXP(-C3*QS3)))
- BETA =G= 0

*  Canal demand-price at node 2 without pigouvian subsidy.
      RHOS1 - RHOD2 + RHOD2*(C0*C1*EXP(-C1*X12) + C2*(1-EXP(-C3*QS3)))
=G= 0
;
*********************************End T-S
insertion***************************************************
*
* Quantity supplied at node 3 (gw pumper) is GE quantiy demanded at
node 3
EQ6C..
      RHOS3 - RHOD3 =G= 0
;
* Quantity transported from node 1 to node 2 - canal seepage (via.
seepage function) = quantity demanded at node 2.
EQ7C..
      X12 - C0*(1-EXP(-C1*X12)) - C2*X12*(1-EXP(-C3*QS3)) - QD2 =G= 0
;
```

```
* Quantity of groundwater pumped at node 3(i.e. transported) = quantity
groundwater demanded at node 3.
EQ8C..
      X33 - QD3 =G= 0
;
* Quantity of canal water supplied at node 1 is GE to the quantity
transported from node 1 to node 2.
EQ9C..
      QS1 - X12 =G= 0
;
* Quantity of groundwater water pumped at node 3 is GE to the quantity
transported from node 3 to node 3.
EQ10C..
      QS3 - X33 =G= 0
;
* The  groundwater pumping constraint at node 3 is GE to the quanitity
pumped at node 3.
QCONSTR..
      QS3LIMIT - QS3 =G= 0
;
********************************* ALPHA and BETA
calculation**************************************************
BETACALC..
*        Calculation of BETA, the subsidy received by canal diverters.
*        BETA is calculated by integrating the marginal pumping cost
function between pumping rate 0 and QS3,
*        yielding the total cost of pumping QS3 AF of groundwater.
The derivative
*        with respect to canal diversion X12 then yields QS3 pumping
cost per AF of canal diversion.

     BETA =E= A31*A32*A34*EXP(-A34*X12)*(EXP(A33*QS3)-1)/A33

*        CANAL MUST BE UNLINED IF BETA SUBSIDY EQUATION IS INCLUDED IN
EQ5C.
;

ALPHACALC..
*  Calculation of ALPHA, the tax paid by gw pumpers for (induced)
seepage damage to canal diveter.
*
*  ALPHA is calculated by integrating the seepage cost function between
diversions 0 and X12, yielding
*  the total cost of seepage for X12 AF of diversion. The derivative
with respect to QS3 then yields
*  the damage per AF of groundwater pumped.

    ALPHA =E= RHOD2*C2*C3*X12*EXP(-C3*QS3)

*  For Managed Aquifer Recharge or Coase Scenario
*  ALPHA*QS3 is set equal to BETA*X12
*  In the Coase scenario gw pumpers make a direct payment to canal
diverters equal to the
*  benefit they derive from canal seepage.

*   ALPHA*QS3 =E= BETA*X12
;
```

```
************************************ end A&B
calculation*************************************************

* A model called EXTMODEL is defined by the following equations with
specification of variable results to be displayed .
MODEL EXTMODEL
   /
   EQ1C.QD2
   EQ2C.QD3
   EQ3C.QS1
   EQ4C.QS3
   EQ5C.X12
   EQ6C.X33
   EQ7C.RHOD2
   EQ8C.RHOD3
   EQ9C.RHOS1
   EQ10C.RHOS3
   ALPHACALC
   BETACALC
   QCONSTR.RHOCON
   /

;
* ALPHA AND BETA ARE solved for by the model. Initial values are
required.
ALPHA.L = 0;
BETA.L = 12;

* The EXTMODEL uses a mixed complementary programming solver. The MCP
solver is PATH .
* The EXTMODEL is solved twice for greater accuracy. the second uses
results from first
*  as starting values. Only the results from the second solution are
* displayed.

SOLVE EXTMODEL USING MCP;

ALPHA.L = 0;
BETA.L = 12;

SOLVE EXTMODEL USING MCP;

* Seepage is calculated using EXTMODEL results
SCALAR SEEPAGE;

SEEPAGE = C0*(1-EXP(-C1*X12.L)) + C2*X12.L*(1-EXP(-C3*QS3.L));

* EXTMODEl results are displayed

DISPLAY
QD2.L,QD3.L,QS1.L,QS3.L,X12.L,X33.L,RHOD2.L,RHOD3.L,RHOS1.L,RHOS3.L,SEE
PAGE,ALPHA.L,BETA.L;

* Consumer surpluses are also calculated using EXTMODEL results.
* The calculation depends on the form of the demand function used,
whether from the IDEP calculator or not.
```

```
SCALAR CONSUP2,CONSUP3,PROSUP3,tt1,tt2,tt3,TOTSUP;

* Consumer surplus with canal diverter marginal value function P=f(Q)
*CONSUP2 = B20*QD2.L - (B20*B21*QD2.L**(B22+1))/(B22+1) - QD2.L*RHOD2.L;

* Consumer surplus with inverse canal diverter marginal value function
Q=f(P) coming from IDEP calculator.
CONSUP2 = (-B20/B21)*(B22/(1+B22))*(-(QD2.L-B20)/B20)**((1+B22)/B22)-(-
B20/B21*(B22/(1+B22)))-QD2.L*RHOD2.L;

* Consumer surplus with gw pumper marginal value function P=f(Q)
*CONSUP3 = B30*QD3.L - (B30*B31*QD3.L**(B32+1))/(B32+1) - QD3.L*RHOD3.L;

* Consumer surplus with inverse gw pumper marginal value function Q=f(P)
coming from IDEP calculator.
CONSUP3 = (-B30/B31)*(B32/(1+B32))*(-(QD3.L-B30)/B30)**((1+B32)/B32)-(-
B30/B31*(B32/(1+B32)))-QD3.L*RHOD3.L;


***************************************Groundwater pumper producer
surplus*******************
* tt1 and tt2 are the reductions in gw producer surplus due to gw
pumping
tt1 = A31*A32*EXP(-A34*X12.L)/A33;
tt2 = EXP(A33*QS3.L)-1;

* tt3 is the contribution of canal seepage to the gw producer surplus.

  tt3 = -RHOD2.L*C2*X12.L*(EXP(-C3*QS3.L)-1);
  PROSUP3 = QS3.L*RHOS3.L - A30*QS3.L - tt1*tt2+tt3;
***********************************************************************
**********************


* Total consumer surplus
TOTSUP = CONSUP2 + CONSUP3 + PROSUP3;

DISPLAY CONSUP2,CONSUP3,PROSUP3,TOTSUP,RHOCON.L;

* calculate total payment by groundwater pumpers for canal seepage,
either tax or damages
SCALAR DSEEP,VSEEP,TPAY,ESEEP;

DSEEP = RHOD2.L*C2*C3*X12.L*EXP(-C3*QS3.L);
VSEEP = DSEEP*RHOD2.L;
TPAY = VSEEP*QS3.L;
ESEEP = TPAY/X12.L;
DISPLAY DSEEP,VSEEP,TPAY,ESEEP;

*cDisplay groundwater pumper producer surplus
DISPLAY tt3;
*PROSUP3 = QS3.L*RHOS3.L - A30*QS3.L - tt1*tt2+tt3;
DISPLAY PROSUP3,tt1,tt2;

* qpay is the subsidy/AF of canal diversion at the river multiplied by
quantity diverted
SCALAR QPAY total benefits of water in canal for pumper ;
```

```
* xpay is the tax/AF of pumping multiplied by quantity pumped
SCALAR XPAY total damages caused by pumping;

XPAY = ALPHA.L*QS3.L;
QPAY = BETA.L*X12.L;
DISPLAY QPAY,XPAY;
$EXIT
```

## *Appendix C  GAMS PE Model Data for Hydrologic Externalities*

```
*Active variables in this file represent base-case scenario conditions

SCALAR A10 parameter for the supply function for node 1
   /
*   13.27
   15.00
   /
;

SCALAR A30 first parameter for the supply function for node 3
   /
*   9.46
   9.5
   /
;

SCALAR A31 second parameter for the supply function for node 3
   /
   0.08
   /
;

SCALAR A32 third parameter for the supply function for node 3
   /
*   132.27
*   900
    1000
   /
;

SCALAR A33 fourth parameter for the supply function for node 3
   /
*   1.6959E-4
*   3.0E-4
    1.7e-4
   /
;

SCALAR A34 fifth parameter for the supply function for node 3
   /
*  Along with canal seepage coefficients, A34 must be set to zero when
canal is lined.
*  This is so the marginal cost function for the gw pumper does not
include the benefit of canal
*  diversion when the canal is lined.
*  (below)
*  A30 + A31*[A32*EXP(A33*QS3-A34*X12)]- RHOS3 + RHOCON =G= 0
*
*  Increasing the value of A34 increases the effect that canal water
has upon
*  the pumper’s marginal cost and increases the value of BETA.
*  Reducing this number can be used for partial canal lining scenarios.
```

```
*
   5.0E-4
*    0
   /
;

SCALAR B20 first parameter for the demand function for node 2
   /
  2888.
   /
;

SCALAR B21 second parameter for the demand function for node 2
   /
   .009
   /
;

SCALAR B22 third parameter for the demand function for node 2
   /
   0.818181818
   /
;

SCALAR B30 first parameter for the demand function for node 3
   /
   1350.
   /
;

SCALAR B31 second parameter for the demand function for node 3
   /
   0.009
   /
;

SCALAR B32 third parameter for the demand function for node 3
   /
   2.33333333
   /
;

SCALAR C0 first parameter for the seepage function
   /
   15000
* Note: A34 must also be set to zero when the canal is lined and
seepage = 0
*   0
   /
;

SCALAR C1 second parameter for the seepage function
   /
    1.5E-5
*    0
   /
;
```

```
SCALAR C2 third parameter for the seepage function
   /
    0.10
*   0
   /
;

SCALAR C3 fourth parameter for the seepage function
   /
    0.002
*    0
   /
;
```

## *Appendix D  GAMS PE Model Code with Rival and Non-Rival Demands*

```
$ONTEXT

Partial Spatial Equilibrium Water Distribution Model

* Henrys Fork 9/23/2013 RDS


By Leroy Stodick

16 June 2011

$OFFTEXT

$SETGLOBAL PROGPATH C:\watermodel\Henrys Fork folder\rival and non rival
HF\Rival and non rival fisheries\

$SETGLOBAL TEXTNAME 16June2011

$ONEMPTY
*
*
OPTION MCP = PATH;
OPTION LIMCOL = 3, LIMROW = 3;

* base-case models (no rentals)
$INCLUDE "%PROGPATH%HF_FMID_base_non_rival_irrigation.gms"
*$INCLUDE "%PROGPATH%HF_FMID_base_RNR4.gms"

FILE KDATA3 / "%PROGPATH%DEMANDFUNC2.csv" /;
KDATA3.pw = 900;
FILE KDATA2 / "%PROGPATH%ALL_SUP&DEM.csv" /;
KDATA2.pw = 900;
PUT KDATA2;
PUT "QSOUT"//;
PUT ","

"EGIN_BENCH_BARLEY,EGIN_BENCH_WHEAT,EGIN_BENCH_POTATOES,EGI
N_BENCH_ALFALFA,"
"L_WATERSHED_BARLEY,L_WATERSHED_WHEAT,L_WATERSHED_POTATO
ES,L_WATERSHED_ALFALFA,"
"N_FREEMONT_BARLEY,N_FREEMONT_WHEAT,N_FREEMONT_POTATOES,N
_FREEMONT_ALFALFA,"
```

```
"ST_ANTHONY_FISH,ISLAND_PARK_FISH,EGIN_BENCH_RECHARGE,L_WAT
ERSHED_RECHARGE,N_FREEMONT_RECHARGE,"
",PUMPERS_BARLEY,PUMPERS_WHEAT,PUMPERS_POTATOES,PUMPERS_AL
FALFA,"
"SUP_CON$_EGIN_BENCH_IRR_N,CON$_N_FREEMONT_IRR_N,CON$_L_WAT
ERSHED_IRR_N,CON$_EGIN_BENCH_IRR_S,"
"CON$_N_FREEMONT_IRR_S,CON$_L_WATERSHED_IRR_S,CON$_EGIN_BEN
CH_NON_N,CON$_N_FREEMONT_NON_N,CON$_L_WATERSHED_NON_N,"
"CON$_EGIN_BENCH_DRAIN,SCON$_L_WATERSHED_DRAIN,"/;

VARIABLES

  WELFARE        value of objective function
  QD(DEM)        quantity demanded
  QS(SUP)        quantity supplied
  X(SUP,DEM)     quantity transported from node I to node J
  RHOS(SUP)      supply prices
  RHOD(DEM)      demand prices
*   RHOG(SUP)     COST OF GROUNDWATER CONSTRAINT
  RHOM(SUP)      cost of drain water constraint
  RHOF(SUP)      cost of fixed drain constraint
  RHOC(SUP)      cost of canal constraint
  SEEPAGE        total seepage from canal
  RECH_SEEP      recharge seepage
  RECHDPR(SUP)   demand price for recharge water per acre foot of water pumped
;

POSITIVE VARIABLES QD,QS,X,RHOD,RHOS,RHOM,RHOC,RHOF;

EQUATIONS

  OBJ            objective function
*Kuhn Tucker conditions complementary slackness equations
*  1
  DEMCONS(I)     demand must be met at all nodes
*  2
  SUPCONS(I)     cannot ship more than is produced
  DEMPRIN(I)     marginal utility equal to demand price inverse demand function
  DEMPR(I)       marginal utility equal to demand price forward demand function
  SUPPR(I)       marginal cost equal to supply price

*
  SUPPRB(I)      marginal cost equal to supply price (base model)
  PRLINKB(I,J)   price linkage equation (base model)
*
```

```
   DRNCONS(I)          right hand side of drain water supply variable constraints
   DRNFIXED(I)         right hand side of fixed drain constraints
   CANALCONS(I)           canal quantity constraints
   CALCSEEP            total seepage
   CALCRECH             seepage for the recharge water
   CALCDPR(I)          calculate demand price for recharge water
;



 DEMCONS(DEM)..
    SUM(SUP,X(SUP,DEM)) - QD(DEM) -
SUM(CANAL,S0(CANAL,DEM)*X(CANAL,DEM))
    - SUM(RECHNODES,RECH_S0(RECHNODES,DEM)*X(RECHNODES,DEM))
=G= 0
;

SUPCONS(SUP)..
   QS(SUP) - SUM(DEM,X(SUP,DEM)) =G= 0
;

**********************************************************************
**********************
DEMPRIN(DEM1)..
* Inverse of marginal demand-price function, Q=f(P), Compatible with IDEP demand
calculator coefficients.
   RHOD(DEM1)-(1/B1(DEM1)*(-(QD(DEM1)-
B0(DEM1))/B0(DEM1))**(1/B2(DEM1))) =G= 0
;
**********************************************************************
**********************
* forward demand price function
* second term (B3, B4 & B5)represents non rival demand
DEMPR(DEM2)..
*      RHOD(DEM2) - B0(DEM2)*(1 - B1(DEM2)*(QD(DEM2)**B2(DEM2))) =G= 0
     RHOD(DEM2) - B0(DEM2)*(1 - B1(DEM2)*(QD(DEM2)**B2(DEM2)))-
B3(DEM2)*(1 - B4(DEM2)*(QD(DEM2)**B5(DEM2))) =G= 0
*     RHOD(DEM2)-B3(DEM2)*(1 - B4(DEM2)*(QD(DEM2)**B5(DEM2))) =G= 0
;
**********************************************************************
**********************
SUPPR(SUP)..
      A0(SUP)
* + A1(SUP)*A2(SUP)*EXP[A3(SUP)*QS(SUP)-
A4(SUP)*(SEEPAGE+RECH_SEEP)]
```

```
- RHOS(SUP)
     + RHOC(SUP) + RHOF(SUP) + RHOM(SUP)
*      +
SUM(AGDRN,RHOM(AGDRN)*C1(AGDRN)*C3(AGDRN)*EXP[C2(AGDRN)*SEE
PAGE - C3(AGDRN)*SUM(PUMP,QS(PUMP))])$PUMP(SUP)
      =G= 0;
;


SUPPRB(SUP)..
     A0(SUP)
*+ A1(SUP)*A2(SUP)*EXP[A3(SUP)*QS(SUP)-A4(SUP)*(SEEPAGE+RECH_SEEP)]
 - RHOS(SUP)
     + RHOM(SUP) + RHOC(SUP) + RHOF(SUP)
     + RECHDPR(SUP)$PUMP(SUP)
      =G= 0;
;

************************************************************************
********************************
PRLINKB(SUP,DEM)$ARCS(SUP,DEM)..
     RHOS(SUP) - RHOD(DEM) + T(SUP,DEM) + RHOD(DEM)*S0(SUP,DEM)
        =G= 0
;
*-----------------------------------------------------------------------------------------------------
*Seepage is proporational to diversion
*Drain return supply is also proportional to diversion (drain return is partly seepage)
* Drain constraint multipler x the seepage proportion (table S0) = the proportion of
diversion that is drain return.
* e.g if seepage proportion of diversion is .25 and the drain return multiplier of seepage is
0.1, then
* the drain return portion of diversion, QS(AGDRN), is 0.025.  C0 (below) is the drain
constraint multiplier
*------------------------------------------------------------------------------------------------------
DRNCONS(AGDRN)..
   C0(AGDRN)*SEEPAGE - QS(AGDRN) =G= 0
;

DRNFIXED(AGDRN)..
   CFIXED(AGDRN) - QS(AGDRN) =G= 0
;

CANALCONS(CANAL)..
   D0(CANAL) - QS(CANAL) =G= 0
;
*GWCONS(PUMP)..
```

```
*   E0(PUMP) - QS(PUMP) =G= 0
*;
*$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$
CALCSEEP..
  SEEPAGE - SUM((CANAL,DEM),X(CANAL,DEM)*S0(CANAL,DEM)) =E= 0
;

CALCRECH..
  RECH_SEEP -
SUM((RECHNODES,DEM),RECH_S0(RECHNODES,DEM)*X(RECHNODES,DEM))
=E= 0
;

CALCDPR(PUMP)..
  RECHDPR(PUMP) -

[SUM((RECHNODES,DEM),X(RECHNODES,DEM)*RECH_S0(RECHNODES,DEM)
)]
*A1(PUMP)*A2(PUMP)*A4(PUMP)/A3(PUMP)
*     *[EXP(A3(PUMP)*QS(PUMP))-1]*EXP(-
A4(PUMP)*(SEEPAGE+RECH_SEEP)))]/QS(PUMP)
    =E= 0
;

X.FX(SUP,DEM)$NO_ARCS(SUP,DEM) = 0;
RHOM.FX(NONAGDRN) = 0;
RHOC.FX(NONCANAL) = 0;
RHOF.FX(NONAGDRN) = 0;
RECHDPR.FX(NONPUMP) = 0;


** Third solution using MCP and Path solver with externaities.
MODEL BASEMODEL
  /
  DEMCONS.RHOD
  SUPCONS.RHOS
  DRNCONS.RHOM
  DRNFIXED.RHOF
  CANALCONS.RHOC
  DEMPR.QD
  DEMPRIN.QD
  SUPPRB.QS
  PRLINKB.X
  CALCSEEP
  CALCRECH
  CALCDPR
```

```
  /
;

SET MNAMES names of models
  /
  BASE
  /
;
PARAMETER QDOUT(DEM,MNAMES) quantity demanded;
PARAMETER QSOUT(SUP,*) quantity supplied;
PARAMETER RHOSOUT(SUP,*) supply price;
PARAMETER RHODOUT(DEM,*) demand price;
PARAMETER RHOMOUT(SUP,*) marginal cost of variable constraint for drain water
users;
PARAMETER RHOCOUT(SUP,*) marginal cost of canal constraints;
PARAMETER RHOFOUT(SUP,*) marginal cost of fixed constraint for drain water
users;
PARAMETER XOUT(*,SUP,DEM) quantity supplied from node SUP to node DEM;
PARAMETER CANSEEP(*,SUP,DEM) seepage in canal from node SUP to node DEM;
PARAMETER SEEPOUT(*) Total seepage;
PARAMETER RECHOUT(*)  recharge seepage;
PARAMETER PROSUP(*,SUP) Producer surplus;
PARAMETER CONSUP(*,DEM) Consumer surplus;
PARAMETER TOTCONSUP(*) TOTAL CONSUMER SURPLUS
PARAMETER TOTSUP(*) total surplus;

OPTION QDOUT : 0
OPTION QSOUT : 0
OPTION RHOSOUT : 2
OPTION RHODOUT : 2
OPTION RHOMOUT : 2
OPTION RHOCOUT : 2
OPTION RHOFOUT : 2
OPTION XOUT : 0
OPTION CANSEEP : 0

SET LNUM1/LN1*LN1/;
PARAMETER SUP_PRICE1;
PARAMETER SUP_PRICE2;
PARAMETER SUP_PRICE3;
PARAMETER SUP_PRICE4;
PARAMETER SUP_PRICE5;
PARAMETER SUP_PRICE6;

PARAMETER SUP_PRICES2;
PARAMETER SUP_PRICES3;
```

```
PARAMETER SUP_PRICES4;
PARAMETER SUP_PRICES5;
PARAMETER SUP_PRICES6;

PARAMETER SUP_QUAN1;
PARAMETER SUP_QUAN2;
PARAMETER SUP_QUAN3;
PARAMETER SUP_QUAN4;
PARAMETER SUP_QUAN5;
PARAMETER SUP_QUAN6;

PARAMETER XEB1;
PARAMETER XEB2;
PARAMETER XEB3;
PARAMETER XEB4;
PARAMETER XEB5;
PARAMETER XEB6;
PARAMETER XEB7;

PARAMETER DEM_QUAN1;
PARAMETER DEM_QUAN2;
PARAMETER DEM_QUAN3;
PARAMETER DEM_QUAN4;
PARAMETER DEM_QUAN5;
PARAMETER DEM_QUAN6;

PARAMETER SUP_CONSTRN1;
PARAMETER SUP_CONSTRN2;
PARAMETER SUP_CONSTRN3;
PARAMETER SUP_CONSTRN4;

PARAMETER SUP_CONSTRDW1;
PARAMETER SUP_CONSTRDW2;
PARAMETER SUP_CONSTRDW3;
PARAMETER SUP_CONSTRDW4;

PARAMETER CONSUP1;
PARAMETER CONSUP2;
PARAMETER CONSUP3;
PARAMETER CONSUP4;
PARAMETER CONSUP5;
PARAMETER CONSUP6;

*Below is the starting value for quantity demanded for MCP solver. In some cases with
inverse demand
```

```
* functions it must be set to a fairly large number to avoid divison by zero and achieve solution
* convergence.  In the absence of inverse demand functions it can still cause problems. Although
* setting to zero is the default value.

*QD.L(DEM)=100.0;
 QD.L(DEM)=0.0;
SOLVE BASEMODEL USING MCP;
        SUP_PRICE1=A0("FMID_IRRIGATE_NFL");
        SUP_PRICE2=A0("FMID_IRRIGATE_STO");
        SUP_PRICE3=A0("FMID_NON_IRRIGATE_STO");
        SUP_PRICE4=A0("ST_ANTHONY_RETURN_FLOW");
        SUP_PRICE5=A0("MUD_LAKE_GROUNDWATER");
        SUP_PRICE6=A0("FMID_CANAL_SEEPAGE");

        SUP_QUAN1=QS.L("FMID_IRRIGATE_NFL");
        SUP_QUAN2=QS.L("FMID_IRRIGATE_STO");
        SUP_QUAN3=QS.L("FMID_NON_IRRIGATE_STO");
        SUP_QUAN4=QS.L("ST_ANTHONY_RETURN_FLOW");
        SUP_QUAN5=QS.L("MUD_LAKE_GROUNDWATER");
        SUP_QUAN6=QS.L("FMID_CANAL_SEEPAGE");

        XEB1=X.L("FMID_IRRIGATE_NFL","FMID_IRRIGATION");
        XEB2=X.L("FMID_IRRIGATE_STO","FMID_IRRIGATION");
        XEB3=X.L("FMID_IRRIGATE_NFL","ST_ANTHONY_FISHERIES");
        XEB4=X.L("FMID_IRRIGATE_STO","ST_ANTHONY_FISHERIES");
        XEB5=X.L("FMID_NON_IRRIGATE_STO","FMID_IRRIGATION");
        XEB6=X.L("FMID_NON_IRRIGATE_STO","FMID_CARRYOVER");
        XEB7=X.L("FMID_NON_IRRIGATE_STO","ISLAND_PARK_FISHERIES");

        DEM_QUAN1=QD.L("FMID_IRRIGATION");
        DEM_QUAN2=QD.L("MUD_LAKE_IRRIGATION");
        DEM_QUAN3=QD.L("ST_ANTHONY_FISHERIES");
        DEM_QUAN4=QD.L("ISLAND_PARK_FISHERIES");
        DEM_QUAN5=QD.L("FMID_CARRYOVER");
        DEM_QUAN6=QD.L("FMID_IS_PARK_FISH");

QDOUT(DEM,"BASE") = QD.L(DEM);
QSOUT(SUP,"BASE") = QS.L(SUP);
RHOSOUT(SUP,"BASE") = RHOS.L(SUP);


RHODOUT(DEM,"BASE") = RHOD.L(DEM);
XOUT("BASE",SUP,DEM) = X.L(SUP,DEM);
CANSEEP("BASE",SUP,DEM) = S0(SUP,DEM)*X.L(SUP,DEM);
```

```
RHOMOUT(SUP,"BASE") = RHOM.L(SUP);
RHOCOUT(SUP,"BASE") = RHOC.L(SUP);
RHOFOUT(SUP,"BASE") = RHOF.L(SUP);
SEEPOUT("BASE") = SEEPAGE.L;
RECHOUT("BASE") = RECH_SEEP.L;

* STORAGE CONSTRAINT COSTS FOR PRINTING
SUP_CONSTRN1=RHOCOUT("FMID_IRRIGATE_NFL","BASE");
SUP_CONSTRN2=RHOCOUT("FMID_IRRIGATE_STO","BASE");
SUP_CONSTRN3=RHOCOUT("ST_ANTHONY_RETURN_FLOW","BASE");
SUP_CONSTRN4=RHOCOUT("FMID_NON_IRRIGATE_STO","BASE");

SUP_CONSTRDW1= RHOM.L("FMID_IRRIGATE_NFL");
SUP_CONSTRDW2= RHOM.L("FMID_IRRIGATE_STO");
SUP_CONSTRDW3= RHOM.L("ST_ANTHONY_RETURN_FLOW");
SUP_CONSTRDW4= RHOM.L("FMID_NON_IRRIGATE_STO");


* RECHPX is the value of an acre foot of water in the recharge canal to the
* groundwater pumper. It is The integral of marginal pumping cost with respect to his
pumping rate
* then the derivative of this integral (total pumping cost) with respect to canal seepage
* This gives change in his total pumping cost per unit of canal seepage
* which is the value of seepage in terms of reduced pumping cost

*RECHPX(RECHNODES,DEM) =
SUM(PUMP,[RECH_S0(RECHNODES,DEM)*A1(PUMP)*A2(PUMP)*A4(PUMP)/A
3(PUMP)]*[EXP(A3(PUMP)*QS.L(PUMP))-1]
*     *EXP(-A4(PUMP)*(SEEPAGE.L+RECH_SEEP.L)));

PROSUP("BASE",PUMP) = - A0(PUMP)*QS.L(PUMP);

*consumer surplus from demands represented by forward demand function
CONSUP("BASE",DEM2) = B0(DEM2)*QD.L(DEM2) -
(B0(DEM2)*B1(DEM2)/(B2(DEM2)+1))*QD.L(DEM2)**(B2(DEM2)+1) -
QD.L(DEM2)*RHOD.L(DEM2);
*consumer surplus from demands represented by inverse demand function
CONSUP("BASE",DEM1) =(-B0(DEM1)/B1(DEM1))*(B2(DEM1)/(1+B2(DEM1)))*(-
(QD.L(DEM1)-B0(DEM1))/B0(DEM1))**((1+B2(DEM1))/B2(DEM1))-(-
B0(DEM1)/B1(DEM1)*(B2(DEM1)/(1+B2(DEM1))))-QD.L(DEM1)*RHOD.L(DEM1);
* total consumer surplus
TOTCONSUP("BASE") =  SUM(DEM2,CONSUP("BASE",DEM2))+
SUM(DEM1,CONSUP("BASE",DEM1));

TOTSUP("BASE") = SUM(SUP,PROSUP("BASE",SUP)) +
SUM(DEM,CONSUP("BASE",DEM));
```

```
DISPLAY
QDOUT,QSOUT,RHOSOUT,RHODOUT,RHOCOUT,RHOFOUT,RHOMOUT,RECH
DPR.L,SEEPOUT,RECHOUT,XOUT,CANSEEP,PROSUP,CONSUP,TOTCONSUP,T
OTSUP;

CONSUP1=CONSUP("BASE","FMID_IRRIGATION");
CONSUP2=CONSUP("BASE","MUD_LAKE_IRRIGATION");
CONSUP3=CONSUP("BASE","ISLAND_PARK_FISHERIES");
CONSUP4=CONSUP("BASE","ST_ANTHONY_FISHERIES");
CONSUP5=CONSUP("BASE","FMID_CARRYOVER");
CONSUP6=CONSUP("BASE","FMID_IS_PARK_FISH");


*Generate excel file supply and demand prices quantities and consumer surpluses

FILE KDATA1 / "%PROGPATH%DEMANDFUNC1.csv" /;
KDATA1.pw = 900;
PUT KDATA1;

PUT "FMID nat flow price, FMID nat flow supplied, FMID storage price, FMID storage
supplied"/;
PUT SUP_PRICE1,",",SUP_QUAN1,",",SUP_PRICE2,",",SUP_QUAN2 /;

PUT "FMID Non-Irr price, FMID Non-Irr supplied" /;
PUT   SUP_PRICE3,",",SUP_QUAN3/;

PUT "St Anthony drain water price, St Anthony drain water supplied"/;
PUT SUP_PRICE4,",",SUP_QUAN4/;

PUT"Mud Lake gw supply price, Mud Lake gw quantity supplied,"/;
PUT SUP_PRICE5,",",SUP_QUAN5/;

PUT"FMID canal seepage supply price, FMID canal seepage quantity supplied,"/;
PUT SUP_PRICE6,",",SUP_QUAN6/;

PUT"FMID irrigation nat. flow constraint, FMID irrigation storage constraint" /;
PUT SUP_CONSTRN1,",",SUP_CONSTRN2 /;

PUT"FMID irrigation nat. flow constraint cost, FMID irrigation storage constraint cost"
/;
PUT SUP_CONSTRN1,",",SUP_CONSTRN2 /;

PUT"St Anthony return flow supply constraint,St Anthoy return flow supply constraint
cost" /;
PUT SUP_CONSTRN3,",",SUP_CONSTRDW3/;
```

```
PUT"FMID non-irrigation supply constraint, FMID non-irrigation supply constraint cost"
/;
PUT SUP_CONSTRN4,",",SUP_CONSTRDW4/;

PUT"FMID irrigation demand quantity" /;
PUT DEM_QUAN1/;

PUT"Mud Lake irrigation demand quantity" /;
PUT DEM_QUAN2/;

PUT"St Anthony fisheries demand quantity" /;
PUT DEM_QUAN3/;

PUT"Island Park fisheries demand quantity" /;
PUT DEM_QUAN4/;

PUT"FMID carryover demand quantity" /;
PUT DEM_QUAN5/;

PUT"Mud Lake irrigation & Island Park fisheries demand quantity" /;
PUT DEM_QUAN6/;

PUT"FMID_IRRIGATE_NFL to FMID_IRRIGATION, FMID_IRRIGATE_STO to
FMID_IRRIGATION"/;
PUT XEB1,",",XEB2/;

PUT"FMID_IRRIGATE_NFL to ST_ANTHONY_FISHERIES,
FMID_IRRIGATE_STO to ST_ANTHONY_FISHERIES"/;
PUT XEB3,",",XEB4/;

PUT"FMID_NON_IRRIGATE_STO to FMID_IRRIGATION,
FMID_NON_IRRIGATE_STO to FMID_CARRYOVER,
FMID_NON_IRRIGATE_STO to ISLAND_PARK_FISHERIES"/;
PUT XEB5,",",XEB6,",",XEB7/;

PUT"FMID irrigation consumer surplus"/;
PUT CONSUP1/;

PUT"Mud Lake irrigation consumer surplus"/;
PUT CONSUP2/;

PUT"Island Park fisheries consumer surplus"/;
PUT CONSUP3/;

PUT"ST Anthony fisheries consumer surplus"/;
```

```
PUT CONSUP4/;

PUT"FMID carryover consumer surplus"/;
PUT CONSUP5/;

PUT"Mud Lake irrigtion & Island Park fish consumer surplus"/;
PUT CONSUP6/;

PUTCLOSE KDATA1 /;
$EXIT
```

## *Appendix E GAMS PE Model Data for Rival and Non-Rival Demands*

```
$SETGLOBAL TITLENAME "FMID Scenarios 26 August 2013"
* Average year Automation model
* revised demand functions "new_demands4.xls"
* base-case nat flow and storage constraints are average year diversions from nat. flow
and storage
* no rental storage to B-unit
* P =adjusted potato demand function TC =adjusted transportation cost
* Updated irrigation and non-irrigation rental storage.

*THIS DATA SET IS UPDATED WITH IRRIGATION AND NON-IRRGATION
RENTAL CONSTRAINTS FOR AVERAGE AND DRY YEARS
*THIS DATA SET ALSO HAS MOST UPDATED COMMENTS 12/2/13 9:30 AM
*zero trib flow 12/4/2013
* eliminated the IS_PARK_NON_RELEASE_LR demand and supply nodes because St
Anthony demand is Jul-Sep., not winter months 12/4/2013
SET I index of the nodes
  /
* supply nodes
  FMID_IRRIGATE_NFL,
  FMID_IRRIGATE_STO,
  FMID_NON_IRRIGATE_STO,
  ST_ANTHONY_RETURN_FLOW,
  MUD_LAKE_GROUNDWATER,
  FMID_CANAL_SEEPAGE,


* demand nodes
   FMID_IRRIGATION,
   ST_ANTHONY_FISHERIES,
   ISLAND_PARK_FISHERIES,
   MUD_LAKE_IRRIGATION,
   FMID_CARRYOVER,
   FMID_IS_PARK_FISH
  /
;

ALIAS (I,J);

SET DEM(I) index of demand nodes
 /
   FMID_IRRIGATION,
   ST_ANTHONY_FISHERIES,
   ISLAND_PARK_FISHERIES,
   MUD_LAKE_IRRIGATION,
```

```
   FMID_CARRYOVER,
   FMID_IS_PARK_FISH
  /
;

SET DEM1(DEM)  INDEX OF MARGINAL DEMAND FNS. QTY=F(PRICE)
      /
*   NONE
     /
;
SET DEM2(DEM)  INDEX OF MARGINAL UTILITY FNS. PRICE=F(QTY)
      /
   FMID_IRRIGATION,
   ST_ANTHONY_FISHERIES,
   ISLAND_PARK_FISHERIES,
   MUD_LAKE_IRRIGATION,
   FMID_CARRYOVER,
   FMID_IS_PARK_FISH
     /
;
SET SUP(I) index of supply nodes (n=naturalflow s=storage)
  /
  FMID_IRRIGATE_NFL,
  FMID_IRRIGATE_STO,
  FMID_NON_IRRIGATE_STO,
  ST_ANTHONY_RETURN_FLOW,
  FMID_CANAL_SEEPAGE,
  MUD_LAKE_GROUNDWATER
  /
;

SET CANAL(SUP) index of canal nodes
  /
  FMID_IRRIGATE_NFL,
  FMID_IRRIGATE_STO,
  FMID_NON_IRRIGATE_STO
  /
;

SET PUMP(SUP) index of groundwater supply nodes
  /
   MUD_LAKE_GROUNDWATER
  /
;

SET AGDRN(SUP) index of drainwater supply nodes
```

```
  /
  ST_ANTHONY_RETURN_FLOW
  /
;
SET RECHNODES(SUP) index of recharge water supply nodes
  /
*   NONE
  /
;
SET NONPUMP(SUP) index of supply nodes other than groundwater;

NONPUMP(SUP) = NOT PUMP(SUP);

SET NONAGDRN(SUP) index of supply nodes other than drain water;

NONAGDRN(SUP) = NOT AGDRN(SUP);

SET NONCANAL(SUP) index of supply nodes other than canal nodes;

NONCANAL(SUP) = NOT CANAL(SUP);

SET ARCS(SUP,DEM) all possible arcs
  /
  FMID_IRRIGATE_NFL.FMID_IRRIGATION,
  FMID_IRRIGATE_NFL.ST_ANTHONY_FISHERIES,
  FMID_IRRIGATE_STO.FMID_IRRIGATION,
  FMID_IRRIGATE_STO.ST_ANTHONY_FISHERIES,
*   FMID_NON_IRRIGATE_STO.ISLAND_PARK_FISHERIES,
  ST_ANTHONY_RETURN_FLOW.ST_ANTHONY_FISHERIES,
  MUD_LAKE_GROUNDWATER.MUD_LAKE_IRRIGATION,
  FMID_NON_IRRIGATE_STO.FMID_CARRYOVER,
  FMID_NON_IRRIGATE_STO.FMID_IS_PARK_FISH
  /
;

SET NO_ARCS(SUP,DEM) arcs which are not possible;

NO_ARCS(SUP,DEM) = NOT ARCS(SUP,DEM);

PARAMETER B0(DEM) First parameter for the marginal utility functions
  /
   FMID_IRRIGATION       27
   FMID_CARRYOVER        27
*fitted for marginal demand price/fish =$22.45
*   Non-rival demands
   ST_ANTHONY_FISHERIES    750
```

```
   ISLAND_PARK_FISHERIES  1600
   MUD_LAKE_IRRIGATION     27

* Vertical additon of Mud Lake Irrigation and Island Park fisheries
* This B0 is first paramter for Mud Lake irrigation
   FMID_IS_PARK_FISH   27
  /
;


PARAMETER B1(DEM) Second parameter for the marginal utility functions
  /
   FMID_IRRIGATION       .00095
   FMID_CARRYOVER        .00095
   ST_ANTHONY_FISHERIES  .9948
   ISLAND_PARK_FISHERIES .9949
   MUD_LAKE_IRRIGATION   .0009

* Vertical additon of Mud Lake Irrigation and Island Park fisheries
* This B1 is the second paramter for Mud Lake irrigation
   FMID_IS_PARK_FISH   .00095
  /
;


PARAMETER B2(DEM) Third parameter for the marginal utility functions
  /
   FMID_IRRIGATION        .612
   FMID_CARRYOVER         .612
   ST_ANTHONY_FISHERIES   .00043
   ISLAND_PARK_FISHERIES  .0004
   MUD_LAKE_IRRIGATION    .613
* Vertical additon of Mud Lake Irrigation and Island Park fisheries
* This B2 is the third paramter for Mud Lake irrigation
   FMID_IS_PARK_FISH  .612
  /
;
PARAMETER B3(DEM) First parameter for the non-rival marginal utility functions
  /
   FMID_IRRIGATION        0
   FMID_CARRYOVER         0
   ST_ANTHONY_FISHERIES   0
   ISLAND_PARK_FISHERIES  0
   MUD_LAKE_IRRIGATION    0
* Vertical additon of Mud Lake Irrigation and Island Park fisheries
* This B3 is the first paramter for non-rival Island Park fisheries
```

```
   FMID_IS_PARK_FISH  1600
  /
;


PARAMETER B4(DEM) Second parameter for the non-rival marginal utility functions
   /
   FMID_IRRIGATION       0
   FMID_CARRYOVER        0
   ST_ANTHONY_FISHERIES   0
   ISLAND_PARK_FISHERIES  0
   MUD_LAKE_IRRIGATION    0
* Vertical additon of Mud Lake Irrigation and Island Park fisheries
* This B4 is the secibd paramter for non-rival Island Park fisheries
   FMID_IS_PARK_FISH  .9949
  /
;


PARAMETER B5(DEM) Third parameter for the non-rival marginal utility functions
   /
   FMID_IRRIGATION       0
   FMID_CARRYOVER        0
   ST_ANTHONY_FISHERIES   0
   ISLAND_PARK_FISHERIES  0
   MUD_LAKE_IRRIGATION    0
* Vertical additon of Mud Lake Irrigation and Island Park fisheries
* This B5 is the third paramter for non-rival Island Park fisheries
   FMID_IS_PARK_FISH  .0004
   /
;
* Marginal supply cost for irrigation water is cost of natural flow and storage water.
There is added transportation cost for this water
* due to return flow, the magnitude of which are indicated in the following three tables
*(Trans. cost, seepage pct. and return multiplier). Natural flow supply costs are what IDs
charge irrigators for water delivered to the canal
* diversion point, not to the headgates.
PARAMETER A0(SUP) First parameter for the marginal cost functions
   /
   FMID_IRRIGATE_NFL       .46
   FMID_IRRIGATE_STO      3.46
   FMID_NON_IRRIGATE_STO   3.46
   ST_ANTHONY_RETURN_FLOW  .01
   FMID_CANAL_SEEPAGE      .01
   MUD_LAKE_GROUNDWATER    10.00
   /
```

;

* O&M transportation costsare the IDs costs for delivery of water from the canal diversion point to the headgate.
*They are applied to all diversions including seepage losses and return flows as well as to water consumptively used by irrigators.
* Seepage costs are assoicated with the supply cost of water that seeps from the canal and never reaches the farm headgate.
* O&M transportation costs are separate from supply costs.

```
  TABLE T(SUP,DEM) per unit conveyance cost from Node SUP to Node DEM O&M charge (per AF charge)

                    FMID_IRRIGATION
  FMID_IRRIGATE_NFL         1.37
  FMID_IRRIGATE_STO         1.37
  FMID_NON_IRRIGATE_STO      0.0
;

  TABLE S0(SUP,DEM) First parameter for the canal seepage functions

                FMID_IRRIGATION
  FMID_IRRIGATE_NFL       .66
  FMID_IRRIGATE_STO       .66
;

TABLE RECH_S0(SUP,DEM) first parameter for the (not incidental) recharge seepage function
*             RECH_DEM
*  RECH_SUP        0.5
;
* The drain return multiplier determines the percentage of seepage loss that is drain return.
* Automation scenario drain return is zeroed out
PARAMETER C0(SUP) first parameter for drain return constraint multiplier
  /
  ST_ANTHONY_RETURN_FLOW   .12
  /
;
PARAMETER G0(SUP) first parameter for GROUNDWATER constraint multiplier
  /
  MUD_LAKE_GROUNDWATER   .88
  /
;
PARAMETER CFIXED(SUP) fixed constraint for  drain water supply
```

```
  /
  ST_ANTHONY_RETURN_FLOW   1.0E10
  /
;

PARAMETER D0(SUP) RHS for canal constraints(natural flow and storage constraints)
/
* average year natural flow useage (constraint)
  FMID_IRRIGATE_NFL      760140

* total available irrigation season storage (average year)
  FMID_IRRIGATE_STO      191227

* Total storage available for irrigation carryover  (average year) (measured at the end of
the irrigation season)
*  = baseline irrigation season storage - baseline FMID irrigation season diversions from
storage.
  FMID_NON_IRRIGATE_STO   136977
  /
;
```