Henrys Fork Hydro-Economic Modeling

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Introduction

Hydro-economic models represent the hydrologic, engineering, environmental and economic aspects of basin scale water resource systems in an integrated framework that accounts for the economic value of water services generated. 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, 1970). Most hydro-economic models share basic elements including spatial representation of hydrologic flows, 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. Development of a node-arc model framework incorporating water suppliers and demanders as nodes, and supply and demand linkages as arcs.
2. Development of marginal water supply-cost and demand-price functions for supply and demand nodes, and conveyance-cost functions for model arcs.
3. Calibration of the baseline model using basin hydrologic and water budget data.
4. Development of model scenarios by modifying baseline model variables to represent alternative water resources plans.
5. Evaluation of scenario results to generate policy insights and reveal opportunities for improved water resource planning.

Two basic approaches exist for hydro-economic modeling. The holistic approach combines hydrology and economic optimization into a single model. The modular approach (figure 1) involves a transfer of exogenous 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).

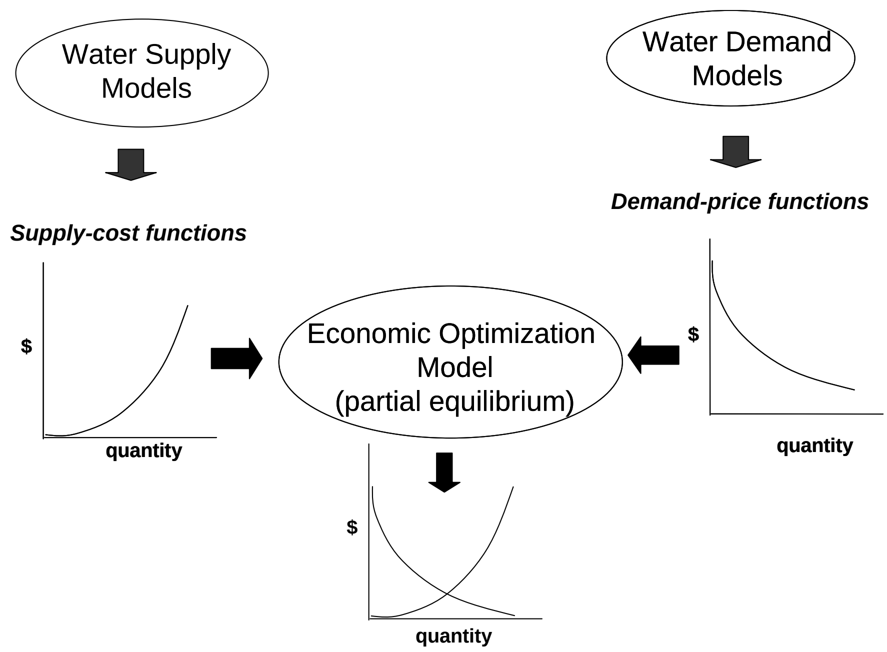


Figure 1: Basin-wide hydro-economic modeling, modular components.

Henrys Fork Basin Hydrologic Setting

The Henrys Fork (HF) River flows for 120 miles in the eastern part of Idaho, joining the upper Snake River from the north near Rexburg, Idaho (Figure 2). The HF basin encompasses approximately 3,300 square miles bound by high desert areas of the Eastern Snake Plain on the west and on the north by the Continental Divide along the Centennial and Henry's Lake mountains. The Yellowstone Plateau and Teton Mountains form the eastern boundary and the southern boundary is marked by the Snake River.
Originating at the northern part of the basin, the main stem of the Henrys Fork River flows generally southward, supplemented by water from tributaries flowing from the mountains to the east. The HF watershed has three major storage reservoirs, and multiple irrigation diversions ranging from small pumps to large canal headworks which regulate the flows in the basin. In the early 1900s, farmers took advantage of an abundant river water supply to sub-irrigate lands. The resulting watertable rise led to greatly expanded groundwater irrigation. Basin soils are highly productive and produce primarily grain, alfalfa, and potato crops.

The total basin water supply, computed as the mean annual rainfall over the total watershed area (30-year average) is about 4.9 million AF. Almost half (2.3 million AF) is lost to evaporation and deep groundwater, and a little more than half (2.5 million AF) is measured as surface water supply (Van Kirk et. al, 2011).

The Island Park Dam was constructed by the Bureau of Reclamation in 1935 as part of the Upper Snake River Division of the Minidoka Project and the Freemont Madison Irrigation District (FMID) was formed from numerous small irrigation companies across Fremont, Madison, and Teton Counties. FMID provides water to about 1,500 water users who irrigate over 285,000 acres. Most of the water in the HF basin is appropriated, and water is available for use only to the extent that flows exceed the demands of FMID irrigators with priority water rights. Figure 3 shows the three sub-basins of the Henrys Fork (North Freemont, Egin Bench and Lower Watershed) which make up the Freemont Madison Irrigation District.

As part of the Greater Yellowstone Ecosystem, the HF basin provides habitat for a variety of large and small mammals and birds. National Forest lands in the basin provide both summer and winter outdoor recreational opportunities which draw tourists from all over the world. The HF has a reputation for world-class fly fishing and the basin supports wild populations of native Yellowstone cutthroat trout and nonnative rainbow and brown trout. However water storage and irrigation deliveries have significantly altered river and stream hydrology in the HF basin (Van Kirk and Jenkins, 2005). Stream flow alterations are greatest during drought years and as a result rainbow trout have largely displaced native Yellowstone cutthroat trout throughout most of the watershed (Van Kirk and Jenkins 2005).

Minimum stream flows necessary to preserve desired stream values have been recommended by the Idaho Department of Fish and Game (IDFG), however except for the high flows of spring runoff, the 30-year average flow in the river is consistently lower than the IDFG flow recommendations to benefit aquatic life. Federal and State agencies, FMID, and the Henrys Fork Foundation (HFF) have worked cooperatively to set the timing and quantity of winter releases from Island Park reservoir in order to promote fish habitat while maintaining the primacy of irrigation demands (Van Kirk 2011).

The HF watershed exhibits a high degree of surface water and groundwater interaction both spatially and temporally. Canal seepage losses account for about 25% of total diversions from the river (Van Kirk, 2011). Seepage from irrigation canals is the primary source of aquifer recharge. Aquifer recharge also occurs by direct delivery of water to managed recharge sites in the basin. Groundwater discharge to agricultural drains is the primary source of instream flows during winter months.

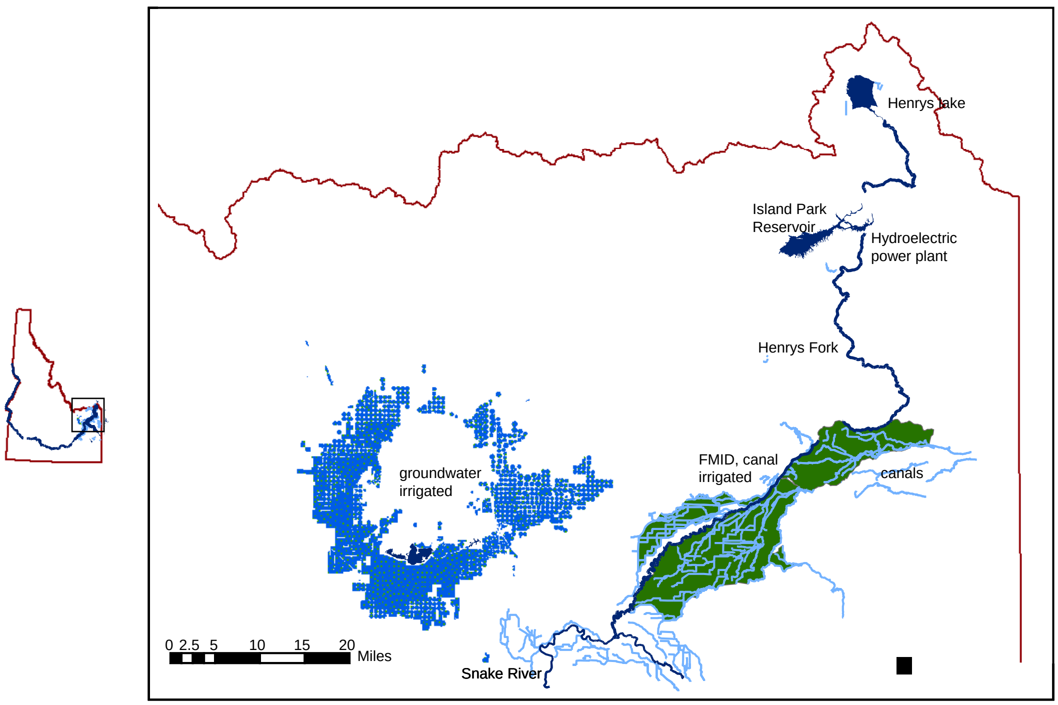


Figure 2: Henrys Fork watershed basin in Eastern Idaho.

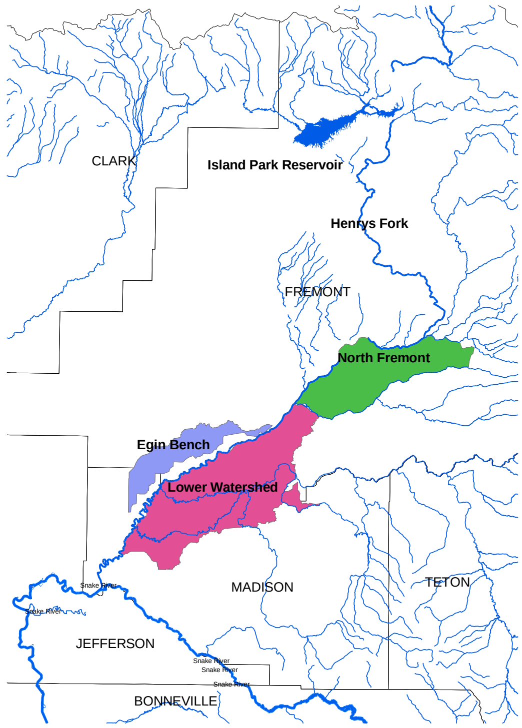


Figure 3: Three Henrys Fork sub-basins which make up the FMID.

Partial Equilibrium (PE) Modeling

The mathematical link between hydrology and economics in hydro-economic modeling is economic optimization. Partial equilibrium (PE) optimization models examine the conditions of market equilibrium that exist when dealing with a single economic commodity (in our case water), all other factors of production are held fixed.

PE economic optimization was introduced in the water literature by Flinn and Guise (1970), who adopted the Takayama and Judge (1964) concept of an interregional trade model. In the hydrologic context, PE modeling generates an optimal allocation of water quantities which maximize basin-wide economic benefit from water use. Individual water quantities and prices vary among demanders because of differences in supply costs and demand prices.

Hydrologic and water engineering features are represented in a PE model by a node-arc network, in which water suppliers and demanders are represented by nodes and arcs denote opportunities for water transfers between nodes. The node-arc network thereby accommodates both the physical and economic distribution of water supply and demand in a watershed system.

PE modeling is not equivalent to advocating water marketing, nor does it assume all water resources are private goods. Constraints on private allocations and demands for public goods such as river system eco-services are readily included in hydro-economic models. PE models also differ from economy-wide general equilibrium models in that hydro-economic PE models focus on how economics affect water resource management rather than on how water resource management affects the entire economic system (Harou, 2009).

The concept of marginality is central in PE modeling to express the supply-cost or demand-price of one additional unit of water (at the margin). 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).

Jointness-of-Production and Hydrologic Externalities

Jointness-of-production occurs when the economic activity of one entity impacts the production possibilities of another, either positively or negatively. Externalities arise when the impacts of jointness-of-production are not fully accounted for (via pricing) in economic decisions (Mishan,1971; Baumol and Oates, 1988). The result is a divergence between private and social benefit or cost, with price institutions failing to sustain desirable activities or to curtail undesirable activities (Bator, 1958).

Market failures resulting from hydrologic externalities most commonly take the form of the underproduction of a positive externality. In the HF basin the market failure is the under production of instream flows to sustain river system eco-services, including fisheries.

Instream flows in the HF which sustain trout fisheries and other eco-services are largely dependent on FMID irrigation demands, and since instream flows are public goods there is no direct compensation by users of HF eco-services for the benefit they derive from these services.

PE models have traditionally been cast as optimization problems in which a quasi-welfare or net social payoff function is maximized subject to constraints. Water allocations which maximize the objective function were then assumed to be the supply and demand equilibrium conditions. The presence of hydrologic externalities means that the traditional method of calculating supply and demand equilibrium conditions is no longer appropriate, since an objective functions exists only with the elimination of externalities.

Calculating Net Benefits with Externalities

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 generic modeling systems such as GAMS (Brooke et al., 1988) and the accompanying PATH solver (Ferris and Munson, 1999) PE equilibrium equations containing externalities can be solved directly using MCP wherein certain equality constraints in the optimization problem are replaced by inequality constraints containing Lagrange multipliers (Kjeldsen, 2000).

Absent non-convexities and assuming a unique solution, six sets of complementary slackness[1] equations define economic equilibrium conditions in the presence of hydrologic externalities.

1. $p_i - \rho_i \leq 0$ and $q_i(p_i - \rho_i) = 0$ for $q_i \geq 0$

2. $\rho^i - p^i \leq 0$ and $q^i(\rho^i - p^i) = 0$ for $q^i \geq 0$

3. $\sum_j x_{ji} + \sum_k \sum_j EX_{kji} - q_i \geq 0$ and $\rho_i(\sum_j x_{ji} + \sum_k \sum_j EX_{kji} - q_i) = 0$ for $\rho_i \geq 0$

4. $q^i - \sum_j x_{ij} - \sum_j \sum_k EX_{ijk} \geq 0$ and $\rho^i(q^i - \sum_j x_{ij} - \sum_j \sum_k EX_{ijk}) = 0$ for $\rho^i \geq 0$

5. $\rho_j - \rho^i - t_{ij} + \sum_k c_{ijk} \frac{\partial F_{ijk}(x_{ij})}{\partial x_{ij}} \leq 0$

6. $F_{ijk}(x_{ij}) - EX_{ijk} = 0$

Equations 1 and 2 insure that if quantity of water transported is greater than zero, then equilibrium demand and supply prices are points that lie, respectively, on the demand and supply curves. Equation 3 insures that no excess water demand exists. Equation 4 allows for an excess water supply. Equation 5 is the price linkage equation, i.e. the difference between the equilibrium water demand price and the equilibrium water supply price is the cost of the externality. Equation 6 insures that the quantity of externality produced is equal to the quantity of externality delivered.

With externalities, the equilibrium equations of Takayama and Judge include a new exogenous function, $F_{ijk}(x_{ij})$, which relates the quantity of un-priced (externalized) water supplied to another quantity of priced (internalized) water that is delivered. The new endogenous variable, EX_{kji}, is then the quantity of un-priced water that is delivered.

The above conditions are solved for equilibrium water prices and quantities using GAMS and the PATH solver. Consumer surpluses, which are the measure of net benefits used in PE model applications, are obtained using equilibrium prices and quantities as limits of integration (figure 4).

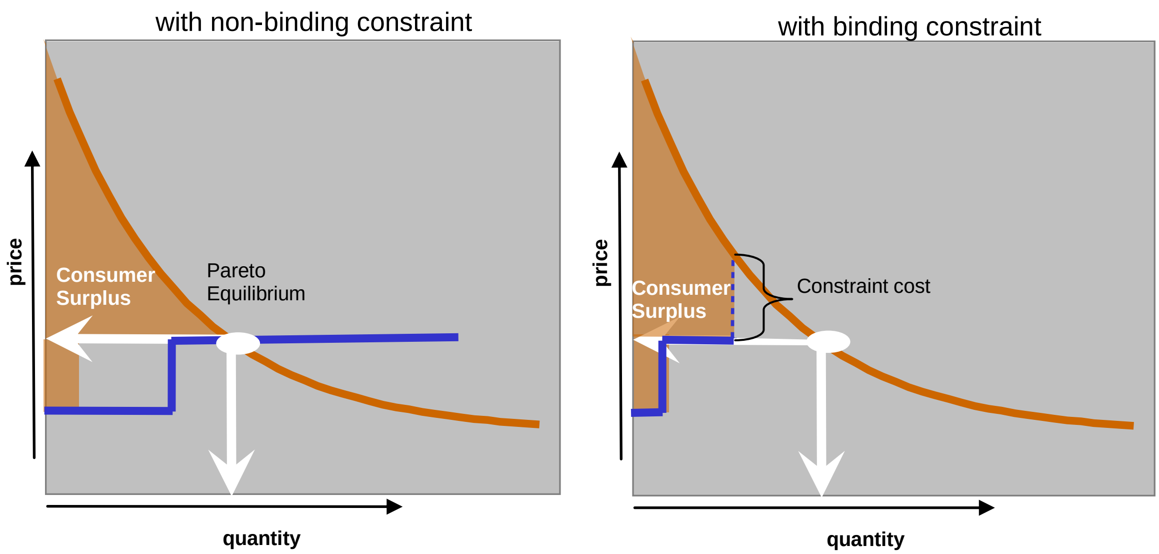


Figure 4: **Calculation of net benefits (consumer surpluses) using equilibrium water prices and quantities as limits of integration.**

FMID Irrigation Supply Cost Functions

Water valuation from the supply perspective results in a supply-cost curves which for canal irrigators typically have a block rate structure. FMID irrigation water supply costs are represented by step functions in which the first step is the per AF cost of natural flow and the second step is the per AF cost of storage water. Currently there are just two steps in the FMID average year and dry year water supply functions (figures 5 and 6). Additional steps would be added if new reservoir storage became available at a higher cost. The average year constraint on natural flow and storage supplies is the 30 year (1978-2008) average, and the dry year constraint is the average of a three year dry period between 2003 and 2005.

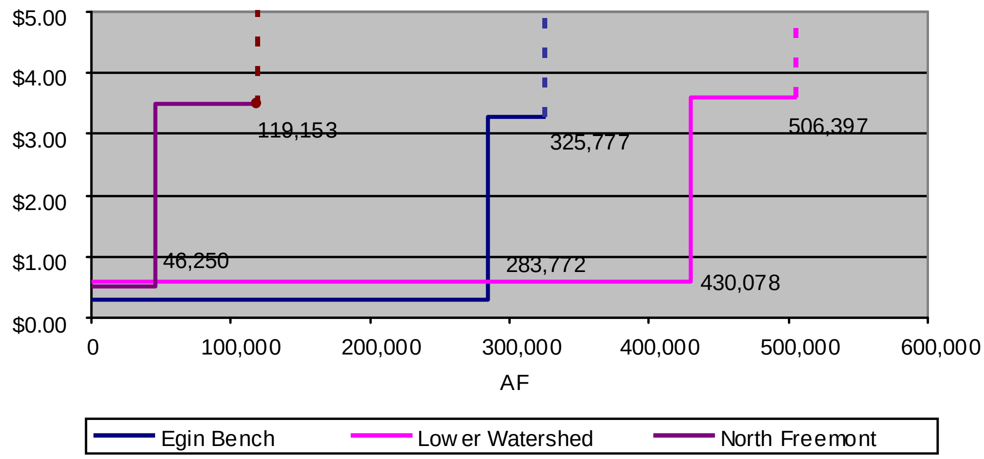


Figure 5: FMID irrigation supply costs and constraints.

Natural flow supply costs for FMID irrigation water vary among the three HF sub basins because canal operation and maintenance (O&M) costs vary. The per AF charges for irrigation water are based on total acreage and total diversions in each sub basin. The Egin Bench natural flow O&M cost is the lowest at $0.29/AF. The North Freemont charge is $0.50/AF, and the Lower Watershed O&M charge iis $0.59/AF. An additional $3.00/AF is added for water that is released from HF storage. Supply costs do not include additional conveyance costs associated with canal seepage losses and return flows.

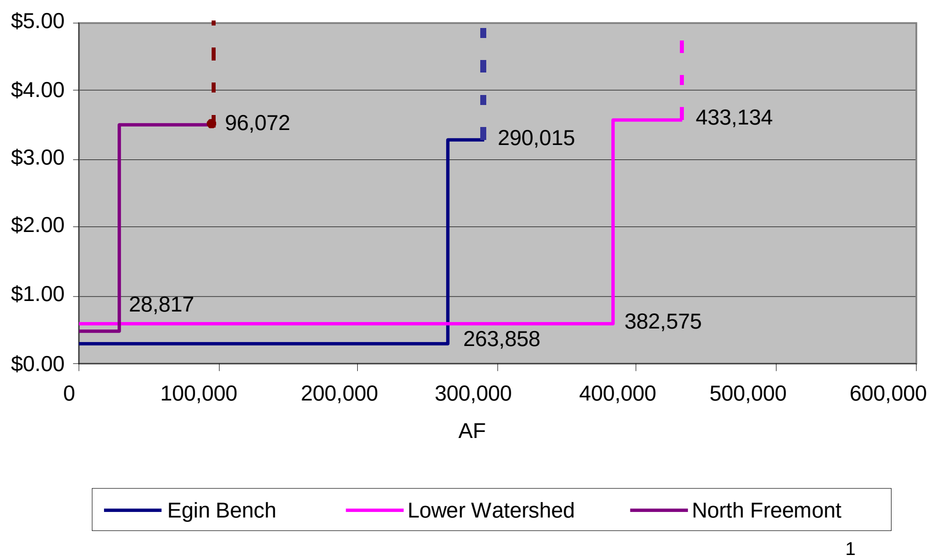


Figure 6: **Dry year (2003-2005 average) FMID irrigation season supply costs and constraints.**

Since natural flow is the sole source of supply for aquifer recharge during winter months, average year and dry year non-irrigation season water supply costs and constraints are represented by functions with a single-step (figures 7 and 8). The much constrained dry year non–irrigation season supply of natural flow results from most HF flows being held in carryover for the next irrigation season.

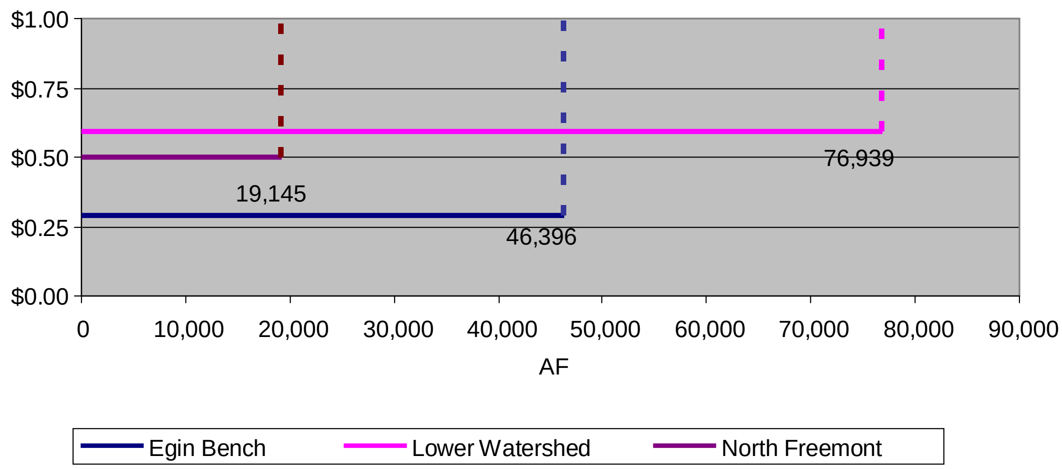


Figure 7: FMID 30 year average non-irrigation season supply cost functions.

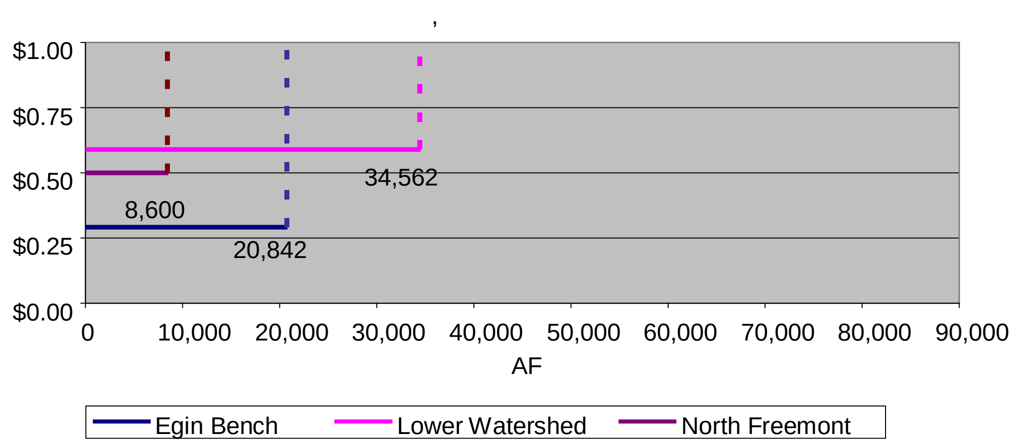


Figure 8: FMID dry year (2003-2005) average <u>non-irrigation</u> season supply cost functions.

The supply of instream flows for HF fisheries, which is critical during the non-irrigation season, is largely dependent on natural flows and reservoir releases made in support of irrigation activities. This includes winter-time aquifer recharge, operational reservoir releases and irrigation return flows. Instream flows that are dependent on irrigation demands are non-rival and un-priced. However reservoir releases that are exclusively for instream flows (and rival with irrigation) are allowed in model scenarios and are arbitrary priced at $3.00 per AF, the same as irrigation releases.

Rival and Non-Rival Water Demands

Recently updated principles and requirements for federal water resource planning (P&R, 2013) place increased emphasis on commensurate valuations of watershed costs and benefits including, where possible, the monetizing of currently un-priced or under-priced river system eco-services. Capturing the value of these services (e.g. boating, fishing, ecological diversity) in river systems that are being managed for irrigation and reservoir storage requires hydro-economic modeling of a mix of both private and public goods.

In contrast to private goods such as irrigation water diversions which are excludable and rival, public goods such as river system eco-services are non-excludable and non rival (Myles 1995). A good is non-exclusive if others cannot be excluded from its use and non-rival if its consumption by one agent does not diminish the amount available to others.

Each person benefiting from a public good pays a price which depends on a personal evaluation of the worth of the good. Since no one can be excluded from using a public good, its valuation is prone to under reporting, and as a consequence the marginal benefit of public goods are under produced, creating a negative externality.

Accurate CBA of water projects that affect river systems being managed for multiple rival and non-rival water uses depends in large measure on the correct valuation of demands for both private and public goods. Rival water demand for a mix of crops is calculated by horizontally summing the demand quantities of individual crops at every marginal price, thus private goods are allocated water on the basis of an equal-marginal price (figure 9). Water demands for eco-services that are non-rival in consumption are calculated by vertically summing the demand prices of individual services at every marginal quantity, thus non-rival public goods are allocated on the basis of their total marginal price (figure 10).

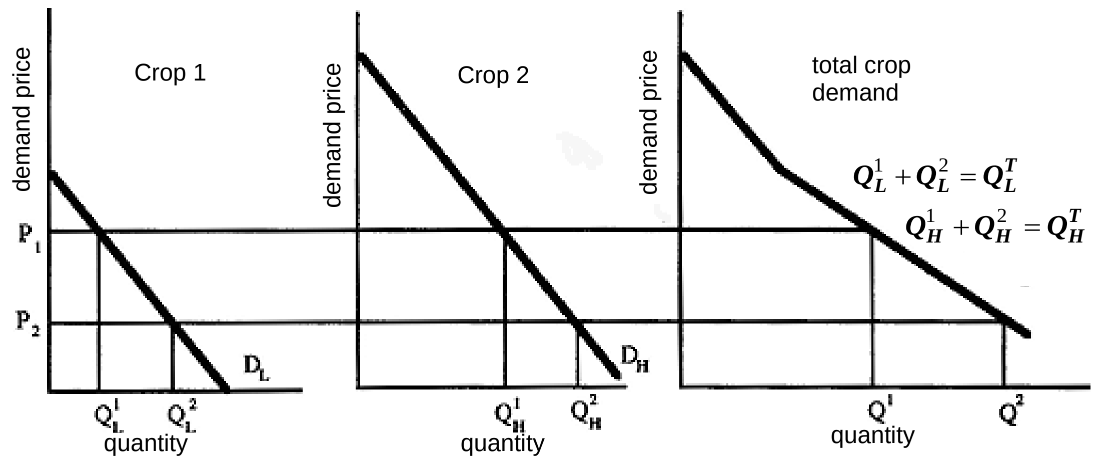


Figure 9: Horizontal summation of water demand quantities for two rival irrigated crops.

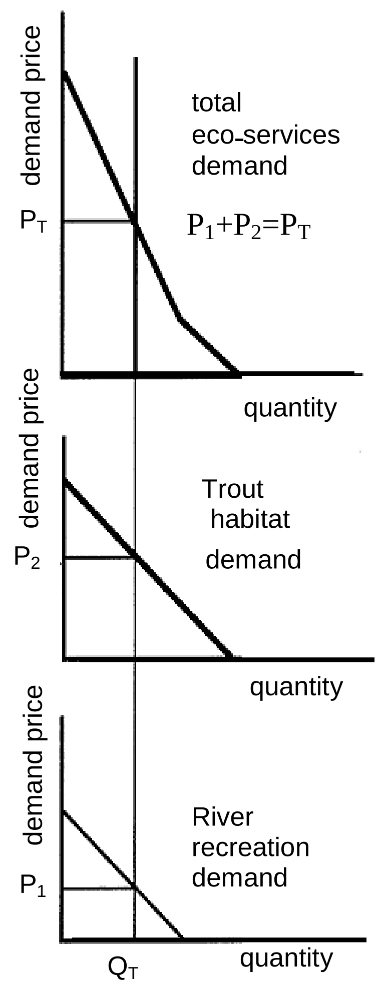


Figure 10: Vertical summation of water demand-prices for two non-rival instream flow eco-services.

As a private good, irrigation may be rival or non-rival with river system eco-services, depending the location and timing of irrigation demands in relation to the instream flows needed to sustain eco-services. If a storage release for irrigation flows through the Island Park reach but is diverted before reaching the St. Anthony reach, then irrigation demand is non-rival with instream flow demand in the Island Park reach but rival with instream flow in the St. Anthony reach. Similarly, if irrigation return flow enters the river below the Island Park reach but above the St Anthony reach, irrigation demand is non-rival with instream flow demand in the St Anthony reach but rival with instream flow demand in the Island Park reach.

FMID Irrigation Demand Price Functions

Two broad approaches are available to model water demand (Kindler and Russell, 1984) and develop demand functions for irrigation and river system eco-services. Inductive techniques rely on econometric or statistical analysis of observed data to estimate price-response. Deductive methods involve production functions and mathematical programming.

A spreadsheet demand function calculator is used to develop the irrigation demand price functions (IWRRI, 2008) (Martin et al., 1984). Crop and production function inputs to the calculator, including commodity prices, crop acreages and evapotranspiration (ET) production functions are obtained from a variety of agricultural and statistical data bases maintained by the USDA, Idaho Dept of Water Resources and the University of Idaho.

Demand price functions are developed for principal crops grown in the FMID, the B-Unit of the A&B district and groundwater pumpers near Thousand Springs (figure 2). Aquifer recharge demand functions are also developed for crops grown in groundwater irrigated areas of the HF (figure 3).

The demand function calculator assumes that market mechanisms have already maximized crop acreages and the mix of crops. Therefore all existing constraints on crop distribution are assumed to be fully reflected in the status-quo allocation of crops to lands.

Although crop mix is fixed, lower value crops may drop out of production at higher prices. Limited water supplies are assumed to be optimally delivered when most needed.

The multiple demand curves developed for the four principal FMID crops (figure 11) illustrate the range of “best fitting” demand data regressions possible. However to insure a unique PE model solution, demand price elasticity is represented only by convex functions.

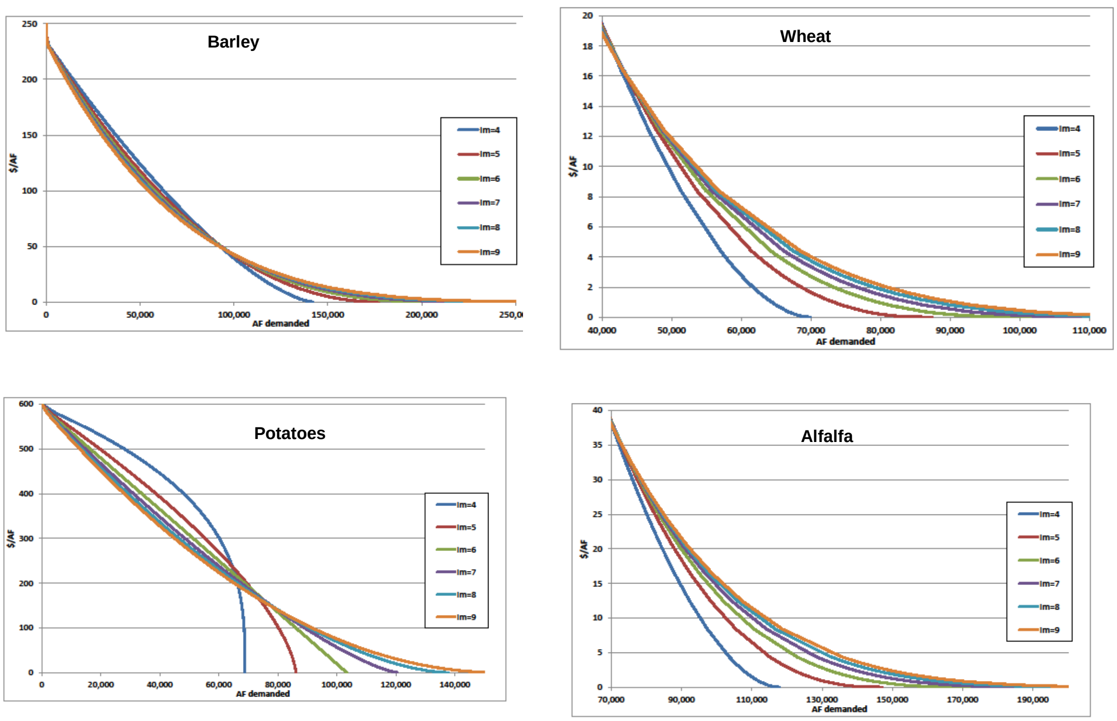


Figure 11: FMID Irrigation demand-price functions for four crops with varying price elasticities.

Henrys Fork Instream Flow Demand Price Functions

A number of inductive methods have been developed for measuring willingness to pay for environmentally-related public goods. Revealed preference methods rely on actual expenditure mainly travel costs, made by consumers (Young, 2005). Stated preference methods involve asking people directly about the values placed on environmental services. Both approaches have been used to infer the willingness to pay for recreational trout fishing in Eastern Idaho Rivers (Loomis, 2005).

Recreational fishing is one example of a river system eco-service that is can be considered a public good, it is non-rival as long as one angler's catch does not measurably diminish the stocks available to others. While "free riders" acting in their own self interest are unwilling to pay anything for river services such as recreational fishing, others who value the experience of HF wilderness and wildlife are willing to pay a considerable sum. Somewhere in between are recreational anglers whose willingness to pay depends on the quality of the fishing experience. For some it is the opportunity to catch additional fish of a common species (e.g. Rainbow trout), for others it is the opportunity to catch even one of a much less common species (e.g. Cutthroat trout).

Flows critical for maintaining Rainbow trout populations in the HF occur in two reaches of the river, the upper HF reach below Island Park dam and the lower reach just above St Anthon. Flows are critical during a three month interval (December–February) in the fry stage of development. Trout fry survival during this period is the key determinant of fishable trout population in subsequent years (Van Kirk, 2013).

Empirically derived equations by Van Kirk (2013) describe fishable trout populations $N(i)$, in both reaches as functions of the previous five years of HF instream flows x_{i-j-1} during this three month period (figure 12). The first pair of equations applies to the HF reach below Island Park and the second pair applies to the reach below St. Anthony.[2] The two functions plot as upward sloping curves (figures 13 and 14) so that increasing instream flow results in an increasing population of fishable trout.

[2] In order to make the equations compatible with the irrigation water supply and demand units of the PE model, instream flow x_{i-j-1} is converted from cfs to AF over a three month interval.

Island Park reach, trout vs cfs (Dec-Feb) (VanKirk, eq 3)

$$N(i) = 132.01 \sum_{j=0}^{4} 0.4^{j} \left(x_{i-j-1}\right)^{0.5276}.$$

Island Park reach, trout vs AF/3month (Dec-Feb)

$$N(i) = 8.5603 \cdot \sum_{j=0}^{4} 0.4^{j} \left(x_{i-j-1}\right)^{0.5276}$$

St Anthony reach, trout vs cfs (Dec-Feb) (VanKirk, eq 4)

$$N(i) = \frac{132.01}{4^{0.5276}} \sum_{j=0}^{4} 0.4^{j} \left(x_{i-j-2}\right)^{0.5276},$$

St Anthony reach, trout vs AF/3month (Dec-Feb)

$$N(i) = 4.109 \cdot \sum_{j=0}^{4} 0.4^{j} \left(x_{i-j-1}\right)^{0.5276}$$

Figure 12: Fishable trout population and flow in two Henrys Fork reaches (Van Kirk, 2012)

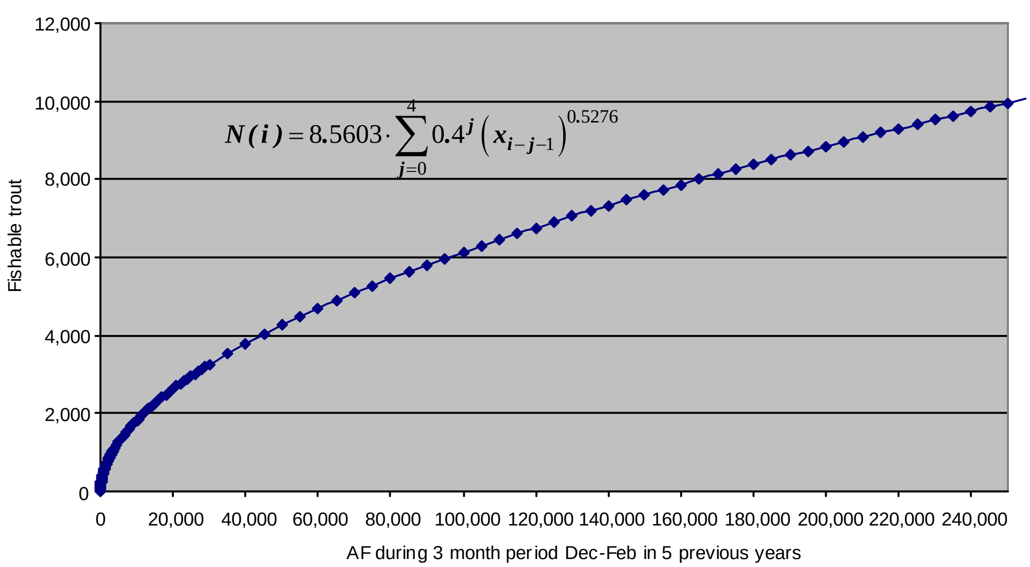


Figure 13: Island Park reach fishable trout vs AF flow during 3 month period (Dec-Feb) of 5 previous years.

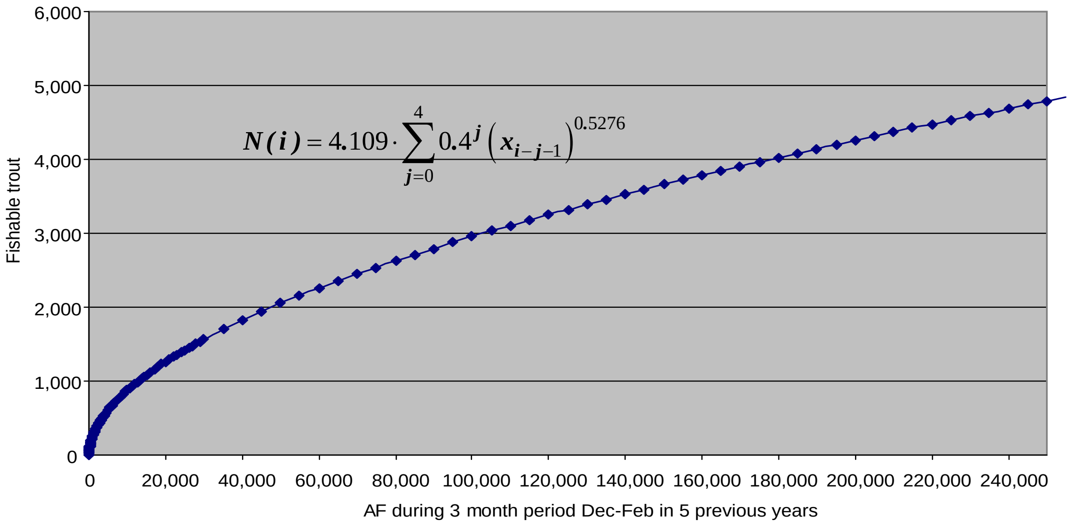


Figure 14: St Anthony reach fishable trout vs AF flow during 3 month period (Dec-Feb) of 5 previous years.

The derivatives of these two functions (figures 15 and 16) with respect to AF of flow yields the marginal rate of increase in fishable trout per AF of flow in each reach, during the critical three month period. For example, in the Island Park reach if flow during the critical period is 60,000 AF, one additional AF would increase the fishable trout population by about 0.04 fish. In the St Anthony reach, if flow is 60,000 AF one additional AF would increase the population by about 0.02 fish.

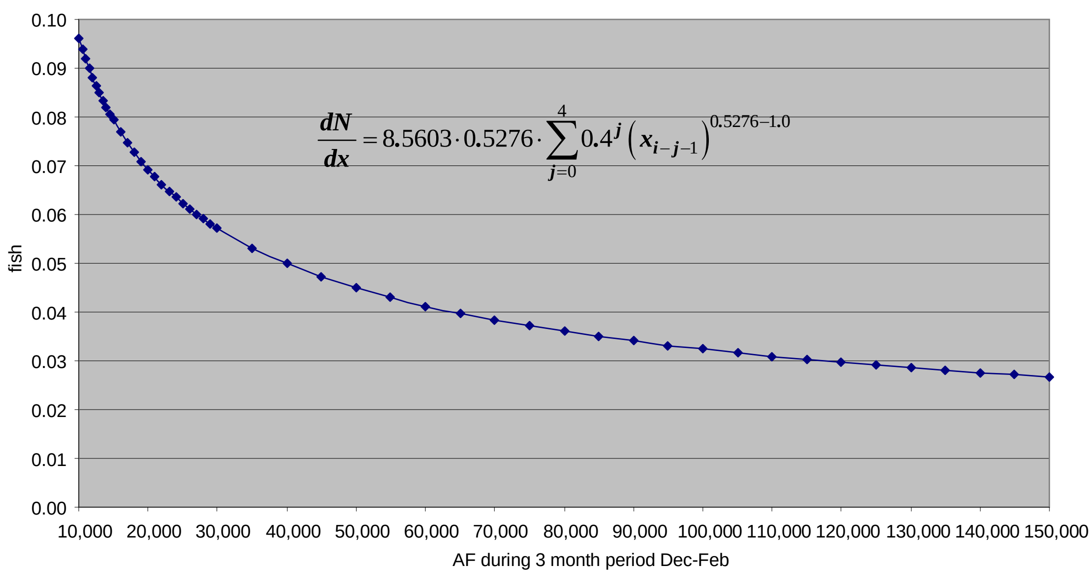


Figure 15: Marginal rate of increase in Island Park trout per AF of flow during 3 month period (Dec-Feb) of 5 previous years.

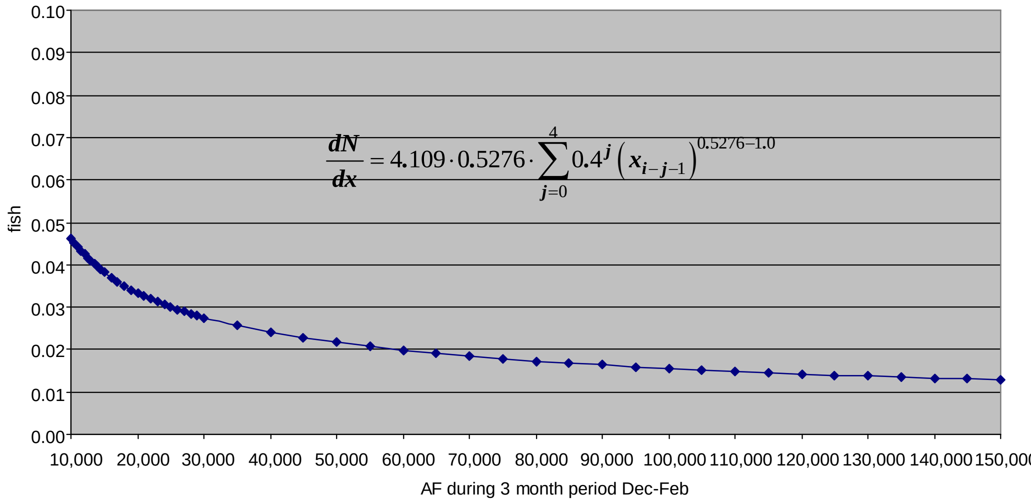


Figure 16: Marginal rate of increase in St Anthony trout per AF of flow during 3 month period (Dec-Feb) of 5 previous years

As noted previously, the marginal value of trout to HF anglers is based on a contingent valuation survey of Snake River anglers (Loomis, 2005). The survey results indicated that a HF angler's willingness-to-pay to catch one additional trout was, on average, \$22.45. The marginal value of instream flow for HF trout can then be determined by multiplying the marginal rate of increase in trout population in the Island Park and St Anthony reaches per AF of instream flow by \$22.45 (figures 17 and 18).

This is not the same however as anglers willingness to pay to catch an additional trout, making it necessary to calculate a relationship between the willingness to pay for trout in the river and willingness to pay for trout caught by anglers.[3] Nevertheless, in the absence of reliable valuations for other river system eco-services, including boating

[3] The average daily catch in HF reaches is 8.2 trout (Loomis, 2005), so one additional trout represents a 12 % increase in catch. Assuming catch is directly proportional to fishable trout population, the population of fishable trout in the river would also have to increase by 12% in order for anglers to catch one additional fish. In Dec-Feb of a dry year (2001-2005) Island Park reach flow averages 195 cfs (35,000 AF in the three month interval). Based on the equations of Van Kirk, the Island Park trout population should therefore be about 3527. Since one additional trout caught by anglers requires a 12% increase in trout population (i.e. 423 trout), the total population needed to enable anglers to catch one additional trout is 3,950. The marginal economic value of an additional trout in the river (to anglers) is therefore \$22.45/423, about \$0.05.

recreation, wildlife viewing etc, an instream flow marginal demand price based on a trout valuation of $22.45 is more reasonable than one based strictly on willingness to pay for successful angling. These marginal demand-price functions for instream flow are therefore used to represent the willingness to pay for the full range of HF eco-services, including a sustainable population of Rainbow trout in the Island Park and St Anthony river reaches.

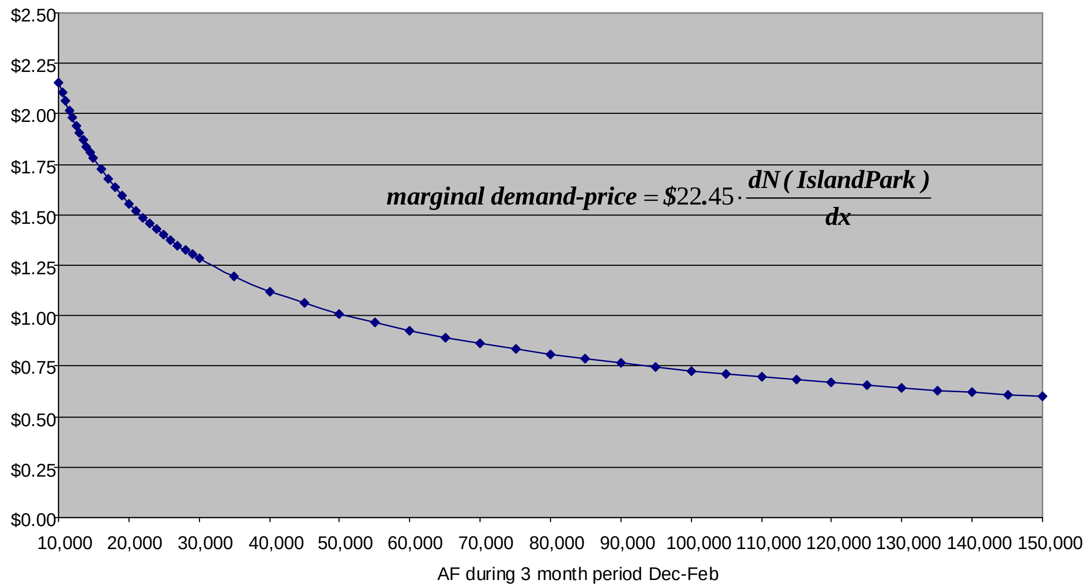


Figure 17: Marginal demand-price function for instream flow to sustain fisheries in the Island Park Reach.

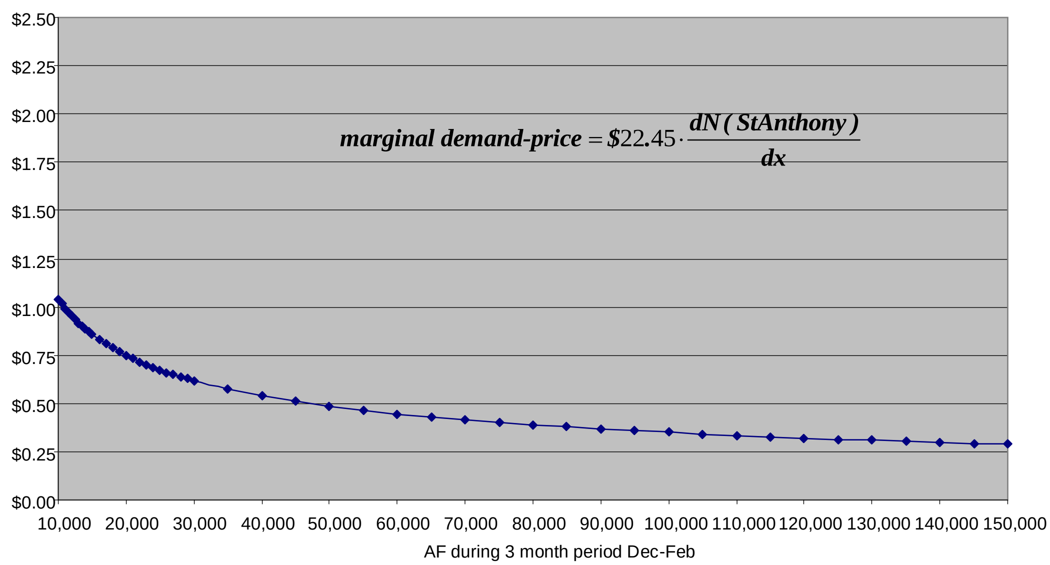


Figure 18: Marginal demand-price function for instream flow to sustain fisheries in the St Anthony Reach.

The two previous demand functions for instream flow in the Island Park reach and the St. Anthony reach are appropriate for valuing instream flows that are rival with each other (but may be non-rival with irrigation). However if a reservoir release is made exclusively for instream flows then the two instream flow demands are non-rival with each other (but rival with irrigation) an the total willingness-to-pay for instream flow in the two reaches is the vertical summation of the two instream flow marginal demand prices (figure 19).

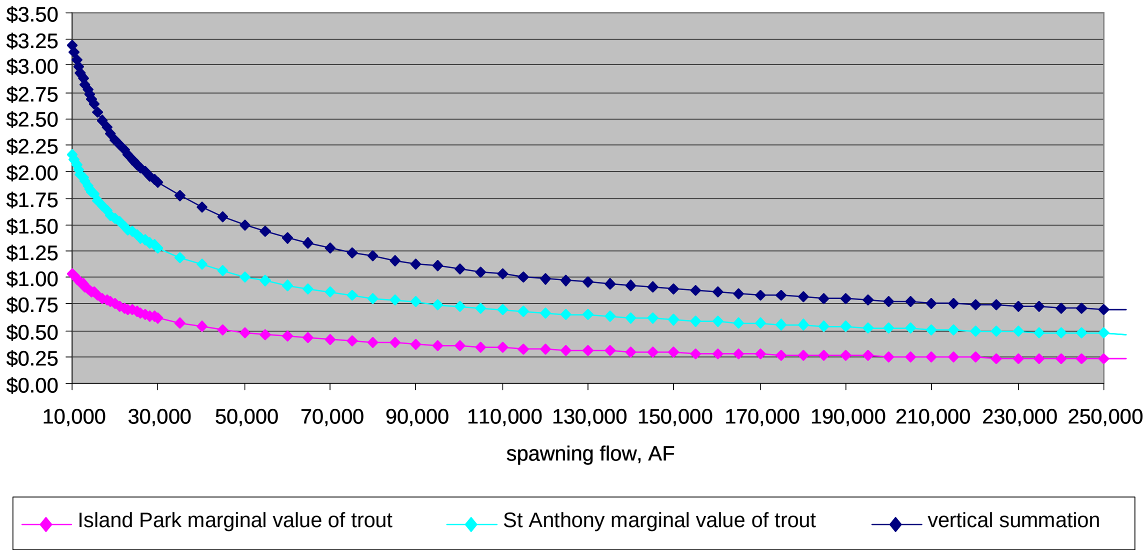


Figure 19: Vertical summation of Island Park and St Anthony reach demand-prices for instream flow.

Henrys Fork PE Model Nodes and Arcs

Supply nodes in the Henrys Fork PE model node-arc network (figure 20) consist of natural flows, storage water and return flows from irrigation. A further seasonal breakdown of supply nodes depends on whether supplies are available during the irrigation season or the non-irrigation season.

Demand nodes in the network include irrigators in the FMID, groundwater irrigators in the HF using aquifer recharge, irrigators in the lower basin, and HF instream flows for fisheries and other river system eco-services in the two reaches .

Transportation (conveyance) costs associated with arcs are the costs of canal seepage losses and return flows and the added charges for storage water delivered to irrigators outside the HF basin.

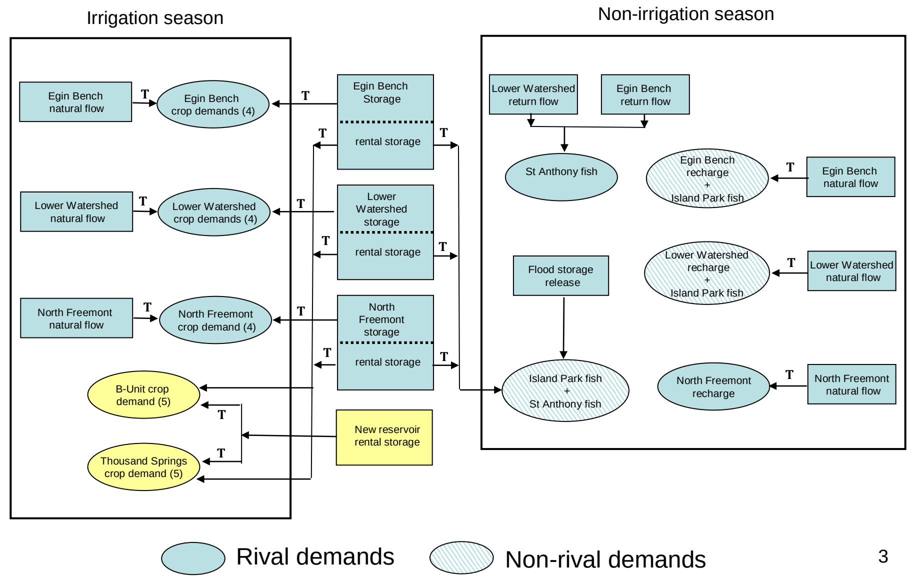


Figure 20: Henrys Fork GAMS partial equilibrium model nodes and arcs (T denotes added transportation cost).

Henrys Fork Hydro-Economic Model Applications

HF hydro-economic modeling consists of two separate applications. The first evaluates rival demands and benefits for irrigation, aquifer recharge and instream flows under the conditions of two proposed FMID water management alternatives; canal automation and new reservoir storage. The second hydro-economic modeling application evaluates the relative basin-wide net benefits associated with rival and non-rival management of HF reservoir water supplies for irrigation and river system eco-services.

1. Two FMID Water Management Alternatives

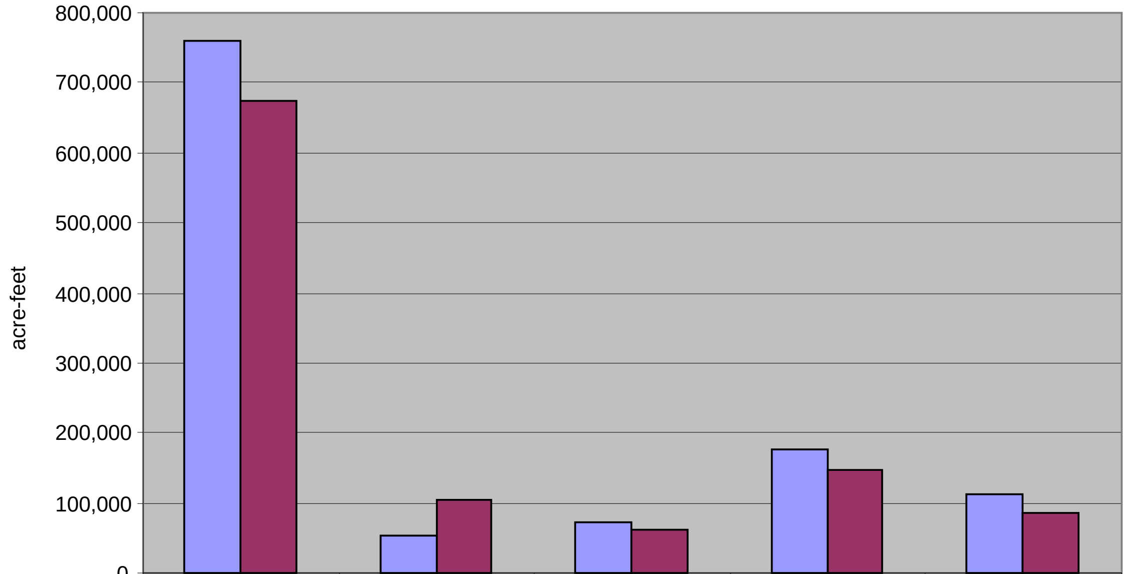
Three PE model scenarios are developed to evaluate the proposed management alternatives. The first is a calibrated HF baseline scenario with two sets of supply constraints representing average year and dry year conditions. The second is a canal automation scenario for average and dry years wherein canal seepage losses are reduced from the baseline by one third and drain returns are reduced from the baseline by one half. The third is a new storage scenario for average and dry years, wherein new storage is added with and without out-basin water transfers. Basin-wide net benefits (consumer surpluses) of each management scenario are presented relative to those of the baseline scenario.

Baseline Scenario

The baseline equilibration of HF supply and demand is subject to existing water rights and is constrained either by 30 year average water availability (1978-2008) or by the average water availability during three dry years (2003-2005). Baseline scenario water allocations for irrigation, aquifer recharge, and instream flow are calibrated using historical records of diversions and river gaging during average and dry years.

In an average year, baseline HF model natural flow and storage water supply totals about 1.1 million AF. Irrigation season diversions by FMID account for about 74 percent of total annual supply. Aquifer recharge deliveries during the non-irrigation season account for another 6.6%. Instream flows through the Island Park and St Anthony reaches during Dec, Jan and Feb are dependent upon FMID drain returns and HF operational releases made to maintain adequate storage space for projected spring runoff. About 8.4 percent of total annual supply flows through the Island Park and St Anthony reaches during the non-irrigation season. A little more than 11% of the initial HF water supply is carried over in storage to the next year (figure 21).

In a dry year, baseline HF water supply is reduced about 9 percent to about 1.0 million AF. Natural flow and storage diversion by FMID increases to about 78 percent of available supply. Deliveries of aquifer recharge decline to about 6 percent and instream flows through the Island Park and St Anthony reaches are down to about 7.4 percent. Carryover in storage is reduced to about 8.6 percent of the initial supply (figure 21).

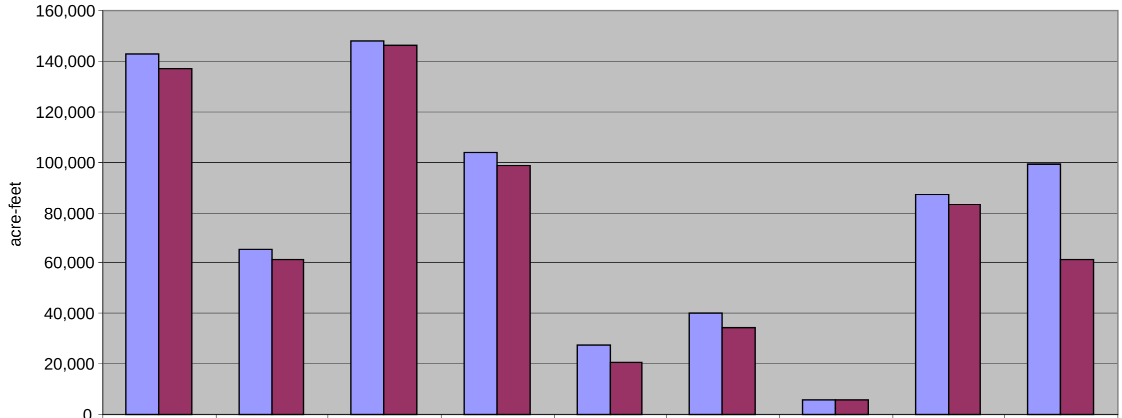


	FMID irrigation from natural flow	FMID irrigation from storage	FMID aquifer recharge	Fisheries flows	Henrys Fork storage carryover
average year	760,140	54,249	72,994	177,326	113,668
dry year	675,250	105,167	61,275	147,530	86,060

Figure 21: Average year and dry year HF water deliveries.

Equilibrated baseline results are broken down further in figure 22. Irrigation supply and demand is split among the four major FMID crops. Fisheries flows are split between the two HF reaches[4], and diversions for aquifer recharge allocated to the three HF sub-basins.

[4] In an average year, HF tributaries (Warm River, Conant Creek, Teton River, Falls River, and Moody Creek) contribute about 156,000 AF to Dec- Feb flows in the St Anthony reach, in dry years these flows drop to about 87,000 AF. (Only the changes in the HF contribution to Island Park and St Anthony spawning flows are presented in PE model results.)



	FMID barley irrigation	FMID wheat irrigation	FMID potatoes irrigation	FMID alfalfa irrigation	Egin Bench aquifer recharge	L. Watershed aquifer recharge	North Freemont aquifer recharge	St Anthony fisheries	Island Park fisheries
average year	142,721	65,459	147,995	103,816	27,254	39,870	5,871	86,893	99,359
dry year	137,001	61,162	145,962	98,673	20,842	34,562	5,871	83,201	61,275

Figure 22: Average and dry year water deliveries by FMID crop, river reach and HF sub-basin.

Consumer surplus, which is the summed difference between willingness to pay for water and the equilibrium water price is the measure of net benefits used in PE modeling. Consumer surplus calculation is subject to binding constraints on water supply (figure 4).[5] For fisheries, the constraint on supply of instream flow depends on required minimum flows[6], HF tributary flows, irrigation returns and reservoir operational releases. While operational releases are common in average water years they are mostly absent in dry years.

During average years FMID net benefit from water use (consumer surplus) is just over $3.8 million (figure 23). During dry years it declines to about $3.65 million. The net benefit from recreational fishing is much smaller, about $15,000 for the Island Park reach and $58,000 for the St Anthony reach during average years. During dry years, the net benefit from recreational fishing in the Island Park reach drops to just over $6,000, and net benefit from the St Anthony reach drops to $51,000.

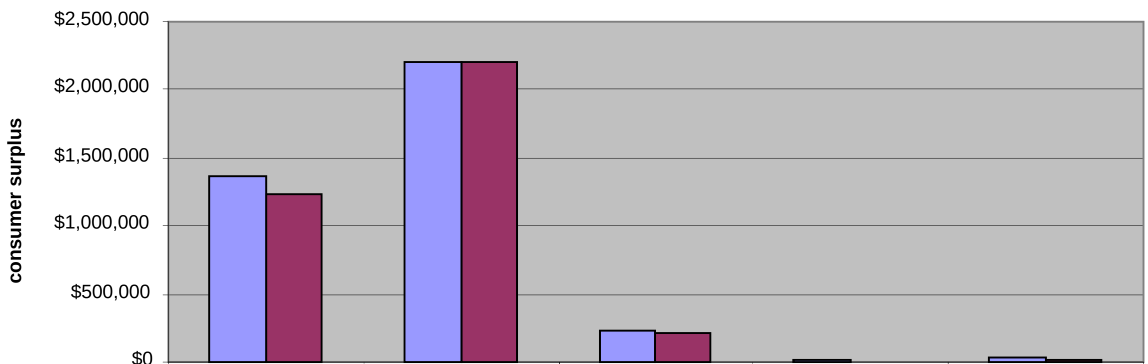
PE model results show that in average water years, constraints on non-irrigation season flow for fisheries in the St Anthony reach are binding, and the users of St. Anthony reach public goods would be willing to pay, on average, $0.73 per AF for

[5] Constraint cost is the difference between the equilibrium supply price and the constrained supply (or shadow) price.

[6] Minimum winter time flow from Island Park reservoir during December January and February is generally about 50 cfs

additional flow. Constraints on flow for fisheries in the Island Park reach are also binding. In average water years users of the Island Park reach public goods would be willing to pay about $1.74 per AF for additional flows. Recall that the PE model supply price for instream flows which are rival with irrigation was set at $3.00 per AF.

Naturally, constraints on fisheries flows are also binding in dry years. St Anthony instream users would be willing to pay slightly more, $0.75 per AF, for additional flow in dry years, and Island Park users would be willing to pay $2.36 per AF for additional flow in dry years (still below the $3.00 per AF that FMID irrigators pay for HF storage water).



	Egin Bench canal irrigation	Lower Watershed canal irrigation	North Freemont canal irrigation	Island Park fisheries	St Anthony fisheries
average year	$1,371,723	$2,202,993	$228,632	$14,896	$25,124
dry year	$1,233,552	$2,202,993	$213,494	$5,701	$23,934

Figure 23: Baseline average year and dry year net benefits (consumer surpluses).

Canal Automation and New Reservoir Storage Scenarios

Canal automation and new reservoir storage represent FMID demand management and supply management alternatives. Demand management alternatives aim to reduce shortages by curbing demand, supply management alternatives aim to accomplish the same by increasing supply.

Canal automation and new reservoir storage scenarios which permit out-basin transfers allow them from either existing or new HF reservoir storage. Groundwater irrigators in the B-Unit (of A&B Irrigation District) and in the Thousand Springs area (figure 24) are then included as supply and demand nodes in the PE model (figure 20).

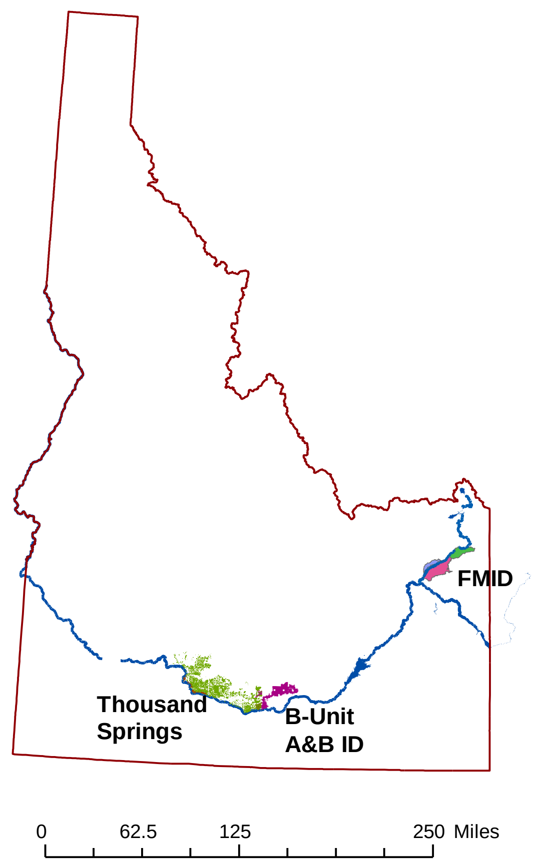
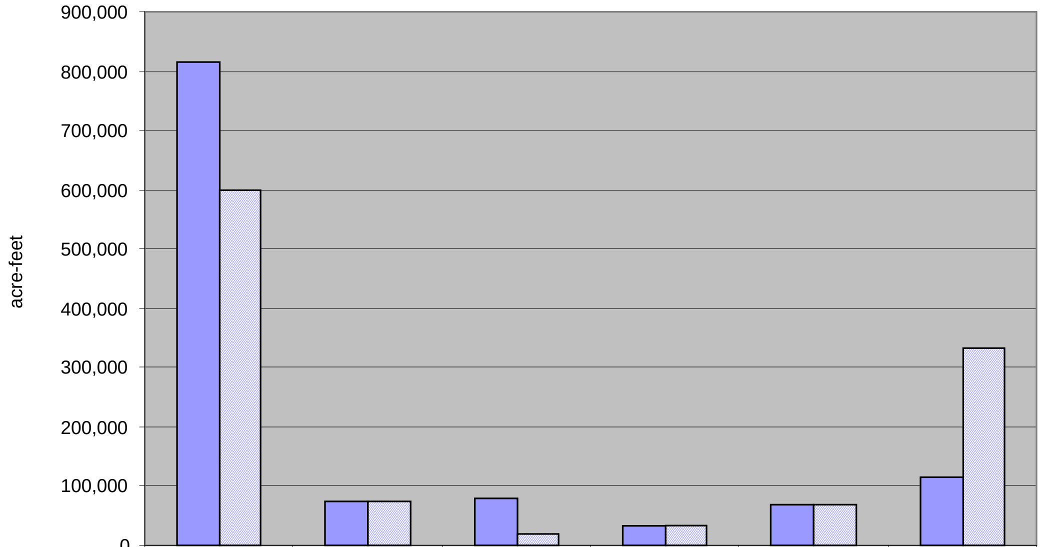


Figure 24: FMID, A&B Irrigation District, and junior groundwater pumpers in the vicinity of Thousand Springs along the Snake River.

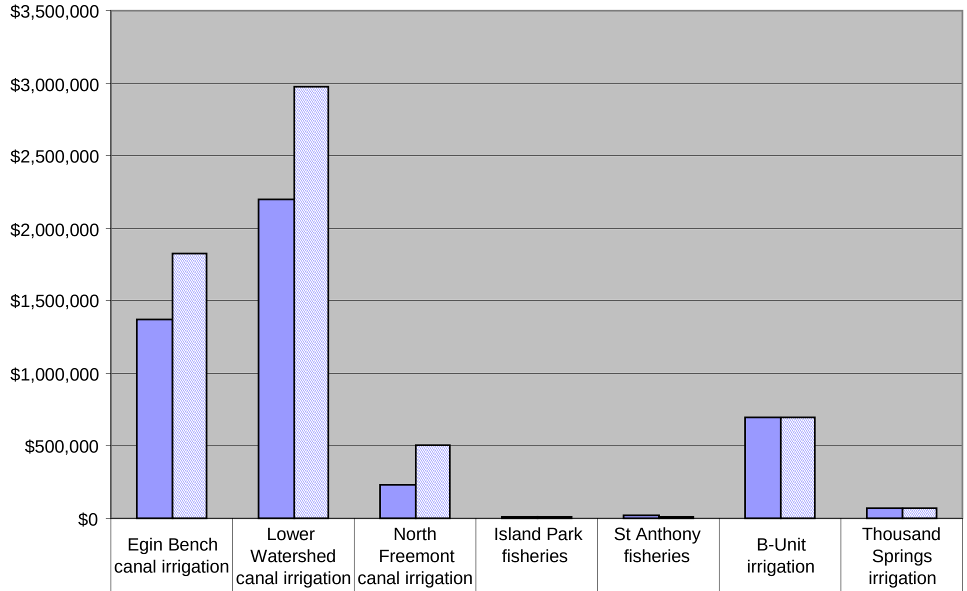
The introduction of new canal automation reduces FMID canal seepage losses and drain returns and thereby the need for storage during the irrigation season. Carryover storage during average water years is increased as a result. Baseline FMID water deliveries from natural flow are unaffected. As a consequence of reduced drain returns however, the supply of (non-rival) HF instream flows for fisheries is cutback by more than 70 percent (figure 25).



	FMID total irrigation diversion	FMID aquifer recharge	Fisheries flow from FMID drain return	Fisheries flow from operational releases	Fisheries flow from aquifer recharge	Henrys Fork storage carryover
Base case average year	814,389	72,994	77,968	32,235	67,123	113,668
Automation average year	599,753	72,994	19,330	32,235	67,123	328,804

Figure 25: Average year water deliveries, baseline with automation (no out basin transfers).

By reducing canal seepage losses and drain returns, canal automation reduces FMID demand for reservoir storage thereby increasing FMID irrigation consumer surpluses (figure 26). FMID consumer surplus increases because water is being used more efficiently. The St Anthony reach instream fisheries consumer surplus decreases because drain returns to this reach are reduced. Fisheries consumer surplus in the Island Park reach is unaffected by automation because this reach does not rely on drain returns for supply.

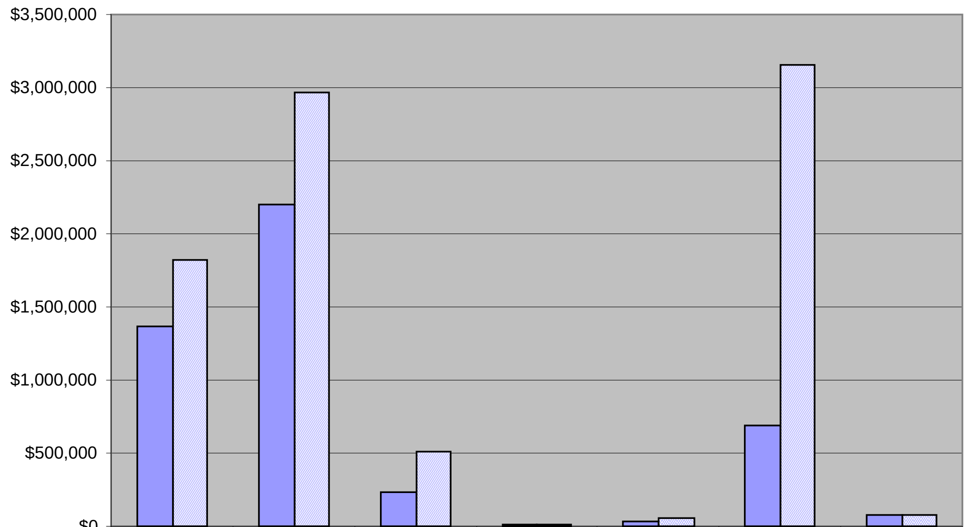


	Egin Bench canal irrigation	Lower Watershed canal irrigation	North Freemont canal irrigation	Island Park fisheries	St Anthony fisheries	B-Unit irrigation	Thousand Springs irrigation
Base case average year	$1,371,723	$2,202,993	$228,632	$14,896	$25,124	$693,223	$72,432
Automation & rental average year	$1,825,921	$2,971,382	$507,674	$14,896	$6,225	$693,223	$72,432

Figure 26: Average water year consumer surpluses (net benefit) baseline with automation (without out basin transfers).

Because of the lower cost relative to B-unit groundwater, B-unit will choose to irrigate with existing HF storage water if it is available, resulting in a substantial increase in the B-unit consumer surplus. Canal automation in combination with HF out basin water transfers increases B-unit consumer surplus more than three fold but has no effect on the consumer surplus of Thousand Springs irrigators (figure 27). The difference between B-Unit and Thousand Springs demand price elasticities accounts for this. B-unit groundwater pumpers grow higher valued sugar beet and potato crops than groundwater irrigators in the Thousand Springs area; consequently their willingness-to-pay for HF storage is greater, leaving Thousand Springs irrigators out of the market.

Instream flows for fisheries during the non-irrigation season are unaffected by out-basin transfers which are assumed to occur only during the irrigation season. Out-basin transfers do however reduce HF carryover storage.

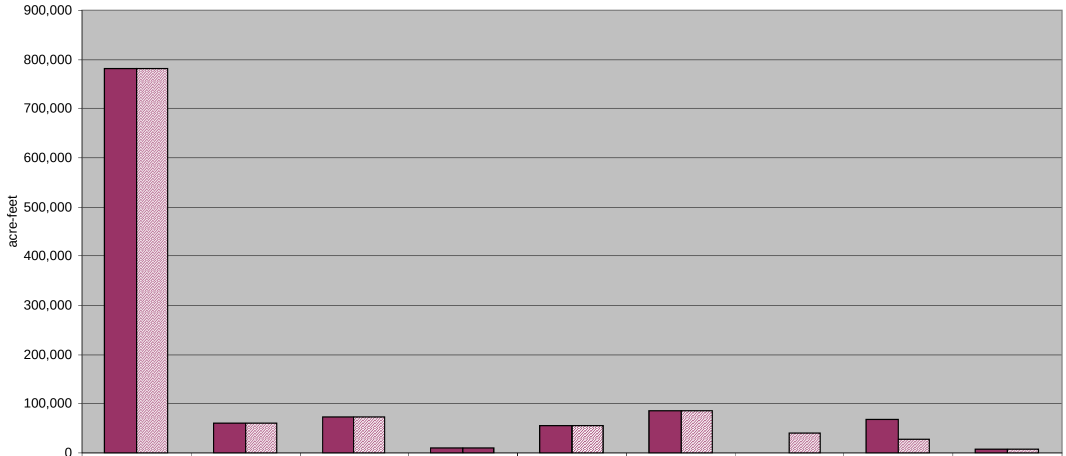


	Egin Bench canal irrigation	Lower Watershed canal irrigation	North Freemont canal irrigation	Island Park fisheries	St Anthony fisheries	B-Unit irrigation	Thousand Springs irrigation
Base case	$1,371,723	$2,202,993	$228,632	$14,896	$29,762	$693,223	$72,432
Automation & rental average year	$1,825,921	$2,971,382	$507,674	$14,896	$40,975	$3,156,735	$72,432

Figure 27: Average water year consumer surpluses (net benefit) baseline with automation (with out basin transfers).

Although several HF reservoir sites have been proposed by Reclamation, for modeling purposes the supply of new HF storage is assumed to be located at the proposed Badger Creek reservoir site. The construction cost for a reservoir at this site with 47,000 AF capacity is estimated to be $77,130,000 (Reclamation, 2013). In an average water year the supply constraint for this reservoir is expected to be 39,552 AF. Assuming construction costs are amortized over 50 years, the supply cost to FMID irrigators would then be approximately $39.00 per AF.

FMID demand for reservoir storage increases during dry years when the current storage constraint is binding, nevertheless because of its higher supply price, there is still no HF demand for new storage water (figure 28). Out-basin transfers to B-Unit and Thousand Springs groundwater irrigators during dry years are available exclusively from new storage. However the increased supply price reduces out-basin delivery relative to average water years. In dry years the B-unit irrigation supply is a combination of groundwater and new HF storage. The Thousand Springs irrigation supply is still entirely groundwater however.



	FMID total irrigation diversion	FMID aquifer recharge	Fisheries flow from FMID drain return	Fisheries flow from operational releases	Fisheries flow from aquifer recharge	Henrys Fork storage carryover	B-Unit and 1000 Springs rental	B-Unit groundwater pumped	Thousand Springs groundwater
Base case dry year	780,417	61,275	74,276	8,925	55,404	86,060	0	67317.16	7994.15
New Storage dry year	780,417	61,275	74,363	8,925	55,404	86,060	39552	27765.16	7994.15

Figure 28: Dry water year water deliveries, baseline and with new storage (with out basin transfers).

2. Rival and Non-Rival Management of HF Water Supplies

The second hydro-economic modeling application represents rival and non-rival demands for instream flow public goods using a PE model comprised of just four nodes; a reservoir supply node, an irrigation demand node, and two spatially distributed demands nodes for instream flow (figure 35).

The application consists of three scenarios. The first scenario calculates instream flow allocations and benefits assuming that the two instream flow demands and the irrigation demand are rival. The second scenario assumes the two instream flows are non-rival in meeting fisheries demands but rival with irrigation demand. The third scenario assumes that the two instream flow demands are also non-rival with irrigation demands during winter months (specifically, with demands for reservoir operational releases and aquifer recharge). It is assumed that these demands are met after flows pass through both fisheries reaches, which means that operational releases are also out-basin transfers, and that aquifer recharge occurs only via canals at or below the Egin Bench.

In the first scenario, net benefits are determined by horizontal summation of all instream flow and irrigation demand quantities. In the second scenario, instream flow net benefits are determined by vertical summation of fisheries flow demand prices in the two reaches, and irrigation net benefits are determined by horizontal summation of irrigation demand quantities. And in the third scenario, non-irrigation season benefits are determined by vertical summation of fisheries flow demand prices and non-irrigation season demand prices for aquifer recharge and out basin releases. Irrigation season net benefits are determined by horizontal summation of irrigation season demand quantities.

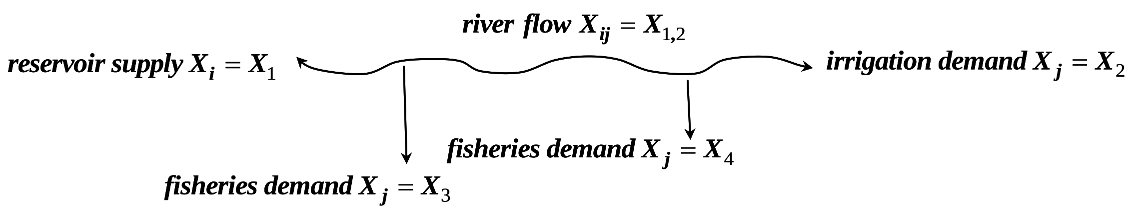


Figure 29: Schematic of four node PE model with rival and non-rival water demands.

The GAMS LIST file for the three scenarios is displayed in Table 1. Results from the first PE model scenario in which it is assumed that the timing requirements to meet HF instream flow and irrigation demands are such that instream flows in the Island Park and St. Anthony reaches are compelled to be rival with each other and with irrigation demands, generates the lowest total benefit for fisheries ($5,539). The second PE model scenario, in which the timing requirements of instream flow are such that the two HF reaches are non-rival with each other but rival with all irrigation demands generates a total benefit for fisheries that is greater then the first by a factor of four ($21,104). Finally, in the third PE model scenario, the timing requirements are further relaxed so that instream flow demands are assumed non-rival with all irrigation demands that occur during the non-irrigation season. Total fisheries benefit generated is nearly two orders of magnitude greater then the first scenario ($584,178).

Of the three scenarios, the third comes the closest to approximating the actual management practices of instream flows for fisheries in the HF (HFAG/JPC, 2005), (FMID, 2013). The difference between scenario 3 and scenario 2 benefits ($584,178-$21,104) comes closest then to representing the value of HF fisheries and other eco-services that could be realized from mostly non-rival management of HF supplies for both irrigation and instream flows.

Table 1: PE model net benefits and equilibrium prices ($/AF) and quantities (AF) for rival and non-rival demand scenarios.

Variable		Scenarios		
Description	Equalities	Rival instream flow & irrigation demands	Part-rival instream flow & irrigation demands	Non-rival instream flow & irrigation demands[1]
Benefit (consumer surplus) node 2		$495,204	$495,204	$495,204
Benefit (consumer surplus) nodes 3 & 4		$5,539	$21,104	$584,178
Demand price node 2 $\bar{\rho}_2$	$\bar{\rho}_2 = \bar{\rho}^2$	$3.46	$3.46	$4.16
Demand price node 3 $\bar{\rho}_3$	$\bar{\rho}_3 = \bar{\rho}^3$	$3.46	$3.46	$4.16
Demand price node 4 $\bar{\rho}_4$	$\bar{\rho}_4 = \bar{\rho}^4$	$3.46	$3.46	$4.16
Total benefit (total surplus)		$500,743	$516,308	$1,079,382
Demand quantity node 2 $\bar{\boldsymbol{q}}_2$	$\bar{\boldsymbol{q}}_2 = \bar{\boldsymbol{q}}^2 = \bar{\boldsymbol{X}}_{12}$	60,338	60,338	60,338
Demand quantity node 3 $\bar{\boldsymbol{q}}_3$	$\bar{\boldsymbol{q}}_3 = \bar{\boldsymbol{q}}^3 = \bar{\boldsymbol{X}}_{`3}$	14,055	14,055	44,257
Demand quantity node 4 $\bar{\boldsymbol{q}}_4$	$\bar{\boldsymbol{q}}_4 = \bar{\boldsymbol{q}}^4 = \bar{\boldsymbol{X}}_{14}$	1,588	7,822	70,960

[1] Irrigation demands that are non-rival with instream flow demands are winter time storage releases made as part of reservoir operations or for aquifer recharge

Appendix A contains the annotated GAMS code for the Henrys Fork PE model with rival and non-rival instream flow demands, and appendix B contains the GAMS data file for this application. The changes necessary for each of the three scenarios are described in the code.

Additional Discussion

Under the prior appropriation doctrine, river flows held in reservoir storage and released only upon irrigation demand are deemed private goods, both excludable and rival. Since ecological and recreational uses of river flows are both non excludable and non-rival, instream flows which sustain river ecology and recreational usage are deemed public goods. Competitive markets are seldom the sole mechanism used to allocate water in river systems where public goods are involved (Harou, 2009).

Uncertainty associated with the demand-prices for eco-services means that it is not always possible to specify a single Pareto optimal allocation of water for both irrigation and instream flow public goods. A Pareto frontier for allocation of instream flow public goods has been advocated (Griffin, 2005) as a way of maximizing the total benefit from private and public goods subject to a public goods pricing policy that incorporates an array of exogenous demand–price functions representing the full range of revealed and stated preferences for river system eco-services.

Depending on irrigation and canal operational efficiency, canal seepage and drain discharge account for a significant portion of total canal diversions that is not consumptively used, and ultimately return to the river to become public goods. The complexity of hydrologic and economic interactions between rival and non-rival water demands can be a challenge for management of instream public goods, especially when new reservoir storage, new groundwater pumping or new irrigation water conservation measures would alter existing hydrologic dependencies and economic externalities.

Hydro economic modeling to evaluate the relative benefits of rival and non-rival approaches to managing water demands is a first step in developing strategies which would maximize basin-wide benefits from both private and public goods.

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Appendix A - 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)/A3(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 B - 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
  /
;
```