Hydro-Economic Modeling of Boise Basin Water Management Responses to Climate Change

Robert Schmidt, Leroy Stodick, Garth Taylor & Bryce Contor

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Abstract

This report presents a hydro-economic modeling methodology for conducting benefit-cost analysis of water management responses to climate change. Three hydro-economic modeling scenarios are developed. The first estimates the affects of projected climate change water shortages on the basin-wide economic benefit in the Lower Boise River Basin. The next two are representative of typical demand management and supply management responses to climate change; respectively, introduction of new canal lining conservation measures or new reservoir storage. Boise Project groundwater and drain return response zones in the lower basin are identified and marginal demand-price and supply-cost functions are developed for Project canal irrigators and non-Project groundwater and drain water irrigators using river/reservoir and groundwater hydrologic model response data. Flood flow probability and damage functions are used to develop marginal utility functions for new flood control storage. Irrigation and flood control demands are not requirements. All demand functions are developed assuming demand-price elasticity. The base-case equilibrium price-quantity positions and consumer surpluses of Project and non-Project irrigators are calculated using a partial equilibrium (PE) economic model in which all factors of production except for water are held fixed. Subsequent PE model scenarios impose varying climate constraints on irrigation water supplies, along with a progression of new Boise Project canal lining conservation measures, and/or the addition of new Boise River reservoir storage. Rival demand is assumed to exist for new storage, which can be released prior to April 1 to meet demand for flood control, or after April 1 as natural flow to meet demand for irrigation. Preliminary Reclamation and Corp of Engineers construction cost estimates for new Boise Project canal lining and new reservoir storage are used calculate benefit-cost ratios, in which net basin-wide benefits of alternative responses to climate change are derived from hydro-economic modeling.

Introduction

River-reservoir operations models and groundwater hydrologic models have long been used by Reclamation water managers as tools for decision making. However the integration of hydrologic and economic models (hydro-economic models) in order to calculate the basin-wide economic benefit of various water management alternatives is relatively new to Reclamation.

Many scientists engaged in water management and water policy making believe that in the future the variation of water values in time and space will increasingly motivate efforts to address water scarcity. Hydro-economic models are capable of representing spatially distributed water resource systems, infrastructure, management options and economic values in an integrated manner. Using these modeling tools, water allocations and management are either driven by the economic value of water or economically evaluated to provide policy insights and reveal opportunities for better management. A central concept is that water demands are not fixed requirements but rather functions where quantities of water use at different times have varying total and marginal economic values (Harou et. al., 2009).

The Lower Boise River basin and Reclamation’s Boise Project in particular, are well suited for the introduction of hydro-economic modeling. Recent development of a Boise river/reservoir RiverWare (CADSWES, 2013) operation and planning model (Reclamation, 2011b), a well-calibrated MODFLOW (USGS, 2013) groundwater model (Reclamation, 2012), and a lower basin distributed parameter water budget database (USBR and IDWR, 2006), are essential components for hydro-economic model development.

Changes in temperature and precipitation in the Boise River Basin due to climate change will have an impact on the Boise Project supply and demand for irrigation water and on Boise River-Reservoir flood control operations. Concerns for the effects of climate change on water supply and demand have put pressure on Reclamation to increase reservoir storage. However conservation, regulation, and market-based water management are also seen as viable strategies for responding to these changes. In this application however hydro-economic modeling is used to calculate the net benefits and costs of two of the most likely management responses to climate change; introduction of new irrigation water conservation measures, and construction of new reservoir storage.

While the Riverware and MODFLOW models used in this application are necessarily specific to the Boise River system and Reclamation’s Boise Project, the partial equilibrium economic model that has been developed is not. To facilitate its application in other basins, this report focuses on developing partial equilibrium model inputs and on interpreting partial equilibrium model results, albeit in the context of Boise river/reservoir operations and lower basin conjunctive surface and groundwater use.

Partial Equilibrium (PE) Economic Modeling

A partial equilibrium (PE) model is a type of economic model that examines the conditions of market equilibrium that exist when dealing with a single economic commodity. Applications of partial equilibrium modeling are generally associated with problems of utility maximization (Takayama and Judge, 1971). In hydro-economic modeling, the PE model maximizes the utility (or benefit) of a single factor in the production functions of multiple water users. All other factors of production besides water are assumed to be fixed.

The measure of net economic benefit calculated by the PE model is consumer surplus. In the context of hydro-economic modeling, consumer surplus is the difference between what water demanders are willing to pay for water and what they actually have to pay (Griffin, 2006). The current PE model calculates an equilibrium position for all water suppliers and demanders which maximize the basin-wide benefit (i.e. sum of consumer surpluses) of water use. Depending on the scenario, basin-wide benefit is limited to Boise Project and Non-Project irrigation or to Project irrigation and flood control[1]. Equilibrium quantities supplied and demanded, and

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[1] Flood control demand for water is in the form of water released from storage prior to the start of the irrigation season in order to create flood control storage space in reservoirs.

equilibrium prices differ among water supply and demand entities because of differences in supply-cost and demand-price functions of irrigators and flood control demanders.

A software package that is often used for PE modeling problems is GAMS (General Algebraic Modeling System) (Ferris and Munson, 1999). A GAMS-based PE algorithm developed for Boise Basin hydro-economic modeling (Taylor et al, 2013) solves the utility maximization problem using mixed complementary programming and the method of Lagrange_multipliers. With the Lagrange method, certain equality constraints in the maximization problem are replaced by inequality constraints containing multipliers. Collectively, these are referred to as Kuhn-Tucker or complementary slackness conditions (Karush, 1939), (Kuhn, Tucker, 1951). The GAMS PE algorithm developed by Leroy Stodick for hydro-economic modeling is briefly described in Appendix A.

Supply Management and Demand Management Responses to Climate Change

Traditional approaches to water management can be classified as either supply management or demand management. Supply management approaches focus on increasing supply to meet new demands, such as by building new reservoirs. Demand management approaches concentrate on limiting demand through pricing, conservation or by regulation (Brekke et. al., 2009).

The two approaches incorporate different assumptions about price-elasticity. The traditional Reclamation approach to evaluation of a water supply project is from the supply perspective, which assumes that demand is fixed, i.e. completely inelastic and therefore not responsive to price. Water demand is a requirement that must be met by increasing the supply of water. In effect, there is a fixed amount of water demanded and that water has infinite value. The price-quantity relationship expressed in the water users marginal demand function therefore appears as a vertical line (Figure 1a).

Economic evaluation from the demand perspective assumes the exact opposite; supply is fixed (i.e. quantity is limited) and water demand is assumed to be price responsive. Water pricing can then be used to reduce the quantity of water demanded so as not to exceed the limited quantity available. From the demand management perspective, the price-quantity relationship expressed in the water users marginal demand function is a downward sloping line, reflecting the water users' decreasing willingness to pay for increasing quantities of water (Figure 1b). The demand management perspective underlies Reclamation's more recent focus on improving the operational efficiency of existing Projects by developing more efficient water delivery systems.

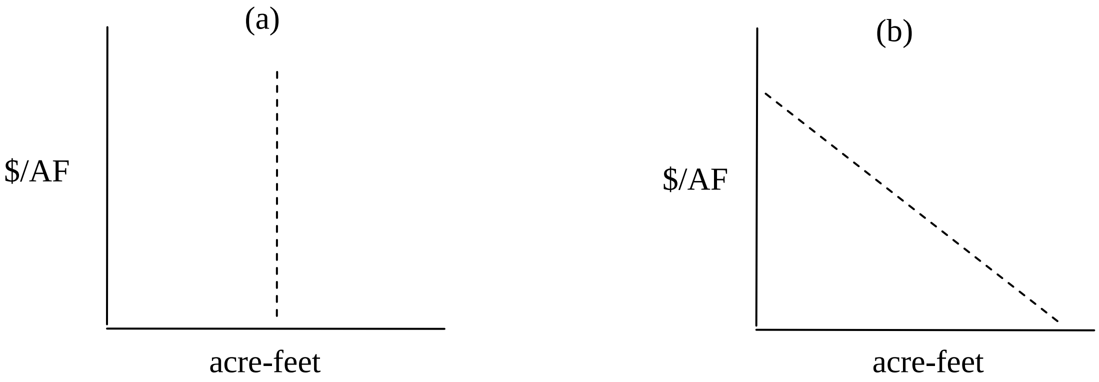

Figure 1 Inelastic (requirement) and elastic marginal water demand-price functions

Jointness of Production and Conjunctive-Use Externalities

Jointness-of-production occurs when the economic activity of one entity impacts the production possibilities of another, either positively or negatively. Jointness in the production functions of canal, drain and groundwater irrigators in the Lower Boise basin occurs as a consequence of canal seepage losses. Diversions that are made to meet demands of Project irrigators produce canal seepage which recharges the underlying aquifer, thereby reducing pumping costs for groundwater irrigators, and increasing drain return flows for drain water irrigators. An externality exists when there is no compensation for the benefit (or detriment) that results (Griffin, 2006).

From an economics perspective, the presence of externalities violates the underlying assumption of an ideal market thereby creating a market failure, with the result that quantities of water supplied to and demanded by irrigators are sub-optimal, and therefore do not maximize total economic benefit (Taylor et al, 2013). Nevertheless, benefit (sum of consumer surpluses) can still be calculated by a partial-equilibrium model incorporating conjunctive-use externalities. Benefit in this case is relative, in the sense that it is conditional upon the existence of the externalities[2].

Externalities that are the result of conjunctive use of surface and groundwater are referred to here as conjunctive-use externalities[3]. Since groundwater and drain water irrigators benefit from the canal seepage, canal seepage exists as an economic externality which is positive (beneficial) for

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[2] In this PE model application, the "maximized" consumer surplus calculated by PE model scenarios with externalities is presented relative to the consumer surplus of a base-case scenario, which may or may not include externalities.

[3] The inclusion of conjunctive-use externalities requires modifications to two of the five complementary slackness equations in the basic partial equilibrium model (see Appendix A).

groundwater pumpers and drain irrigators, but potentially negative (detrimental) for canal irrigators[4].

In view of the fact that new water conservation measures are widely advocated as a means of reducing the vulnerability of managed water systems to climate change, valuing conjunctive-use externalities is an essential part of determining whether the basin-wide benefits of new canal lining conservation measures outweigh those of the status quo condition involving conjunctive-use externalities[5].

This is accomplished in PE modeling by first recognizing that canal, groundwater and drain water irrigators all have a common water supply source, and that groundwater and drain water irrigators' supply depends in part at least on canal irrigators' water demand, i.e. jointness of production.

The Boise Project Arrowrock Division and Lower Boise Basin Water Budget

The Arrowrock Division of the Boise Project irrigates approximately 130,000 acres in the Lower Boise basin, south of the Boise River (Figure 2). The five Arrowrock subdivisions have natural flow rights and storage rights in three reservoirs (Arrowrock, Anderson Ranch and the Corps of Engineers' Lucky Peak) on the North Fork and Middle Fork of the Boise River, with combined storage capacity of just under one million acre-feet. The Division also includes a 9000 acreoff-stream reservoir (Lake Lowell). Major Arrowrock canals include the 73 mile New York canal, the 88 mile Mora Canal, the 81 mile High and Low Line Canals.

Arrowrock irrigation activity has greatly enhanced and enlarged the underlying Lower Boise basin aquifer system. Records of groundwater level rise are incomplete, but sufficient to indicate that most of the rise in groundwater levels and drain returns south of the Boise River occurred some 90 years ago, shortly after the Project was completed. Seepage from Arrowrock canals, laterals and off-stream reservoirs raised groundwater levels in one area of the basin by 140 feet (Nace et al, 1957) and in several others by between 36 and 134 feet (Stevens, 1962).

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[4] Conjunctive water management of surface and subsurface resources therefore implies the management of conjunctive-use externalities as well.

[5] An alternative demand management response to climate change that is potentially as effective as canal lining conservation (i.e. eliminating the externality) would be to internalize conjunctive-use externalities through pricing of seepage losses.

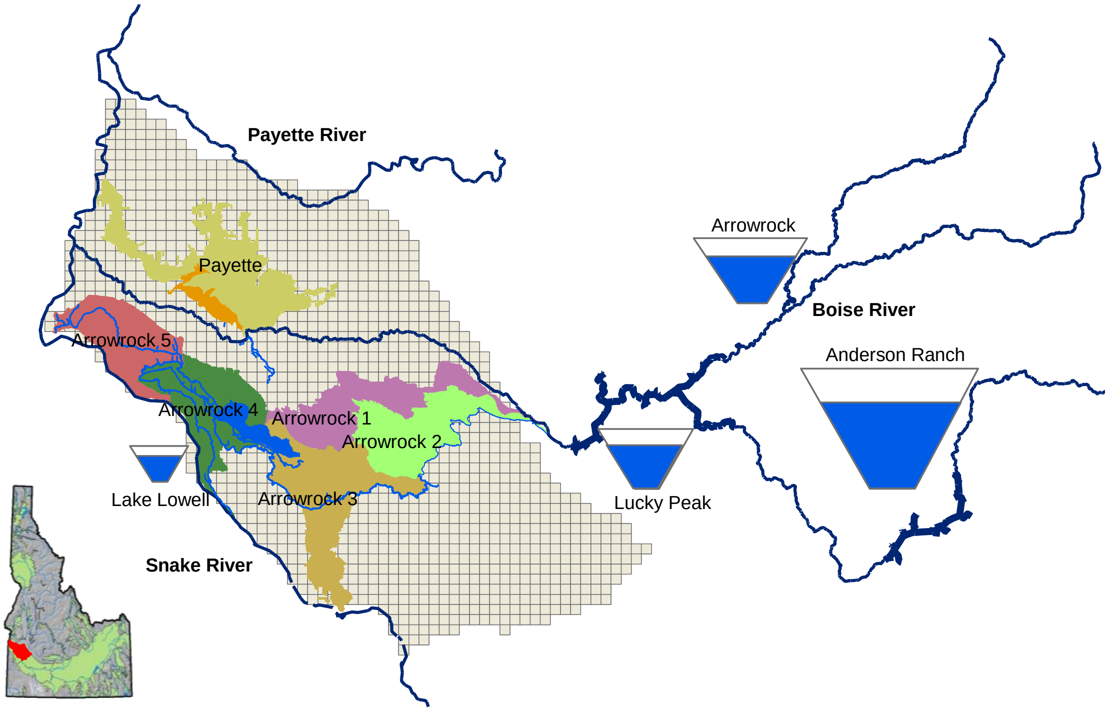

Figure 2 Boise Project lands and major canal and reservoir features overlying the Boise basin MODFLOW model grid**.**

The elevated groundwater level also resulted in year-round increased flow from dry creek beds and agricultural drains. The 42 mile long Notus Canal delivers drain return water from the Arrowrock Division across the Boise River to 7,000 acres in the Payette Division. Project drain water is also re-diverted by irrigators on non-Project lands south of the Boise River.

Estimates of Boise Project contribution to the groundwater budget vary, but the most recent data indicates that a little more than 60 percent (about 327,000 acre feet per year) of basin-wide canal seepage is from Arrowrock canals and laterals. In addition about 47 percent of Lower Boise Valley farm infiltration and 48 percent of drain discharge occurs on Arrowrock lands. Overall, Arrowrock canal and reservoir seepage accounts for about 32 percent of the total aquifer recharge in the Lower Boise River basin (USBR and IDWR, 2006). Figure 3 summarizes the components of shallow aquifer recharge and discharge on irrigated lands in the Lower Boise River basin, and on Boise Project lands in particular.

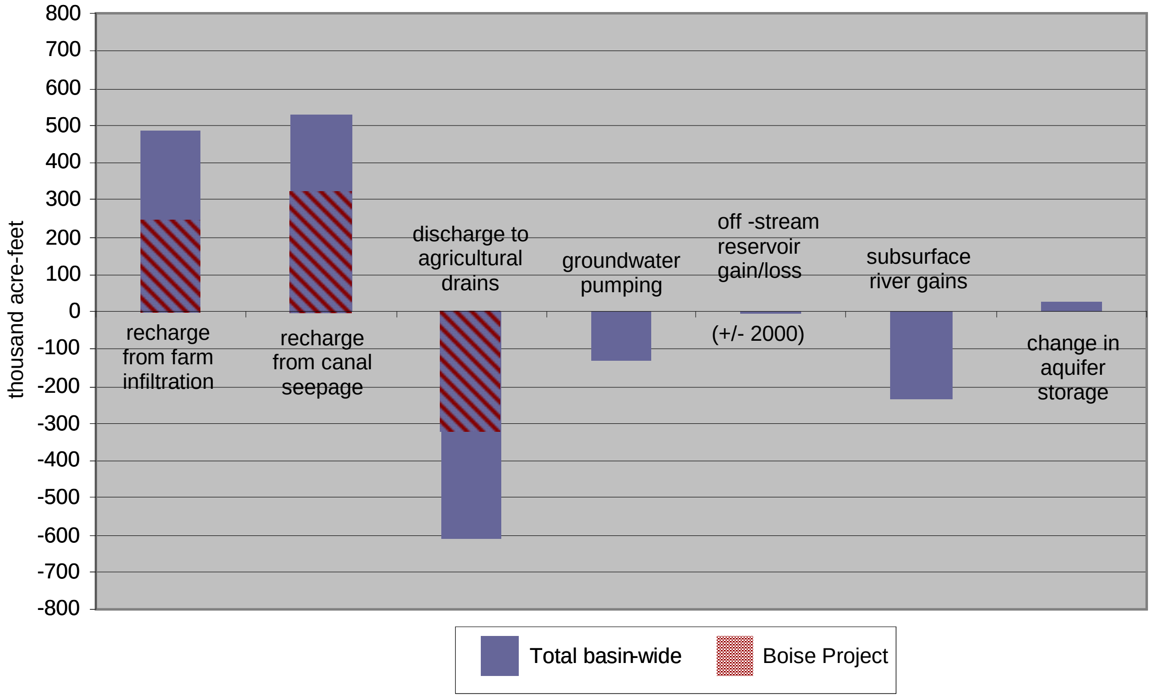

Figure 3 Lower Boise Valley groundwater recharge and discharge components (USBR and IDWR, 2008).

From the standpoint of Lower Boise basin irrigators, the hydrologic impact that the Arrowrock Division of the Boise Project has on groundwater and drain water availability in the Lower Boise basin is mostly positive. Arrowrock canal and reservoir seepage have resulted in a significant expansion of groundwater and drain water resources in the basin, greatly increasing the agricultural production possibilities of groundwater pumpers and drain water re-diverters. Notably however, groundwater pumpers and drain water diverters make no direct payments to canal diverters for the benefit they derive from canal seepage.

Boise Project Hydrologic Response Zones

Boise Project groundwater and drain return response zones are those areas in the Lower Boise basin where Arrowrock Division canal seepage has had a significant impact on shallow aquifer groundwater level and drain return flow. The response zones were identified using the Lower Boise River basin MODFLOW model after removing the component of aquifer recharge that is attributed to Boise Project canal seepage.

The groundwater response zone is defined as the area within the lower basin where Project canal seepage has caused a rise in groundwater levels of 50 feet or more (Figure 4). The contoured groundwater level change ranges from 50 to 110 feet. Almost all of the color shaded area is south of the Boise River, indicating that the historic rise in groundwater levels is the result of seepage losses from the Arrowrock Division of the Project.

The Idaho Dept. of Water Resources has granted well over 4000 groundwater rights in the lower basin, about half these water rights are for irrigation. In an average water year, primary right holders pump about 200,000 acre-feet to (sprinkler) irrigate approximately 103,000 acres. Figure 4 also shows the locations of these primary irrigation wells. Of the 636 primary wells in the basin, 441 are located within the contoured response zone. Clearly the advantageous pumping conditions created by Project canal and reservoir seepage have not gone unnoticed by groundwater irrigators,

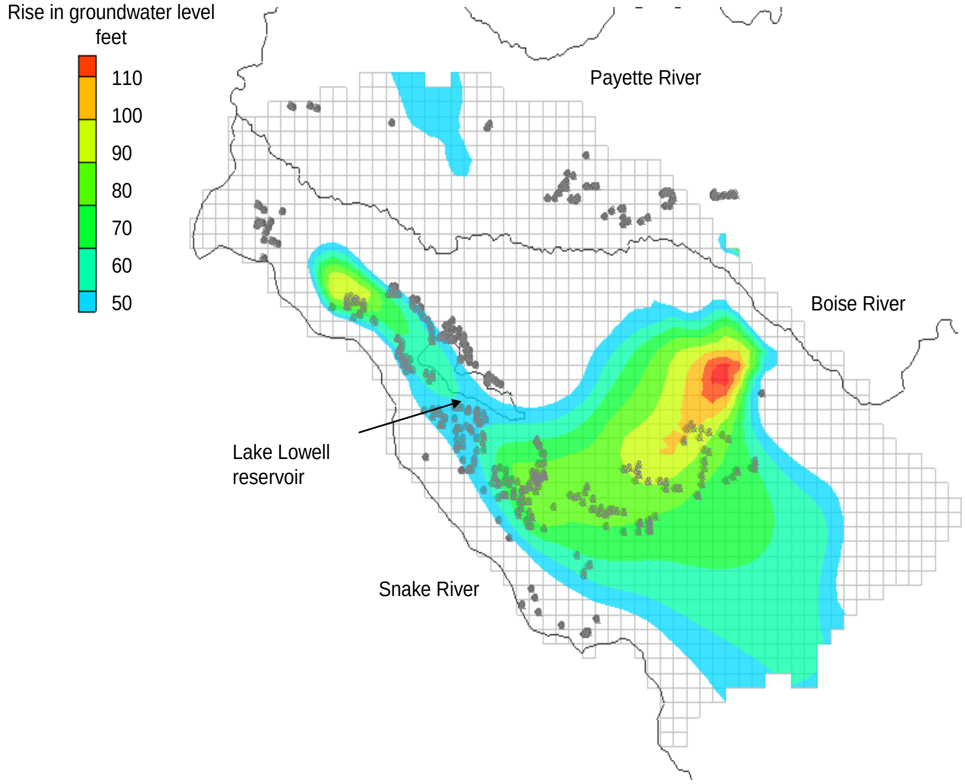

Figure 4 Rise in groundwater level due to Boise Project canal seepage

The drain water response zone is defined as the area within the lower basin where elimination of Project canal seepage results in an increase in drain discharge of 1000 acre-feet or more per square mile grid cell (Figure 5). Removing Project canal seepage from the hydrologic model reduces total drain discharge in the basin by about 271 thousand acre-feet. The contoured increase in drain discharge ranges from 1000 to 8000 acre-feet per grid cell.

Drain water irrigators re-divert about 322 thousand acre-feet of water during an average irrigation season. Assuming .01 cfs per acre, which is about average for furrow (siphon tube) irrigated crops in the Lower Boise Valley, about 88,000 acres in the Lower Boise Valley are being irrigated with drain water. Points of diversion for drain water right holders are also indicated on Figure 5. Nearly 40 percent of total drain water irrigated acreage is situated in this highly advantageous part of the basin for recapturing Arrowrock Division drain water.

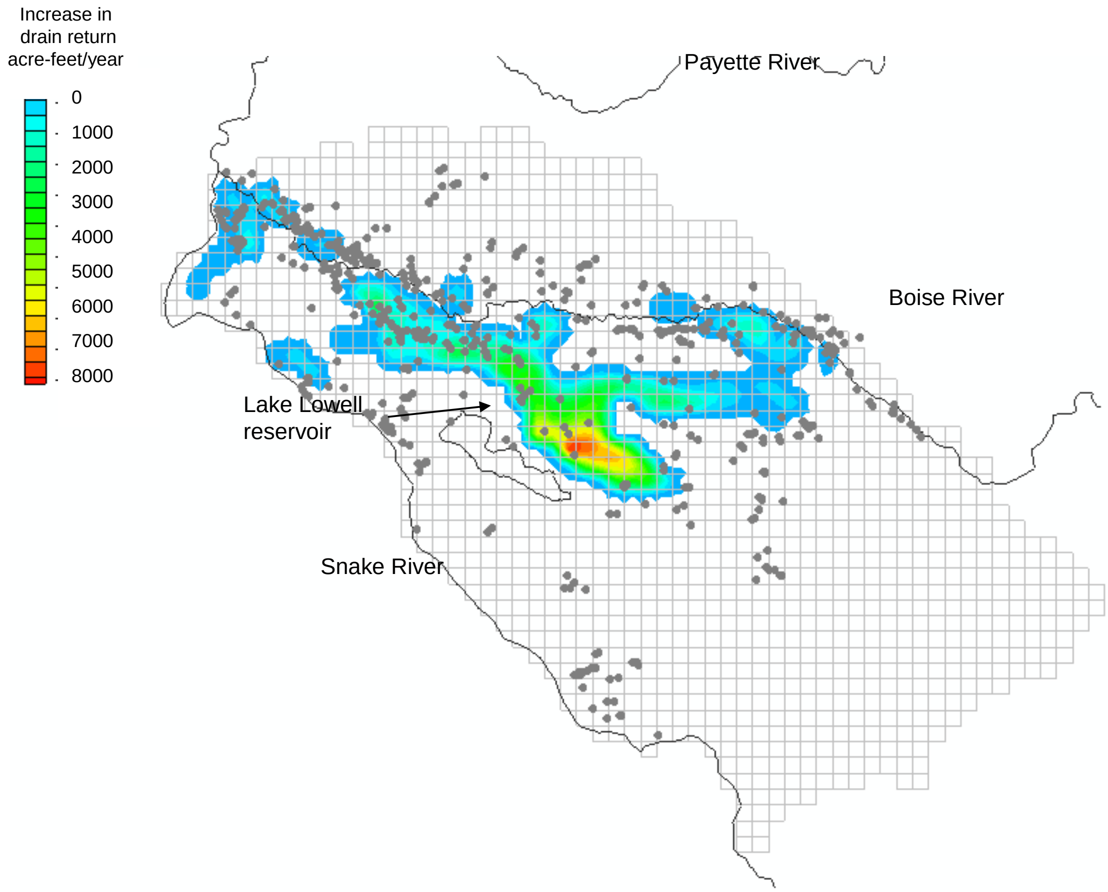

Figure 5 Increase in drain return flow due to Boise Project canal seepage.

Although the relative proportions vary considerably across the basin, water budget data indicates that on average about 65 percent of drain return is water that first infiltrates the shallow aquifer and then reemerges in a down-gradient drain, the remaining 35 percent is direct runoff from irrigated fields.

When it comes to the introduction of new Project-wide water conservation measures in the Boise basin, one of the main concerns is the impact of those measures on irrigators who historically have come to rely on the incidental aquifer recharge and drain return flow that originates from Project canal and reservoir seepage losses.

Irrigation Water Supply Cost and Demand Price Development

Hydrologic response functions generated by river/reservoir and groundwater hydrologic models are used here to develop many of the water supply-cost, transportation-cost and demand-price relationships that are required for PE modeling.

The Boise River/reservoir (RiverWare) operation and planning model is used to calculate Boise Project natural flow and storage water allocations as a result of operational responses to climate change. The Lower Boise basin (MODFLOW) groundwater model calculates the surface and subsurface hydrologic interactions that result from the same operational responses. These arise primarily as a consequence of the affect that water allocations to the Boise Project have on groundwater and drain water irrigators who rely on Project canal and reservoir seepage losses for their supply.

The spatial and temporal elements of river/reservoir and groundwater hydrologic responses are then linked to a partial equilibrium economic model via the exogenous marginal demand-price and supply-cost functions of lower basin water demanders and suppliers. Marginal demand-price functions are developed in different ways depending on the demand entity. For agricultural irrigation demand, crop production functions and crop acreage data are used to develop an irrigation water demand-price relationship (Contor, 2010). The method of point expansion (residual imputation) is used to generate a demand-price function for residential irrigation (Griffin 2006).

Canal Water Marginal Supply-Cost Functions

Marginal supply-cost functions describe the price-quantity relationship that exists per AF of Lower Boise River basin irrigation water, whether it is diverted from canals, agricultural drains or pumped from the aquifer. MODFLOW model projections of the basin-wide hydrologic responses to Arrowrock Division canal seepage are used to develop these interdependent functions.

For Boise Project irrigation districts, the supply cost of water is determined by applicable Reclamation operating and maintenance (O&M) charges and the Project repayment schedule. Reclamation's O&M charges for Project storage water are about $1.60/AF and the Project repayment is mostly completed. Most Boise Project irrigation districts charge their members based on their irrigated acreage, not on the actual quantity of water diverted by the district. For example, Arrowrock 1 averages 24,777 irrigated acres with average annual diversion of 248,209 AF. The assessment to members in 2008 was $52.25 per acre of irrigated land, so the supply-cost of district water to members was about $5.22/AF, for water at the Boise River point of diversion. Similarly, Arrowrock 2 charges members the equivalent of $4.17/AF, Arrowrock 3 the equivalent of $5.35/AF and Arrowrock 4 and 5 the equivalent of $8.80/AF for irrigation water at the river point of diversion.

Natural flow diversions are not subject to Reclamation's O&M charge, so the natural flow supply cost is on average about $1.60 less than the supply cost of storage water. The supply of irrigation water available to Project irrigators at the river point of diversion and at the above prices is also constrained by irrigation district rights for both natural flow and storage. Individual rights vary among the five Arrowrock divisions (Figure 6) .[6]

The supply cost of irrigation water at the canal headgate depends on the seepage losses that occur between the river point of diversion and the headgate. Seepage losses from some canals are

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[6] Although natural flow and storage rights exist separately for irrigation districts in the Boise Project, they are administered collectively by the Board of Control for Project lands as a whole.

greater than others because of their diversion capacity, length and elevation relative to the underlying watertable. Project canals at higher elevations (mainly Arrowrock 2, 3 and the part of 4 south of Lake Lowell) experience higher seepage losses than those at lower elevations (mainly Arrowrock 1, 5 and the part of 4 north of Lake Lowell) (see Figure 2).

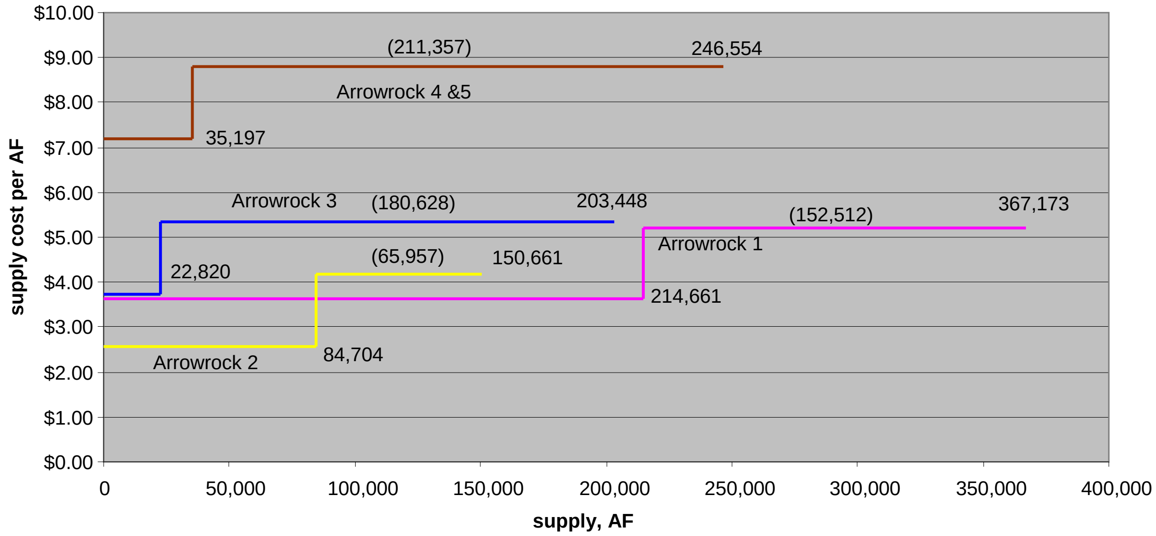

Figure 6 Boise Project canal diverter's supply cost for natural flow and storage water at point of river diversion.

Canal seepage losses are represented in the PE model as "transportation costs" associated with delivering canal water from the river point of diversion to the lateral head-gates of each Arrowrock subdivision. The marginal cost of canal water at the subdivision head-gates, includes the transportation costs as a fixed percentage of Boise River diversion and has the form, ***head-gate supply cost = river point of diverson supply cost · (1+ average seepage loss).***

Boise Project canal seepage loss survey data is limited, but most seepage occurs over about 260 miles of four major canals; the New York canal, the Deer Flat High Line and Low Line canals, and the Mora Canal (USGS 1996) (USBR 2004), (Figure 2). The assignment of average canal seepage losses to individual Arrowrock Divisions depends on canal length, diversion capacity and elevation (Table 1).

The New York canal skirts the boundaries of Arrowrock 1, 2 and 3, but delivers water to all five Arrowrock Divisions. Although the distance from the Boise River point of diversion to Lower Arrowrock Divisions 4 & 5 is considerably longer than the distance to Upper Divisions 1, 2 & 3. The High Line and Low Line canals deliver to Arrowrock 4 and 5, the Mora canal delivers to Arrowrock 3. Water delivered to Divisions 3 & 4 is transported through canals that are at the highest elevations.

Table 1 Distribution of seepage losses across Boise Project divisions

division	Pct seepage New York canal	Pct seepage Low Line canal	Pct seepage Lower Mora canal	Pct seepage Upper Mora canal	Average pct Arrowrock Division seepage losses
1	9.8				9.8
2	9.8				9.8
3	9.8			30.0	19.9
4	9.8	21.9	17.8	30.0	19.8
5	9.8	21.9			18.4

Groundwater and Drain Water Hydrologic Response Functions

The marginal supply cost of groundwater and drain water irrigators is determined mainly by cost of pumping. For both groundwater and drain water irrigators, pumping costs involve per AF power costs and per AF pumping lift. For groundwater irrigators, the later is determined partly by the ambient depth to groundwater and partly by pumping rate. For drain water irrigators pumping lift is fixed, so pumping cost is determined by pumping rate alone.

The depth to water (DTW) and drain flow responses to reduced Boise Project canal seepage, is determined by a series of MODFLOW model runs in which Boise Project canal seepage is reduced in increments from the base-case calibrated model rate until it is eliminated entirely. . Hydrologic responses within the groundwater and drain return response zones are then fit to analytic and continuously differentiable response functions.

The response function chosen for average pumping lift within the groundwater response zone has the form

$$\textit{pumping lift} = C_1 \cdot e^{(C_2 \cdot \textit{canal seepage} + C_3 \cdot \textit{groundwater pumping rate})}, \qquad (1)$$

and the response function chosen for total drain flow within the drain return response zone has the form

$$\textit{drain flow} = C_1 \cdot e^{(C_2 \cdot \textit{canal seepage})} + C_3 \cdot \textit{groundwater pumping rate}). \qquad (2)$$

The non-linear pumping lift and drain flow responses to reduced canal seepage are the result of a shallow confined aquifer becoming unconfined as canal seepage is reduced. Increased groundwater pumping also affects a non-linear pumping lift response. However once the aquifer becomes unconfined beneath the drain, increased groundwater pumping has no affect on drain flow. Coefficients C_1, C_2 and C_3 are obtained using a non-linear least squares regression procedure (Table 2) (UBC, 2009).

Table 2 Hydrologic response function coefficients. (replace coefficients).

zone	response function	C_1	C_2	$_3$	R^2
Groundwater	Pumping lift (feet)	300.97	-0.58567	1.2673	.983
Drain flow	Drain flow Rate (acre-feet)	47247.0	0.0035269	-.0168	.985

The base-case canal seepage condition is 535,185 acre-feet per year. The fitted groundwater response function (Figure 7) shows that as a consequence of historic Boise Project canal seepage, average DTW within the groundwater response zone has decreased 84 feet on average, from 313 feet to 229 feet below land surface. DTW varies as agricultural pumping varies relative to its base-case condition. In the absence of all agricultural pumping, DTW would be reduced an additional nine to twelve feet.

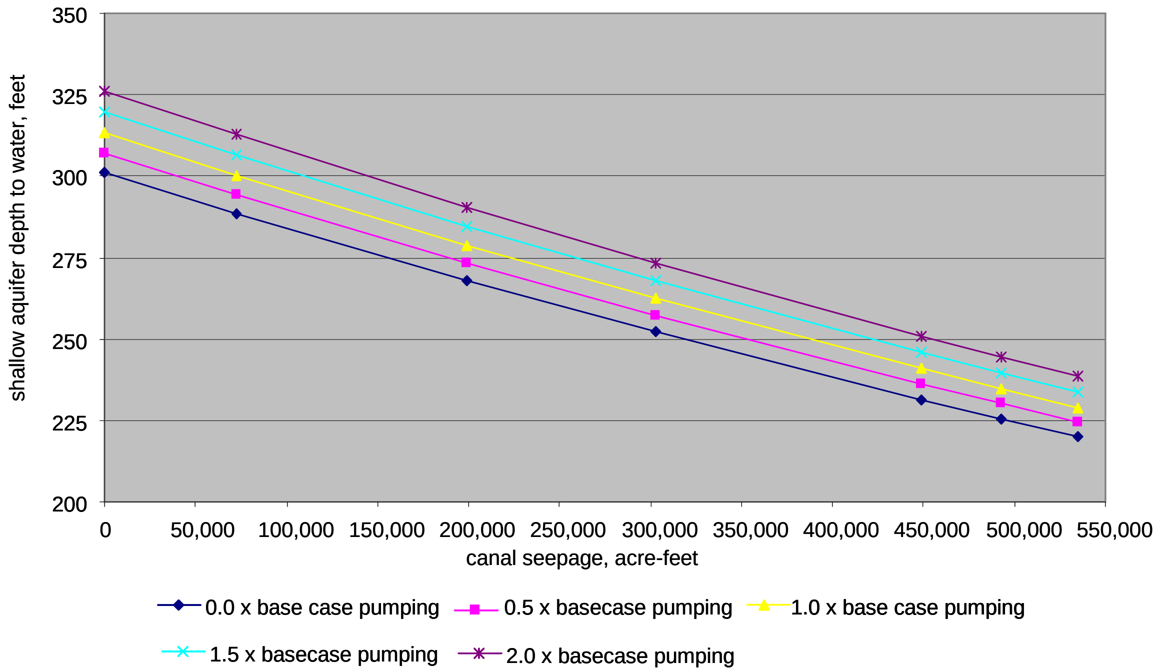

Figure 7 Fitted DTW response to Boise Project canal seepage, for five groundwater pumping rates.

The fitted drain response function shows that return flow within the drain response zone is increased by a factor of about six, from 52,600 to 317,300 acre-feet per year as a consequence of historic Boise Project canal seepage (Figure 8). However base-case agricultural pumping in the drain response zone has reduced return flow by about 5400 acre feet per year.

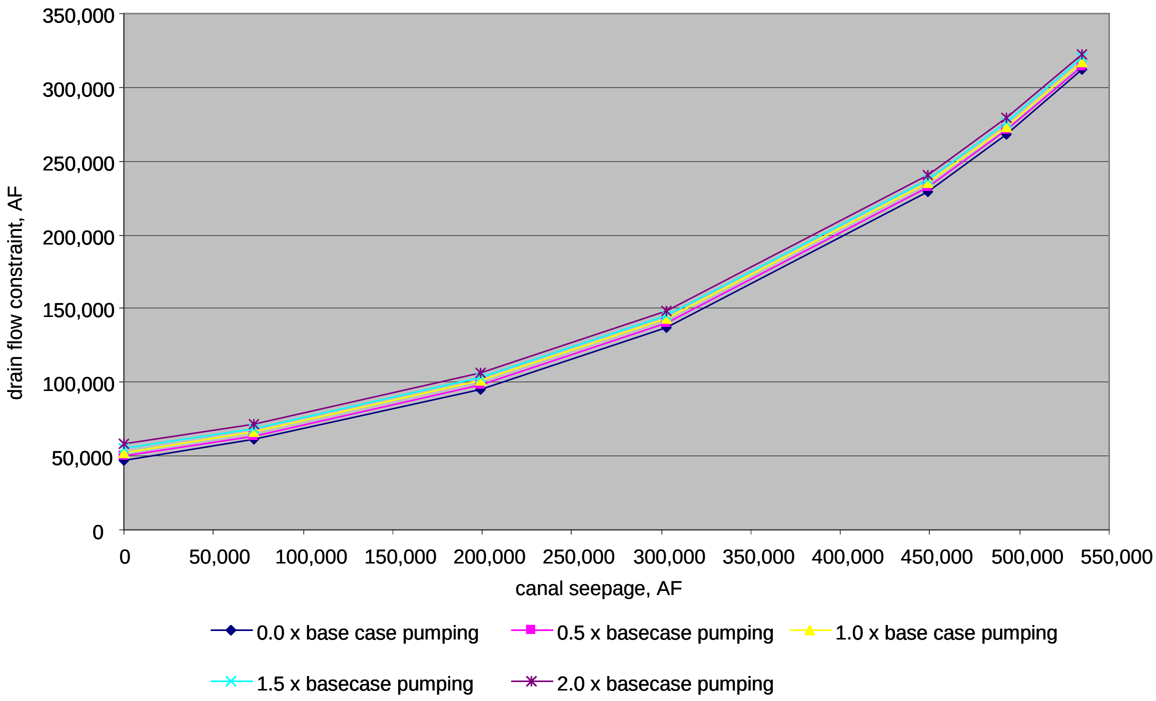

Figure 8 Fitted drain return flow response to Boise Project canal seepage, for five groundwater pumping rates.

Groundwater and Drain Water Marginal Supply-Cost Functions

For groundwater pumpers, unit water supply costs are determined mainly by power costs associated with pumping lift and delivery of irrigation water to the field. Electric power costs for Lower Boise Valley agricultural pumpers are currently about $0.065 per kilowatt hour (US Energy Info, 2011). Assuming a submersible electric pump that is 60 percent efficient and 70 psi pressure is required at the well head (Goodell, 1988), the cost of lifting 1 acre/foot of water 1 foot in the well bore is estimated to be about $0.11 (CIT, 2011). The marginal supply-cost function for groundwater irrigators is then

$$\textit{groundwater supply cost} = \$19.60 + \$0.11 \cdot \textit{pumping lift}, \qquad (3)$$

where pumping lift is obtained from (1) and $19.60 is the pumping power cost per acre-foot associated with delivering water from the well head to the field. Reduced canal seepage results in an increase in pumping lift, and thereby an upward shift in the marginal cost of supply within the groundwater response zone (Figure 9).

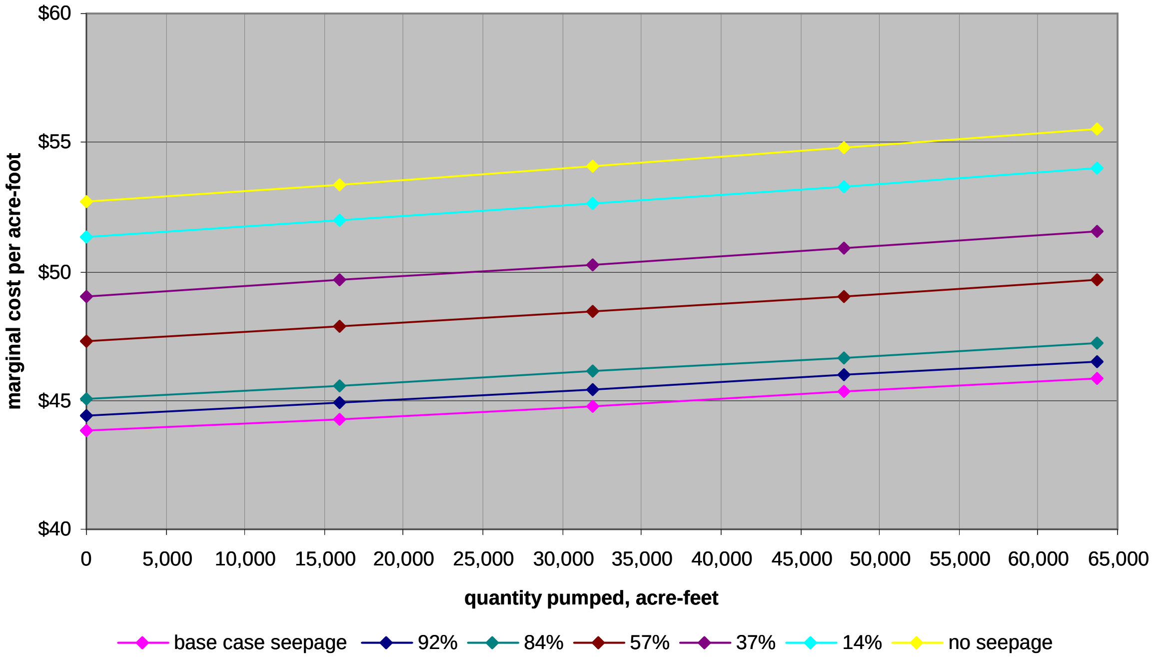

Figure 9 Upward shifts in groundwater irrigator's supply cost due to reduction in Boise Project canal seepage.

For drain water irrigators, water supply costs depend only on the fixed costs associated with delivering an acre-foot of water from the drain to the field. Thus the marginal supply cost function for drain water diverters is simply

$$\textit{drain water supply cost} = \$19.60\ , \qquad (4)$$

regardless of how much water is diverted from the drain. However, drain diverters in the Lower Boise Valley have no control over drain return flow. The available drain water supply is determined by (2) from canal seepage and groundwater pumping rates.

As canal seepage is reduced the drain return supply constraint shifts from left to the right (Figure 10). The influence of increased groundwater pumping on the drain constraint is indicated by the right to left shift in symbols of the same color.

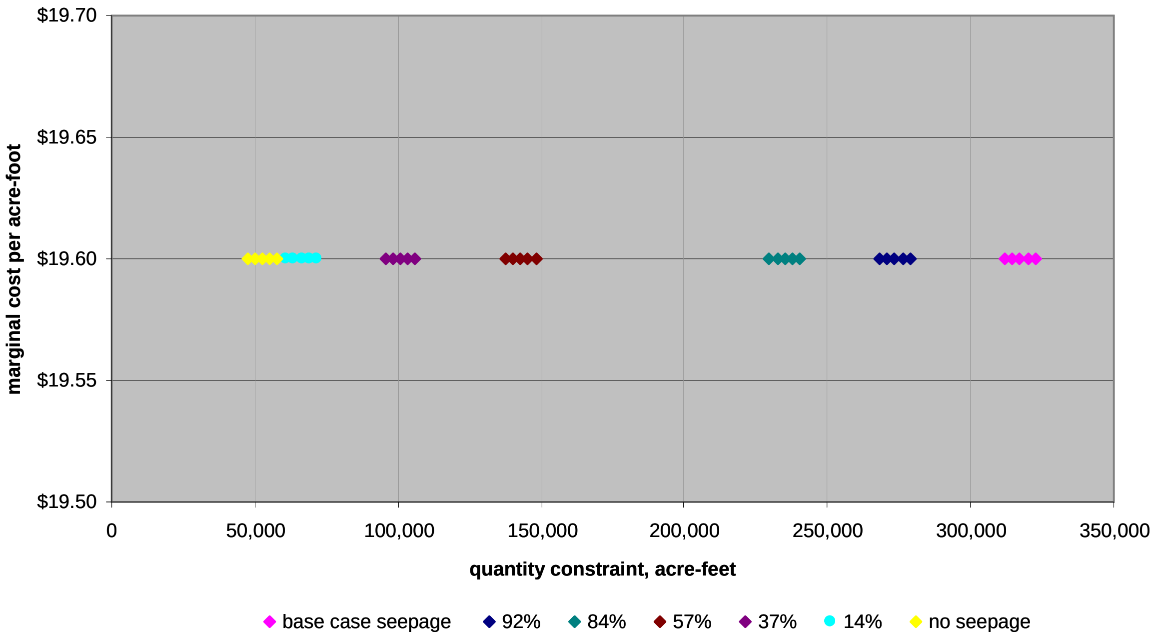

Figure 10 Shift in drain irrigator's supply constraint due to reduction in Boise Project canal seepage and groundwater pumping.

Lower Boise Basin Irrigation Water Marginal Demand-Price Functions

Demand-price relationships for Lower Boise basin irrigation water are developed using the "Irrigation Water Demand from Evapotranspiration Production Functions" (IDEP) calculator (Contor, 2010). The IDEP calculator uses commodity prices and the evapotranspiration (ET) production function of Martin and Supalla (1989) to derive static short-term demand for irrigation water. The ET production function is transformed to an irrigation water production function through the use of an exponent related to crop irrigation efficiency. The exponents for up to six crops can be derived from basin-specific production and agronomic inputs, which include commodity price per yield unit, irrigation depth at full yield, ET depth at full yield, yield at full irrigation, and dry land (non-irrigated) yield. (The IDEP calculator is described in greater detail in Appendix B.)

The IDEP 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.

Aggregate water demand for a mix of crops is calculated by horizontally summing the demands of individual crops at every marginal price, thus crops are allocated water on an equal-marginal basis. Although crop mix is fixed by the horizontal summation, lower value crops may drop out of production at higher prices. The calculator does not consider seasonal demand for irrigation water, only full-season volume delivered. Limited water supplies are assumed to be optimally delivered when most needed. For this application, water demand for crops grown on Boise

Project lands and in groundwater and drain return response zones is aggregated into two demand categories; high-value cash crops, and low-value field crops.

The IDEP horizontal summation of marginal water demand-prices for high value and low value crops generally plots as a series of steps indicating the price points at which different crop lands are taken in or out production as the price of irrigation water decreases or increases (Figures 11 and 12)[7]

Marginal demand-price functions for PE modeling are developed by fitting analytic functions to IDEP calculator price data. Fitted demand-price functions for high value and low value crop irrigation have the form

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

Irrigation demand-price coefficients are developed for each of the five Arrowrock sub-divisions, as well as for the groundwater and drain return response zones based on individual crop distributions, acreages and irrigation efficiencies (Table 3).

Table 3 Irrigation water demand-price function coefficients for low value and high value crops.[8]

	B_0 low value	B_1 low value	B_2 low value	B_0 high value	B_1 high value	B_2 high value
Arrowrock 1	225	.0003	.688	2180	.06	.275
Arrowrock 2	240	.000879	.615	2100	.16	.18
Arrowrock 3	240	.000879	.615	2100	.16	.18
Arrowrock 4	300	.0058	.46	3200	.167	.17
Arrowrock 5	290	.001551	.615	4000	.143	.193
groundwater response zone	320	.00317	.54	4500	.243	.15
drain return response zone	375	.08	.225	4000	.161	.175

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[7] Other possible irrigator responses to climate change include increased dry land farming and changes in cropping patterns and timing of diversions (Windes, 2007).

[8] Demand-price elasticity ranges from -2.5 to -3.2 for low value crops, and from -1.2 to -1.4 for high value crops.

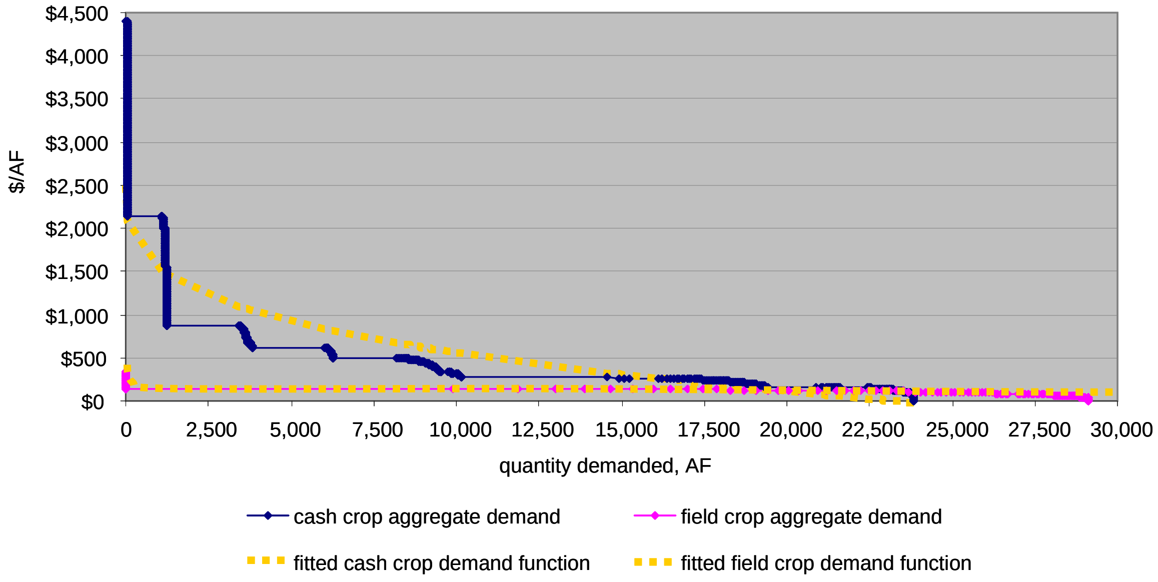

Figure 11 Marginal water demand-price data for high value and low value crops in the groundwater response zone.

There are 19,972 groundwater irrigated acres in the Boise Project groundwater response zone. On average, high value cash crops are grown on 5,217 acres and low value field crops are grown on 14,754 acres. In terms of acreage, the principal high value crops are sugar beets, herbs, dry beans, spring wheat and potatoes and the principal low value crops are alfalfa, silage corn, winter wheat, peas and hay. All of these crops are sprinkler irrigated.

Willingness to pay for groundwater to irrigate cash crops exceeds that for field crops, as indicated by the differences in price elasticity. For instance, when the marginal price of water is $500 per acre foot there is a demand for about 7,500 acre-feet groundwater for fruit trees or grapes. Not until the marginal price is $139 per acre foot is there a field crop demand for groundwater to irrigate alfalfa. However at a price of $20 per acre-foot there are twenty-one cash crops and six field crops being irrigated with groundwater, and the total annual demand is about 53,000 acre-feet.

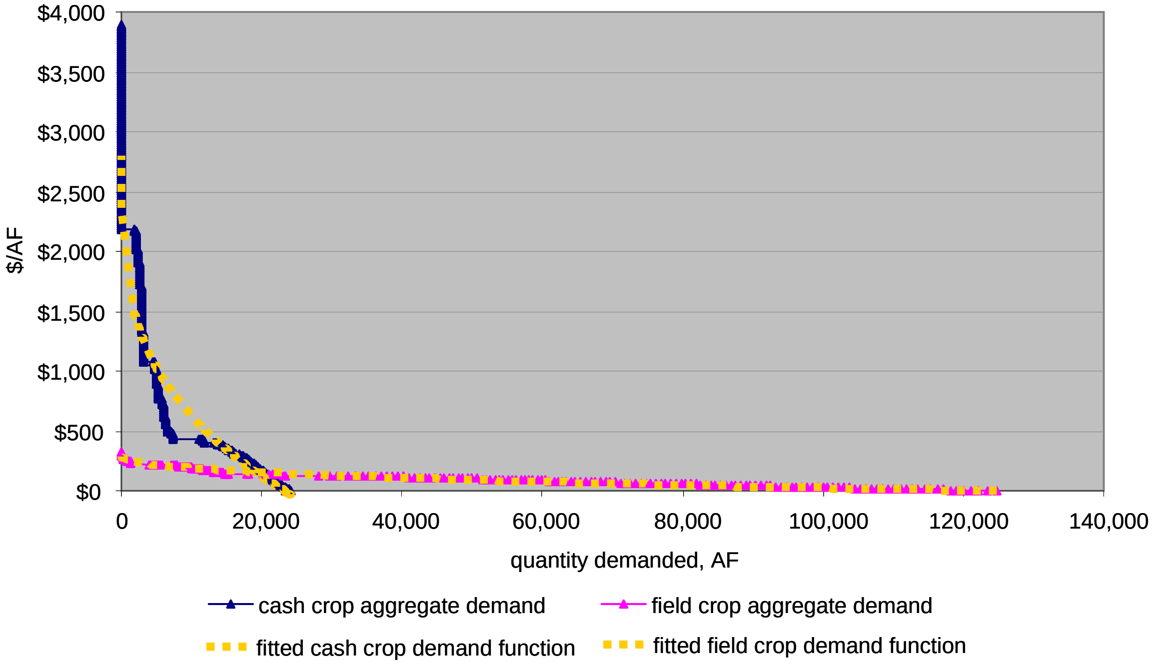

Figure 12 Marginal water demand-price data for high value and low value crops in the drain return response zone.

There are 34,310 drain water irrigated acres in the Boise Project drain return response zone. Cash crops are grown on 7,165 acres and field crops on 27,145 acres. The high value crops by acreage are sugar beets, herbs, onions, potatoes, and sweet corn. The low value crops are the same as those in the groundwater impact zone. Almost all crops in the drain return impact zone are gravity irrigated. The difference in efficiency between gravity and sprinkler irrigation is reflected in IDEP inputs for irrigation depth required for maximum yield, and ET requirement for maximum yield.

Again, when the marginal price of water is $500 per acre foot there is a very small demand for drain water, for grapes and fruit trees. Not until the marginal price drops to $223 per acre foot is there a very small field crop demand for gravity irrigation of silage corn. However when the price drops to $20/acre-foot there are twenty-nine cash crops and twenty-three field crops being irrigated with drain return water, and the total demand for drain water is about 130,000 acre-feet.

Boise River Basin Climate Change, Irrigation and Flood Flow Projections

Boise River basin climate change projections were obtained from the World Climate Research Program’s Bias Corrected and Downscaled Climate and Hydrology Projections website (WCRP, 2012). Six WCRP projections were selected by Reclamation for analysis (Table 4). The projections represent six distinct changes in spatially averaged total precipitation and average temperature conditions in the Pacific Northwest, relative to the historical timeframe of 1950 to 1999 (Reclamation, 2013b).

Table 4 Six transient climate change model projections (adapted from Reclamation, 2011a).

Climate Projections			
Number	Climate Model	Emission Scenario	Study Name
1	ccsm3	B1	ccsm
2	cgcm3.1 t47	B1	cgcm
3	echo g	B1	echo
4	hadcm	B1	hadcm
5	echam5	A1b	echam
6	pcm1	A1b	pcm

Boise River runoff projections were developed from basin climate projections by Reclamation using the Variable Infiltration Capacity (VIC) model (Liang et al, 1994). The six VIC infiltration and runoff projections were then input to the Boise River System RiverWare model in order to generate storage projections using operational rules of the 1950-1999 calibration period. The Riverware simulation period for each climate projection was 1980 through 2098.

The transient Riverware climate scenarios do not retain the timing of seasonal climatic events (e.g., droughts) that occurred during the calibration period, but instead depict a potential drift in river/reservoir system performance over a period of years.

Although the percentages vary, all six Riverware climate scenarios project decreased Boise River basin irrigation diversions and increased irrigation shortages relative to the calibration period scenario (the base-case) (Table 5). The shortages are due mainly to reduced natural flow diversions. Increased diversions from storage make up for part of the shortage. However irrigation storage is constrained by reservoir capacity, storage rights, and reservoir rule curve operations for flood control.

Table 5 Six Riverware projections of average annual irrigation diversions and irrigation shortages in the Boise River basin (adapted from Reclamation, 2011b).

Scenario[1]	Requested Diversion (AF)	Natural flow diversion (AF)	Storage diversion (including rental) (AF)	Total Diversion (AF)	Shortage (AF)	Shortage percentage
base-case	1,543,966	1,085,804	348,033	1,478,457	65,509	4.2%
ccsm	1,472,109	810,026	383,241	1,193,267	278,842	18.9%
cgcm	1,472,109	919,774	485,877	1,405,651	66,458	4.5%
echam	1,472,109	900,052	443,309	1,343,361	128,748	8.7%
echo	1,472,109	762,296	369,857	1,132,153	339,956	23.1%
hadcm	1,472,109	889,129	446,615	1,335,743	136,366	9.3%
pcm	1,472,109	853,561	406,973	1,260,534	211,575	14.4%

[1] Base-case scenario results are calibrated Riverware model 1983-2008 averages. Climate scenario results are averages of 118 year Riverware model projections, 1980-2098.

Boise Project (Arrowrock Division) diversions are also reduced relative to the base-case scenario (Table 6). However, since Boise Project irrigators are far more reliant on reservoir storage than non-Project irrigators, the Boise Project shortages are greater than those for the basin as a whole, as a percentage. The shortage in the Arrowrock Division is smallest (probability of reservoir filling is highest) under the CGCM scenario, and largest (probability of reservoir filling is lowest) under the ECHO scenario.

Table 6 Six Riverware projections of impact on average annual irrigation diversions and irrigation shortages in the Arrowrock Division of the Boise Project (adapted from Reclamation, 2011b).

Scenario[1]	Requested Diversion Arrowrock Div. (AF)[2]	Natural flow diversion Arrowrock Div. (AF)	Storage diversion Arrowrock Div. (including rental) (AF)	Total Diversion Arrowrock Div. (AF)	Shortage Arrowrock Div. (AF)	Shortage percentage
base-case	738,583	440,503[3]	274,434	714,937	23,647	3.2%
ccsm	746,223	313,263	262,876	576,139	170,084	22.8%
cgcm	746,223	366,841	342,932	709,773	36,451	4.9%
echam	746,223	357,493	313,147	670,640	75,584	10.1%
echo	746,223	290,933	250,349	541,282	204,941	27.5%
hadcm	746,223	352,993	313,704	666,697	79,526	10.7%
pcm	746,223	334,527	282,115	616,642	129,581	17.4%

[1] Base-case scenario results are calibrated Riverware model 1983-2008 averages. Climate scenario results are averages of 118 year Riverware model projections, 1980-2098.

[2] New York canal river diversions only.

[3] Includes diversion of reservoir flood release water.

Riverware scenarios indicate that with climate change there is a backward shift in the peak timing of maximum system storage from July to June (Reclamation, 2011b). Reservoirs fill earlier but less often, and as a consequence, an increased potential for flooding in the lower basin.

The target location for Boise River flood flow measurement is the Glenwood Bridge gaging station. During the 30 year model calibration period, flows exceeding 7000 cfs at Glenwood Bridge (for more than five days in a row) occurred on four occasions, with the highest recorded flow being 9,600 cfs (Hydromet, 2012).

The frequency of flows exceeding 7,000 cfs increases under all but one of the Riverware scenarios (Table 7). The CGCM scenario exhibits the highest rate of recurrence, with flows exceeding 7,000 cfs in 45 percent of years, and the ECHO scenario exhibits the lowest, with flows exceeding 7,000 cfs in 12 percent of years.

Table 7 Six Riverware projections of the frequency of Boise River flows exceeding 7,000 cfs (for 5 consecutive days) at the Glenwood Bridge gage (adapted from Reclamation, 2011b).

Climate projection	years of Riverware simulation	Years with peak flow >7000 cfs at Glenwood Bridge[1]	Annual probability of 7000 cfs exceedence	Expected frequency
Base-case	30	4	.13	1 in 7.7 years
CCSM	115	22	.18	1 in 5.6 years
CGCM	115	53	.45	1 in 2.2 years
ECHAM	115	34	.29	1 in 3.4 years
ECHO	115	14	.12	1 in 8.3 years
HADCM	115	28	.24	1 in 4.2 years
PCM	115	23	.19	1 in 5.3 years

[1] for more than five days in a row.

Flows exceeding 16,600 cfs at the Glenwood Bridge gage are deemed one in 100 year flood events (USACOE, 1995). Riverware projections of the annual probability of Boise River flows exceeding 16,600 cfs (for at least one 24 hour period) range from four to fifteen times greater than the base-case probability (Table 8). The CCSM scenario produces the highest probability of one in 100 year flooding and the ECHO scenario produces the lowest.

Table 8 Six Riverware projections of the frequency of Boise River flows exceeding 16,600 cfs at the Glenwood Bridge gage (adapted from Reclamation, 2011b).

Climate projection	Years of Riverware simulation	Days with peak flow > 16600 cfs at Glenwood Bridge	Years with peak flow > 16600 cfs at Glenwood Bridge	Annual probability of 16600 cfs exceedence	Expected frequency
Base-case	30	0	0	0.01	1 in 100 years
ccsm	115	246	18	0.19	1 in 6.4 years
cgcm	115	72	17	0.18	1 in 6.8 years
echam	115	20	9	0.10	1 in 12.9 years
echo	115	9	5	0.05	1 in 23 years
hadcm	115	16	9	0.10	1 in 12.8 years
pcm	115	20	5	0.05	1 in 23 years

The six WCRP climate models project generally drier conditions than in the 30 year base-case calibration period, and as a result reservoirs fill less often and less water is available for irrigation in five of the six Riverware scenarios. Lower basin irrigation shortages range from just over 66,000 AF to almost 340,000 AF (Table 5). Shortages in the Boise Project Arrowrock Division range from just over 36,000 AF to almost 205,000 AF (Table 6) and account for over 50 percent of the total basin-wide shortage. Nevertheless, since peak reservoir runoff occurs one to two months earlier than historical runoff, there is a projected increase of up to eighteen fold in the annual probability of a one in 100 year flood event (Table 8).

Partial Equilibrium Model Scenarios

Three PE model scenarios are developed. The first estimates the affects of projected climate change water shortages on the basin-wide economic benefit (irrigator consumer surpluses) of Boise Project (Arrowrock Division) water. The second investigates the basin-wide economic costs to non-Project irrigators resulting from new Boise Project canal lining conservation measures, as a demand management response to climate change. The third addresses the economic costs and benefits associated with new Boise Project storage that is rival with flood protection, as a supply management response to climate change.

PE Modeling of Climate Change Water Shortages

Figure 13 illustrates the model linkages that exist between surface water and groundwater supply and demand entities in the PE model climate change water shortage scenarios.

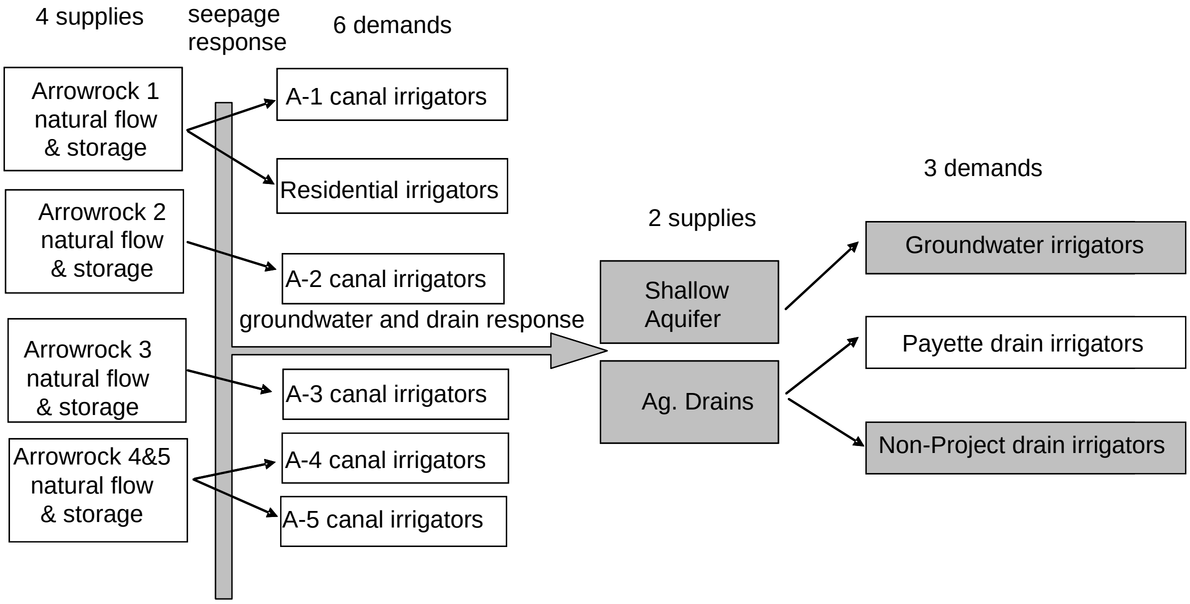

Figure 13 PE model supply and demand linkages for water shortage scenarios.

The five Arrowrock Divisions of the Boise Project are represented in the model as water supply entities, as are shallow groundwater and drain water in the Boise Project hydrologic response zones.

Agricultural water demand entities include canal irrigators in the five Arrowrock Divisions, drain water irrigators in Payette Unit 1 (which receive priority drain water from the Arrowrock Division), and groundwater and drain water irrigators in the response zones.

The black arrows in figure 13 represent standard PE model linkages between irrigation water suppliers and demanders. The gray arrows, labeled canal seepage and groundwater and drain response, are hydrologic responses that underlie the interdependent marginal supply-cost functions of canal, groundwater and drain water irrigators. The gray boxes denote PE model representation of potential conjunctive-use externalities.

The affect of water shortages on net economic benefit (i.e. consumer surpluses) of Project and non-Project irrigators is modeled by inserting the reduced natural flow and storage water supplies projected by Riverware scenarios (Table 7) into the PE model as Project supply constraints. The PE model results for Project and non-Project irrigators are summarized in Table 9.

Relative to the base-case scenario, the **ccsm** and **echo** shortages have the greatest impacts on both Project and non-Project irrigator benefits, while the **cgcm** shortage has the least impact. Boise Project irrigators growing field crops experience about a 12 percent reduction in consumer surplus under the **ccsm** scenario, and a 19 percent reduction under the **echo** scenario. Project irrigators growing cash crop experience less than a 4 percent reduction in benefit.

Projected **ccsm** and **echo** shortages have least impact on the consumer surplus of non-Project groundwater irrigators; a maximum 2 percent reduction for cash crops and 10 percent reduction for field crops. Their greatest impact is on consumer surplus of non-Project drain water irrigators; a maximum of 33 percent for field crop irrigators and 4 percent for cash crop irrigators.

Timing of infiltration and runoff to reservoirs varies among the six WCRP climate model projections, and the reduced reservoir storage projected by the **cgcm**, **echam**, **hadcm** and **pcm** Riverware scenarios occurs at a time of the year that results in little if any impact on irrigation season water supplies. Consequently the shortage projections of these Riverware scenarios have little or no impact on irrigator consumer surpluses.

Table 9 Impacts of projected water shortages on Project and non-Project consumer surpluses.

Boise Project (Arrowrock Division) canal irrigation (in millions).							
	base-case	**ccsm**	**cgcm**	**echam**	**echo**	**hadcm**	**pcm**
cash crops	$64.74	$63.62	$64.78	$64.62	$62.01	$64.59	$64.13
field crops	$37.86	$33.37	$37.99	$37.37	$30.61	$37.22	$35.05
total	$102.60	$96.99	$102.78	$101.99	$92.63	$101.82	$99.18
pct change from base-case							
cash crops	100.0%	98.3%	100.1%	99.8%	95.8%	99.8%	99.1%
field crops	100.0%	88.2%	100.4%	98.7%	80.9%	98.3%	92.6%
total	100.0%	94.0%	100.2%	99.4%	89.6%	99.2%	96.3%
Non-Project groundwater irrigation (in millions)							
	base-case	**ccsm**	**cgcm**	**echam**	**echo**	**hadcm**	**pcm**
cash crops	$6.73	$6.65	$6.73	$6.72	$6.61	$6.72	$6.69
field crops	$2.91	$2.70	$2.91	$2.89	$2.60	$2.88	$2.81
total	$9.64	$9.35	$9.64	$9.61	$9.21	$9.60	$9.51
pct change from base-case							
cash crops	100.0%	98.8%	100.0%	99.9%	98.2%	99.9%	99.5%
field crops	100.0%	92.9%	100.2%	99.3%	89.4%	99.1%	96.8%
total	100.0%	95.8%	100.1%	99.6%	93.8%	99.5%	98.1%
Boise Project (Payette Division) and Non-Project drain water irrigation (in millions)							
	base-case	**ccsm**	**cgcm**	**echam**	**echo**	**hadcm**	**pcm**
cash crops	$18.89	$18.42	$18.90	$18.85	$18.16	$18.84	$18.68
field crops	$4.48	$3.46	$4.51	$4.39	$2.98	$4.35	$4.01
total	$23.38	$21.87	$23.41	$23.24	$21.14	$23.19	$22.69
pct change from base-case							
cash crops	100.0%	97.5%	100.1%	99.8%	96.1%	99.7%	98.9%
field crops	100.0%	77.1%	100.5%	97.8%	66.6%	97.1%	89.4%
total	100.0%	93.6%	100.1%	99.4%	90.5%	99.2%	97.1%

Regardless of whether they are Project or non-Project irrigators, with canal, drain or groundwater supply, those most affected by projected water shortages are the low value field crop irrigators.

PE Modeling of New Water Conservation Measures

New water conservation measures have often been advocated as a means of reducing the vulnerability of managed water systems to climate change (USBR, 2013) (USDA, 2012). Agriculture, being the largest water user in the West, and the lowest cost demander is often viewed as the principal focus of these conservation measures, and installing impermeable liners in leaky canals is a commonly applied conservation measures.

On the face of it, balancing water supply and demand through water conservation measures such as canal lining would seem to have no downside. Canal lining reduces waste, makes more efficient use of existing supplies for irrigation and the environment, and reduces the need for costly water supply infrastructure. However, agricultural water conservation measures can also have unintended hydrologic and economic consequences (NY Times, 2013) (Environmental Working Group, 2013).

Aquifers in many areas of the western United States are created and/or sustained by incidental recharge from surface water irrigation activities. The impact of Reclamation's Boise Project on groundwater levels and drain return flows in the Lower Boise River basin is just one well documented example of this (USBR and IDWR, 2006). One of the concerns when it comes to implementation of new Reclamation water conservation measures is the basin-wide economic impact on non-Project irrigators

The assumption underlying PE model canal lining scenarios is that new conservation measures are implemented in response to a shortage of late season reservoir storage for Project irrigators. A series of PE model scenarios describe the affect of a progression of Boise Project canal lining conservation measures on the equilibrium price-quantity positions and consumer surpluses of non-Project groundwater and drain water irrigators in the Boise Project groundwater and drain return response zones. The canal seepage supplied to groundwater and drain water irrigators is represented in PE model scenarios as a conjunctive-use externality, and is therefore un-priced. PE model supply and demand linkages for the conservation scenarios are the same as those for the previous water shortage scenarios (Figure 13).

Scenario Results: Quantities and Prices

Equilibrium quantities and prices for groundwater and drain water irrigators in eleven PE model scenarios in which basin-wide canal and reservoir seepage is reduced from its current level of 535,000 acre-feet to zero in increments of 10 percent are summarized in Table 10. The first six increments, totaling 327,000 AF, are reductions in Boise Project (Arrowrock Division) canal seepage (Figure 3). The remaining four increments are reductions in non-Project canal seepage.

Irrigators in all four groundwater and drain water demand categories are affected by the reductions in canal seepage. Quantities of irrigation water supplied and demanded decrease and prices increase. The magnitude of change in quantity and price varies however. The elimination of all Boise Project canal seepage increases the groundwater supply price by about 12 percent; however groundwater demand is reduced by less than one percent. The minimal impact on demand is due to the widespread use of more efficient sprinkler irrigation combined with the relatively high proportion of cash crop acreage in the groundwater response zone.

Canal lining does not increase drain water supply costs but it does constrain the supply of drain water. The drain return constraint cost[9] describes the marginal demand price for water over and above the $19.60 per acre-foot that drain water irrigators pay. It reflects drain water irrigators willingness to pay for an alternative supply of water once the drain supply constraint becomes binding.[10] As noted earlier, crop mix is fixed by aggregate demand functions. As drain water supply is constrained, drain water demand is reduced as more and more of the lowest valued crops go out of production (Figure 14).

For irrigators in the drain return response zone, the drain return supply constraint is non-binding as long as total basin canal seepage remains above 321,000 AF (Table 10). This seepage rate yields a supply of drain return water that sustains the 22,690 AF demands of drain water irrigators growing high value cash crops plus the 104,033 AF demands of drain water irrigators growing low value field crops. The drain return constraint becomes binding however once total canal seepage drops below 321,000 AF. Project canal lining which reduces seepage by no more than 214,000 AF (535,000-321,000) does not constrain the supply of drain water irrigators. However any further reduction in Project canal seepage would constrain the supply of drain water irrigators growing field crops.

The outsize impact of the canal lining constraint on drain water irrigators growing field crops is a consequence of two factors. Field crops account for about 80 percent of the total acreage in the drain return response zone, and demand elasticity of low value field crops is considerably less then that of high value cash crops

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[9] Constraint cost is also referred to as the shadow price.

[10] Since exogenous demand functions are independent of one another, there is no opportunity in this model for water exchanges between cash and field crop irrigators.

Table 10 Groundwater and drain water equilibrium quantities (AF) and prices ($/AF) with incremental reductions in Project and non-Project canal seepage.

	Canal Seepage (acre-feet)	Groundwater Irrigator, cash crop		Groundwater Irrigator, field crop		Drain Water Irrigator, cash crop		Drain Water Irrigator, field crop		Drain Return Cost Constraint
		quantity	price	quantity	price	quantity	price	quantity	price	price
Base case	535,000	21,853	$45.36	27,613	$45.36	22,690	$19.60	104,033	$19.60	$0.00
Boise Project Canal Seepage Reductions	481,500	21,828	$46.18	27,583	$46.18	22,690	$19.60	104.033	$19.60	$0.00
	428,000	21,803	$47.03	27,552	$47.03	22,690	$19.60	104.033	$19.60	$0.00
	374,500	21,777	$47.90	27,519	$47.90	22,690	$19.60	104,033	$19.60	$0.00
	321,000	21,751	$48.80	27,486	$48.80	22,690	$19.60	104.033	$19.60	$0.00
	267,500	21,723	$49.70	27,451	$49.72	22,291	$34.40	90,849	$34.40	$14.80
	214,000	21,695	$50.60	27,414	$50.68	21,615	$59.81	70,650	$59.81	$40.21
	160,500	21,666	$51.60	27,376	$51.67	20,978	$84.28	54,006	$84.28	$64.68
Non-Project Canal Seepage Reductions	107,000	21,636	$52.60	27,336	$52.69	20,371	$108.11	40,307	$108..11	$88.51
	53,500	21,605	$53.74	27,295	$53.74	19,783	$131.66	29.053	$131.66	$112.06

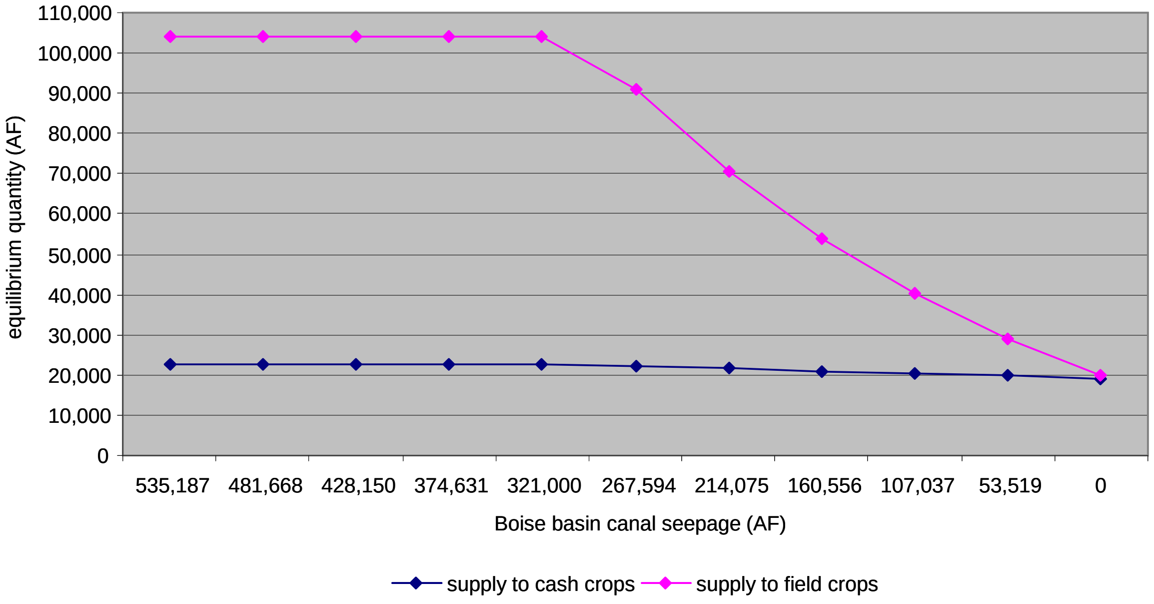

Figure 14 Drain water equilibrium quantity supplied and demanded as canal seepage is reduced.

Scenario Results: Consumer Surpluses

The consumer surpluses of groundwater and drain water irrigators in each of the eleven PE model conservation scenarios are summarized in Table 11. The affect of Boise Project canal lining in which Arrowrock canal seepage is reduced by up to 214,000 AF (about 65 percent of total Arrowrock seepage losses) is relatively modest. Consumer surplus of groundwater irrigators growing cash crops is reduced by less than one percent from the base-case condition, and the consumer surplus of those growing field crops is reduced by about five percent. Consumer surplus of drain water irrigators growing cash or field crops is unaffected, since with a 65 percent reduction in seepage the drain return supply constraint remains non-binding.

Table 11 Groundwater and drain water irrigator consumer surpluses (in millions) with incremental reductions in Project and non-Project canal seepage.

	Canal Seepage (acre-feet)	Groundwater Irrigator, cash crop	Groundwater Irrigator, field crop	Drain Water Irrigator, cash crop	Drain Water Irrigator, field crop	Sum Both Zones
Base case	535,187	$12,379	$2,323	$14,559	$8,335	$37,596
Boise Project Canal Seepage Reductions	481,668	$12,361	$2,300	$14,559	$8,335	$37,554
	428,150	$12,342	$2,277	$14,559	$8.,335	$37,513
	374,631	$12,323	$2,253	$14,559	$8.335	$37,470
	321,000	$12,304	$2,228	$14,559	$8,335	$37,425
	267,594	$12,284	$2,203	$14,226	$6,894	$35,607
	214,075	$12,263	$2,177	$13,668	$4,848	$32,956
Non-Project Canal Seepage Reductions	160,556	$12,241	$2,149	$13,147	$3,329	$32,956
	107,037	$12,219	$2,122	$12,655	$2,210	$30,867
	53,519	$12,197	$2,093	$12,182	$1,397	$27,869
	0	$12,173	$2,063	$11,717	$819	$26,772

However, reductions in Project canal seepage that go beyond 214,000 AF will significantly reduce the consumer surpluses of groundwater and drain water irrigators growing low-value crops (Figure 15). The elimination of all Project canal seepage would result in about a 34 percent reduction in consumer surplus for this group of irrigators. (Basin-wide elimination of all canal seepage would result in a 73 percent reduction in consumer surplus for this group.)

With 65 percent reduction in Boise Project canal seepage, the total basin-wide reduction in groundwater and drain water irrigator consumer surplus (relative to the base-case) is only about $170,000 (Table 11), whereas with the basin-wide elimination of canal seepage the reduction in groundwater and drain water irrigator consumer surplus is about $10.8 million.

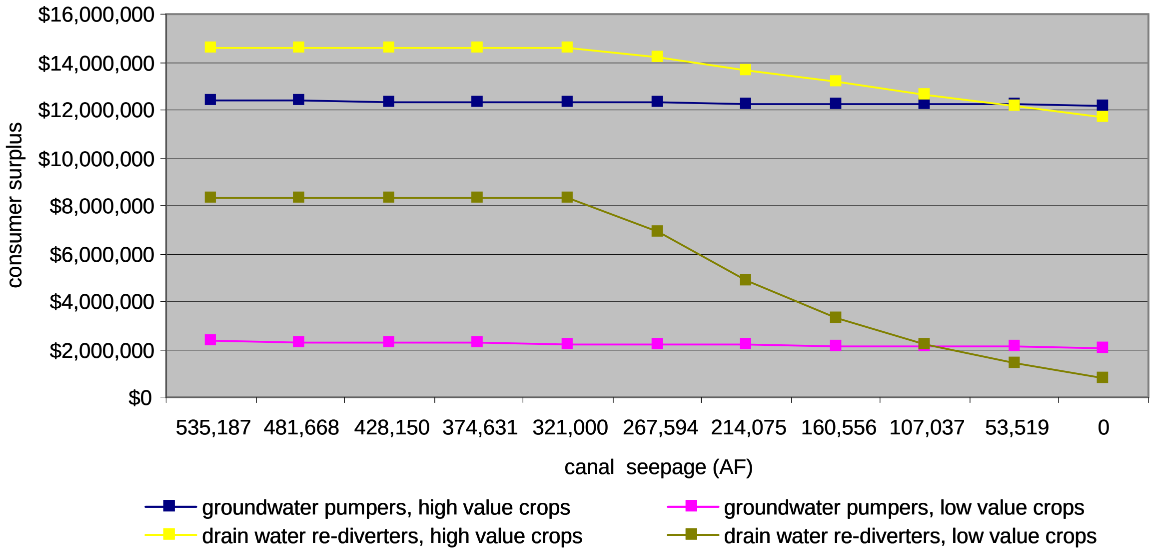

Figure 15 Impacts of progressive Boise Project canal lining on irrigator consumer surplus.

Benefit-Cost of New Boise Project Water Conservation Measures

The estimated annualized construction and maintenance costs for membrane lining of major Boise Project canals is derived from a ten year Reclamation canal lining demonstration study (Reclamation, 2002). For membrane liner with 40-60 year lifespan, annualized cost on average is $0.048 per square foot. Average effectiveness in seepage reduction is 75 percent. Boise Project Arrowrock Division has approximately 360 miles of what may be considered major canals, i.e. canals 10 miles or longer and excluding laterals and ditches, with cross section of canal bottom and sides of 60 feet or more. Assuming total area of about 114 million square feet, the annualized cost for construction and maintenance for membrane lining is estimated to be about $5.5 million.

Based on recent seepage surveys of Boise Project canals (USGS, 1996), (Reclamation, 2004) it is estimated that average seepage loss from major canals is about 2.2 cfs per mile of canal, for total irrigation season loss of about 280,000 AF. With full membrane lining, seepage losses could be expected to be reduced by about 212,000 AF (roughly 65 percent of total Arrowrock Division canal seepage)[11]. The annual supply cost of conserved water is therefore about $25.80/AF.

Barring the worst-case climate change projection for impacts to Boise Project natural flow and reservoir storage diversions (i.e. the Riverware **echo** scenario shortage of 204,000 AF in Table 2)

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[11] Canal lining inputs to the PE model which are intended to reduce seepage losses by 65 percent also have the effect of reducing demand for Project irrigation water at the river point of diversion by about 23 percent (from 882,200 AF to 681,100 AF). At the same time, because of reduced supply cost at the head gate, canal lining increases demand by about seven percent (from 555,400 to 594,000 AF). The actual PE modeled reduction in canal seepage losses between base-case and canal lining scenarios is therefore closer 73 percent.

a significant portion of water conserved by canal lining may go unused by Project canal irrigators. However the $25.80 /AF supply cost of conserved canal water may be seen as a preferable supply alternative to groundwater pumping, since in the absence of 212,000 AF of annual canal seepage recharging the aquifer, non-Project groundwater irrigators supply cost increases from $47.90/AF to $48.80/AF (Table 11). On the other hand, the $19.60/AF (Table 11) supply of drain water irrigators would not be constrained by a 212,000 AF reduction in Arrowrock canal seepage.

PE Modeling of New Reservoir 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. Rule-curve operations provide assurance that Boise River flows at the Glenwood Bridge do not reach flood stage and that reservoirs refill to meet subsequent irrigation demand. Assuming accurate forecasting, reservoir rule curve operations mean that irrigation and flood control allocations of reservoir storage are mostly non-rival (USACOE, 1985).

The quantity of reservoir storage space that can be allocated, either for irrigation storage or flood control, is constrained by the existing reservoir capacity and by reservoir operating rules. Based on total runoff storage capacity, the current supply of flood control storage is assumed to be the total capacity of all reservoirs in the system, currently about 987,000 AF (USACOE, 1958).

Lower Basin Flood Flow Recurrence and Flood Damages

As noted earlier, the maximum Boise River flow at the Glenwood Bridge gaging station which avoids flood damages downstream of Lucky Peak Dam is 7,000 cfs. Flows less than 7,000 cfs are regulated by downstream demands for irrigation, hydropower and in stream flow. Flows exceeding 7,000 cfs are described as unregulated (USCOE, 1981). As part of a recent USACOE Lower Boise River Reconnaissance Study (USACOE, 1995) a frequency curve averaging technique was used to estimate the recurrence of unregulated flows at Glenwood Bridge. Flows exceeding 7,000 cfs were estimated to be between a one in ten and a one in twenty year event[12]. Flows exceeding 16,600 cfs were estimated to be a one in 100 year event, and flows exceeding 35,000 cfs a one in 500 year event (Figure 16).

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[12] The 1995 USCOE reconnaissance study describes 7,000 cfs flow at Glenwood Bridge as 1 in 10 or 1 in 20 year events. The 2010 USACOE Water Storage Screening Analysis describes 7,000 cfs as one in 35 year event.

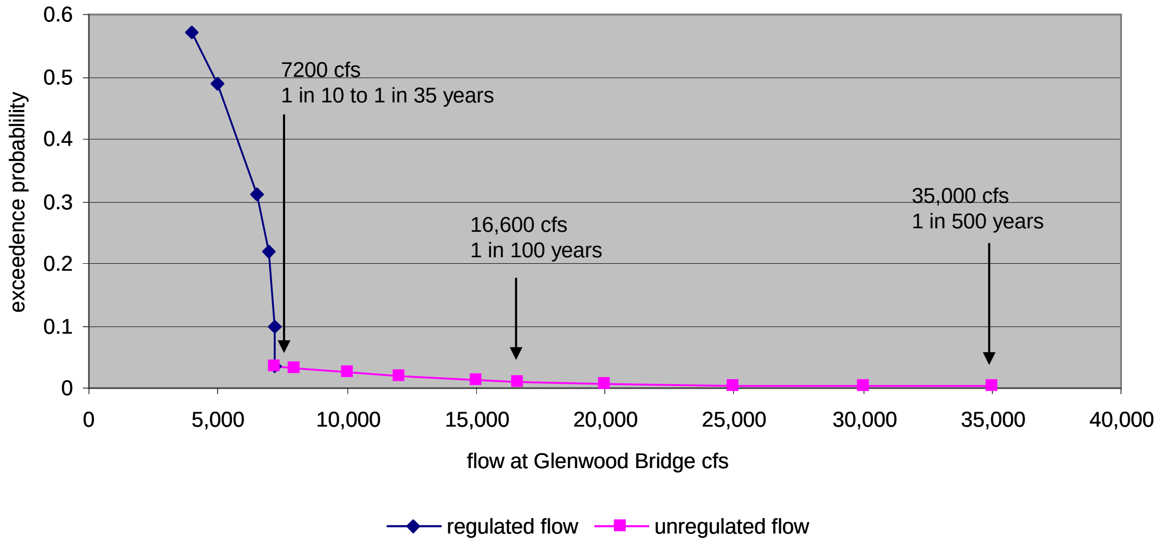

Figure 16 Estimated recurrence of regulated and unregulated flows at Glenwood Bridge (USACOE, 1995; Appendix B, Table B-17).

The 1995 USACOE Lower Boise River Reconnaissance Study also estimated the damage costs within the 500 year flood plain of the Boise River as a function of discharge at the Glenwood Bridge gaging station. The study summarizes eleven different categories of flood damages in both Canyon and Ada Counties (USACOE, 1995; Appendix C, Table C-3). Based on 1994 lower basin population and price levels, flood damages resulting from unregulated flows between 7,000 cfs and 35,000 cfs range from $390,000 to $329 million.

Since 1994 however the population living within the 500 year Lower Boise Basin flood plain has increased by more than 70 percent (2010 US Census facts) and the inflation rate has increased price levels by about 40 percent. It is not unreasonable to assume that that Lower Boise basin flood damage estimates may have more than doubled since 1994. For the purposes of this analysis, the flood flow versus damage curve in Figure 17 has applied a multiplier of 2.5 to the 1994 USACOE damage estimates.

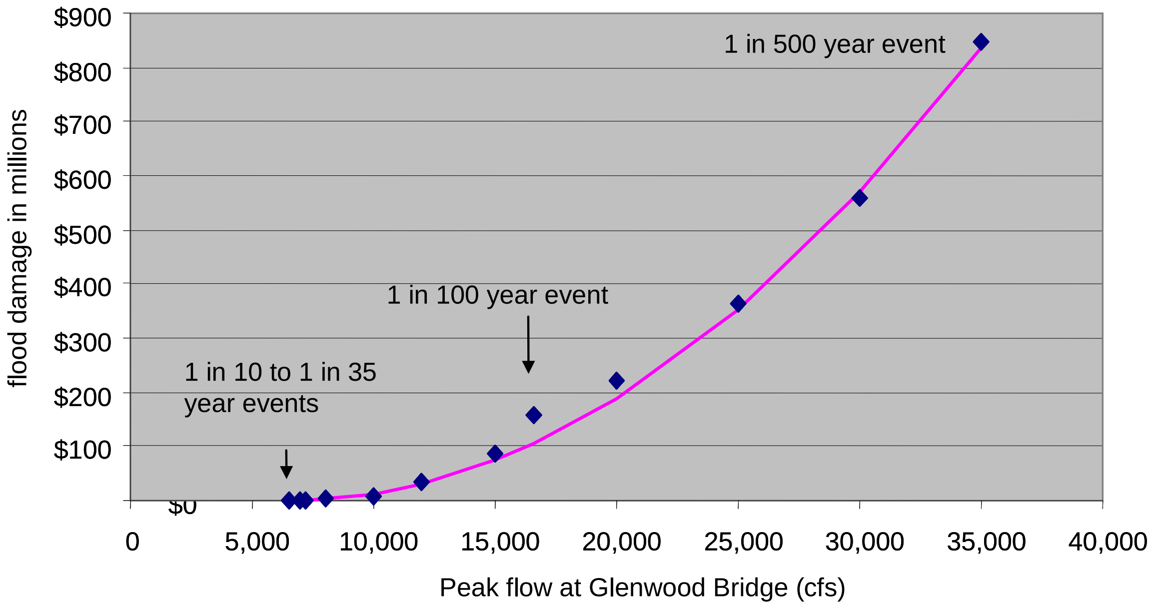

Figure 17 Lower Boise Basin unregulated flow versus damage, with current storage (modified from USACOE, 1995)

Flood Storage Utility and Marginal Demand-Price Functions

Annually expected damage due to flooding is obtained by multiplying the exceedence probability of flood flows (Figure 16) by damage associated with those flood flows (Figure 17). The result is a relationship that can be described as the annually expected damage from peak unregulated flood flow at Glenwood Bridge (Figure 18).

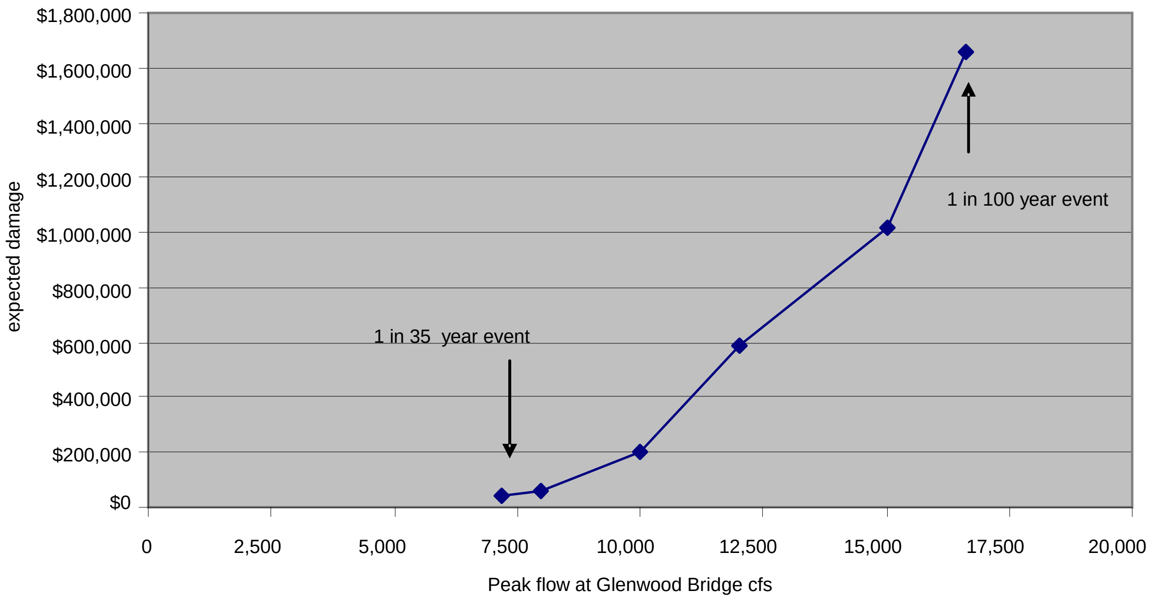

Figure 18 Annually expected flood damage as a function of unregulated flow at Glenwood Bridge

The Boise River water storage feasibility study (USACOE, 2010) assumed that for adequate flood control, 60 days of storage would be required for each cfs of peak flow. The same time interval assumption is made here. The relationship between peak unregulated flow and available reservoir storage space is then defined, and the reduction in annually expected flood damage with increasing flood storage space can be represented by a fitted utility curve. For the 60 day storage equivalent of unregulated flows up to 16,600 cfs (one in 100 year event), the fitted flood storage utility curve has the form of a power function,

$$\boldsymbol{annual\ utility} = 10^7 \cdot \boldsymbol{(}1 - \boldsymbol{.}030754 \cdot \boldsymbol{storage}^{0.23972}\boldsymbol{)} \qquad (6)$$

The fitted curve (Figure 19) is downward sloping because of the inverse relationship between unregulated flows at Glenwood Bridge and the availability of flood storage space. 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.

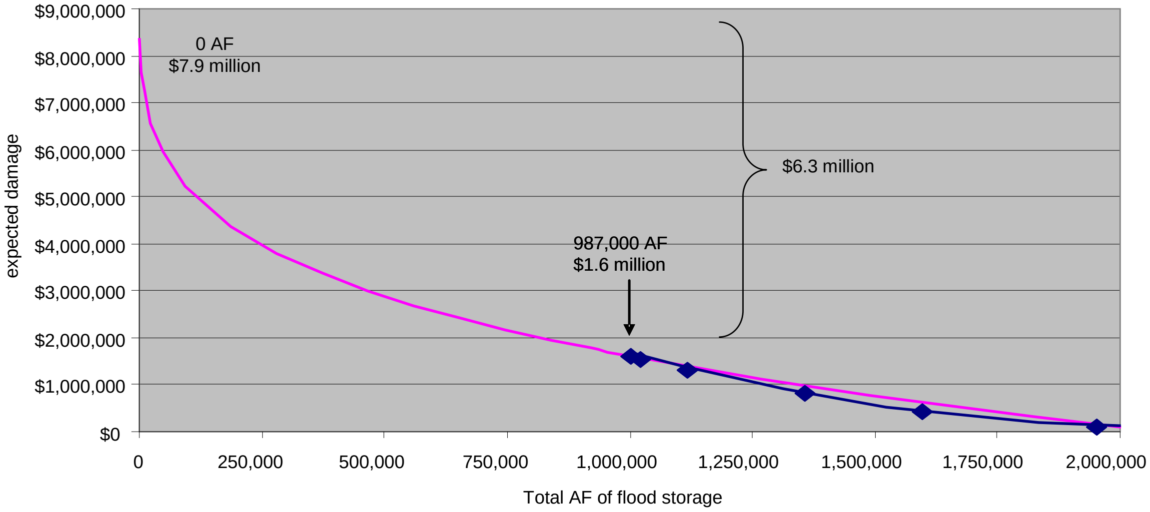

Figure 19 Utility function for flood storage.

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.[13] The marginal utility function which is the derivative of (6) is therefore,

$$\boldsymbol{annual\ marginal\ utility} = -\boldsymbol{.}030754 \cdot \left(0\boldsymbol{.}23972\right)\boldsymbol{storage}^{-0.76021} \qquad \textbf{(7)}$$

---

[13] .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.

The marginal utility function generates a demand price for each additional AF of flood storage. For example, in Figure 22 given 5,000 AF of available flood storage, the demand price for one additional AF is $112.00. Likewise, 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 because with each additional AF, the annually expected damage from flooding decreases. [14]

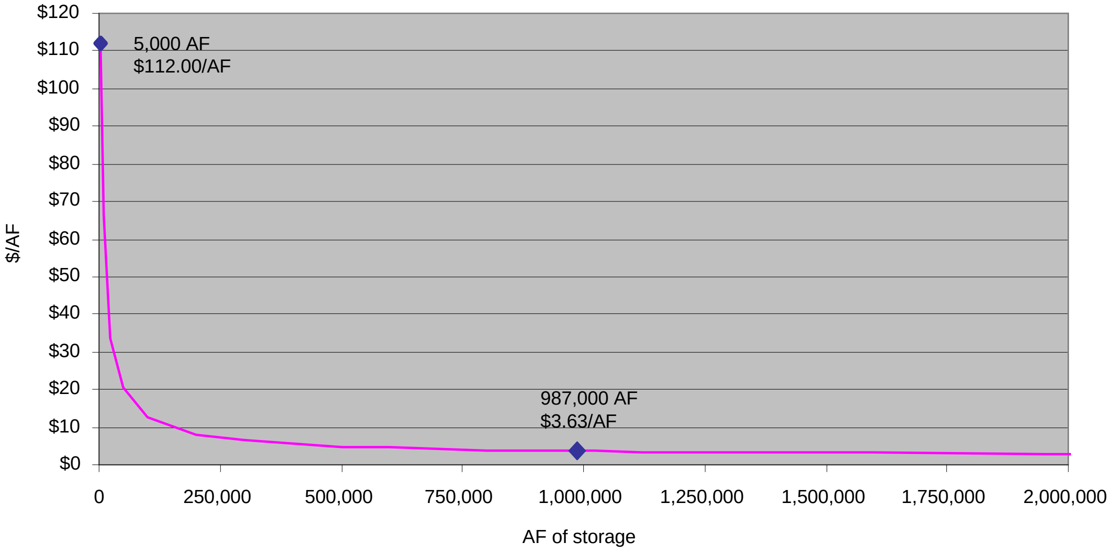

Figure 20 Marginal utility (demand-price) function for flood storage.

The Boise River reservoir system may not have been designed and built with an equilibrium supply and demand assumption in mind, but it has since been operated under that assumption via rule curves, which have been formulated to balance the probability of flood prevention with the probability of refill for irrigation. If one assumes that a price-quantity equilibrium condition currently exists in the Lower Boise basin with respect to flood storage space, then by definition $3.63/AF is the equilibrium supply and demand price for additional flood storage. Appendix C discusses the importance of marginal as opposed to average water demand pricing in making infrastructure investment decisions.

Shifts in Marginal Demand Pricing of New Flood Control Storage

Historically, Lower Boise basin reservoir system flood releases to maintain flood control storage space have also contributed to the natural flow supply of Boise Project irrigators. However as noted previously, most down-scaled climate models project earlier snow melt and earlier runoff to reservoirs in Snake River sub-basins. Earlier runoff means that flood control releases are more likely to occur prior to the start of the irrigation season on April 1[15]. Riverware model projections bear this out. Altered timing of runoff to the reservoir system reduces the availability

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[14] Demand-price elasticity for flood control storage is -1.315 = (1/-0.76021).

[15] Flood releases made after April 1 are also more likely to be the result of extreme hydrologic events and therefore unregulated (i.e. greater than 7,000 cfs at Glenwood Bridge) while releases made prior to April 1 are more likely to regulated.

of natural flows for irrigation (Tables 5 & 6) while increasing the probability of flooding in the lower basin (Tables 7 & 8).

The 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. Outward shifts in the marginal demand-price function mean an increased willingness to pay for flood control storage over and above the equilibrium price of $3.63/AF. The shifts displayed in Figure 21 are for 5, 10 and 20 fold increases in flood flow probability, approximating the six Riverware model projections (Table 8). Note that the increased willingness to pay applies not only to new rival storage but to existing non-rival storage as well.

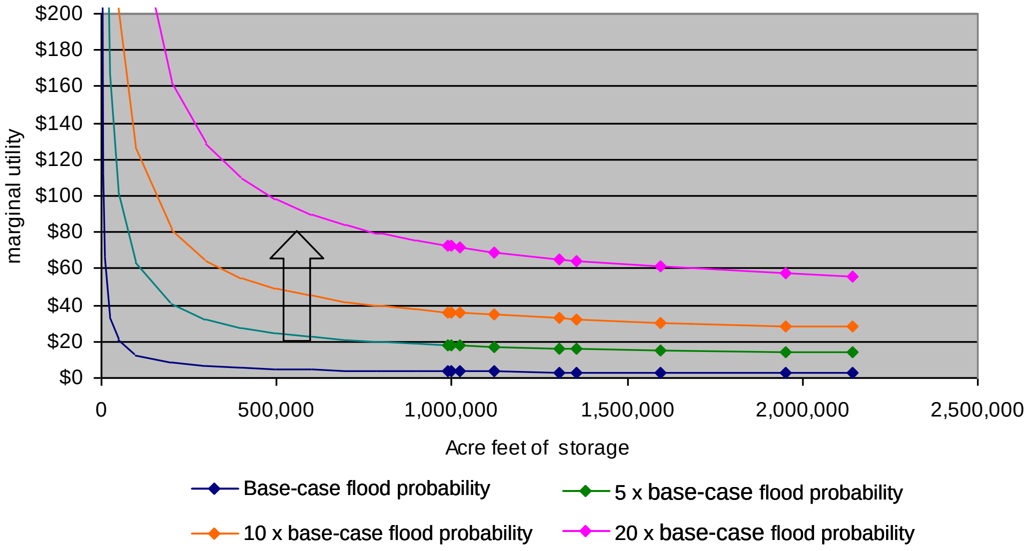

Figure 21 Shifts in the marginal utility function for flood control storage due to increased flood probability.

New Flood Storage Marginal Supply-Cost Functions and Constraints

For this analysis, the supply cost of new reservoir storage in the Boise River basin is again based on options presented in the USACOE Boise Basin Water Storage feasibility study (USACOE, 2010). The two highest rated new storage options analyzed were a New Arrowrock dam and reservoir which would provide 317,000 AF of new storage at an estimated construction cost of $2700/AF, and a Twin Springs dam and reservoir which would provide 304,000 AF of new storage at an estimated construction cost of $3600/AF.

For the purposes of this analysis, it is assumed that new dams and reservoirs have 100 year life spans and that construction costs are not discounted. The annualized per AF reservoir construction cost are therefore assumed to be $27/AF/year for New Arrowrock reservoir storage and $37/AF/year for Twin Springs reservoir storage. The per AF reservoir operating cost is assumed to be $1.60 /AF, the same as that charged to irrigators. New Arrowrock flood storage supply cost is therefore $28.60 /AF/year and Twin Springs supply cost is $38.60/AF/year.

Exogenous supply pricing for new storage is inserted in the PE model in the form of a step function (Figure 22), with the first price step being a new Arrowrock dam and reservoir (317,000 AF) and the second price step being the Twin Springs Dam (304,000 AF).

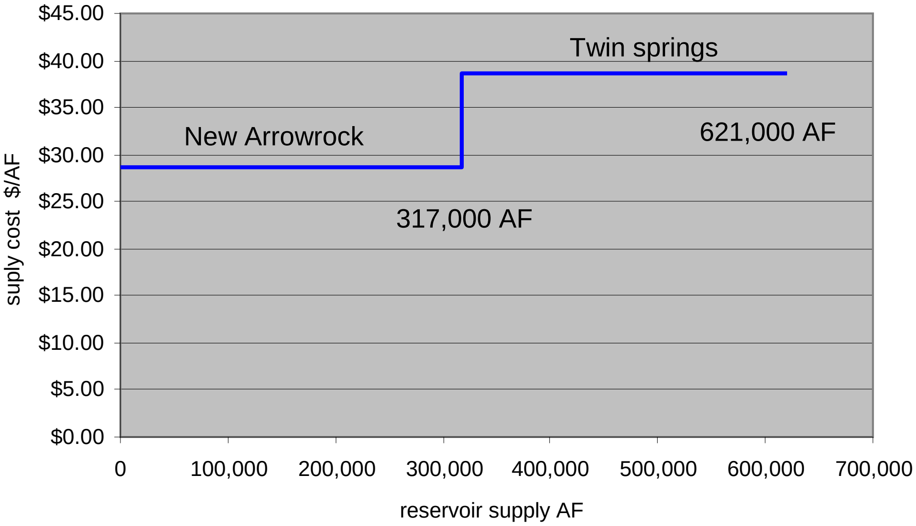

Figure 22 New reservoir storage marginal supply-cost function.

New Storage PE Model Supply and Demand Linkages

The modified PE model network of arcs linking Boise Project water suppliers and demanders (Figure 21) includes the irrigation and flood control demands for existing reservoir storage which are assumed non-rival as a result of current rule curve operations. It also includes the rival demand for up to 621,000 AF of additional storage, which can be released prior to April 1 to meet demand for flood control, or released after April 1 as natural flow to meet demand for irrigation. No flood control rule-curve constraints are specified for the new storage. Instead, the quantity of new reservoir storage space demanded is determined by equilibrating the rival demands for flood control and irrigation.

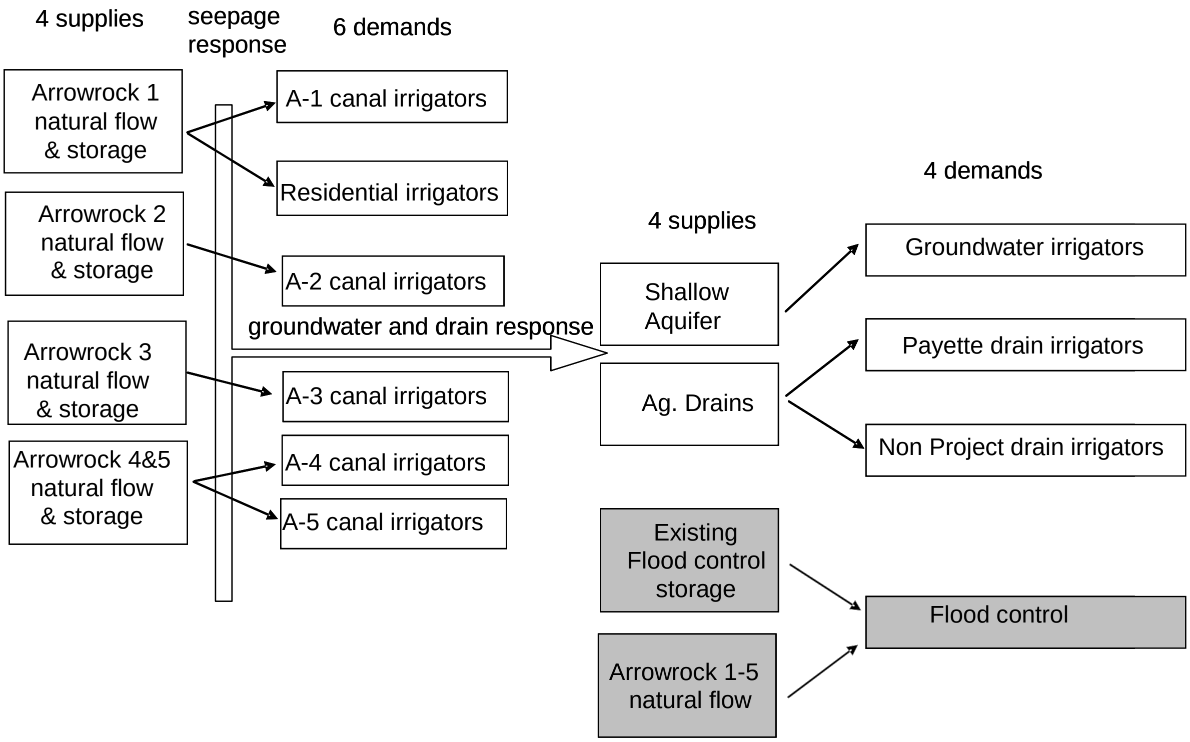

Figure 23 PE model supply and demand linkages for rival irrigation and flood control scenarios.

Scenario Results: Quantities Demanded and Benefits

New storage PE model scenarios consist of a base-case scenario with existing storage and six climate-change scenarios with existing storage and 621,000 AF of new flood control storage. The six climate-change scenarios incorporate the Riverware model projections of reduced availability of Boise Project natural flow that is attributed to climate change (Table 6), and the outward shifts in flood storage marginal utility function (Figure 21) corresponding to the 5, 10 and 20 fold increases in flood probability projected to occur under Riverware climate scenarios (Table 4).

The base-case PE scenario assumes that the supply and demand for existing flood control storage are in equilibrium. In other words, the current total storage capacity of 987,000 AF is the quantity of storage demanded for one in 35 year flood protection (assuming a 60 day storage requirement for Glenwood Bridge unregulated flows) and the willingness to pay for additional flood control storage is $3.63/AF. The scenario also assumes that the post April 1 Boise Project (Arrowrock Division) demand for natural flow and storage is constrained only by the Project's 358,000 AF natural flow right and 617,000 AF storage right. Lastly, the marginal demand-price function in the base-case scenario (Figure 23) assumes historic probability of flooding in the lower basin.

PE model results for the new storage scenarios are presented in tabular fashion in Table 12.

Column 1 identifies the PE base-case climate scenario and the six PE climate-change scenarios.

Columns 2-3 are PE model inputs from Riverware model scenarios.

> Column 2 contains the (equilibrium) supply and demand for existing flood control storage.
>
> Column 3 is the probability of exceeding 16,600 cfs at Glenwood Bridge without new storage.

Columns 4-9 are PE model equilibrium supply and demand outputs.

> Columns 4 and 5 are, respectively, the rival demand for natural flow released from storage for flood control before April 1, and the rival demand for natural flow diverted by irrigators after April 1.
>
> Columns 6 and 7 are the consumer surpluses (benefits) that accrue to flood control and to Boise Project irrigation given Riverware model inputs and rival demand for New Arrowrock storage.
>
> Columns 8 and 9 are the changes in flood control and irrigation benefits, relative to base-case conditions.

The equilibrated demand for new storage in the base-case scenario, which assumes historic flood probability, is zero. Demand for new flood control storage exists only when there is an increase in flood probability, represented by a shift in the flood control demand function (Figure 21). Relative to the base-case, the equilibrium quantity of natural flow available to Arrowrock Division irrigators' decreases, and the equilibrium quantity of flood controls storage increases.

The quantities of new flood storage demanded are greatest for the Riverware **ccsm** and **cgcm** scenarios and smallest for the **echo** and **pcm** scenarios. The difference is due to the **ccsm** and **cgcm** projection of a one in 100 year flood flow almost every 5 years, while the **echo** and **pcm** projection of a one in 100 year flood flow is every 20 years.

The PE model scenarios generate an increase in flood control benefit that is proportional to the 100 year flood probability, and a corresponding decrease in irrigation benefit relative to the base-case. The loss of irrigation benefit is less than 20 percent of the gain in flood control benefit in the **ccsm**, **cgcm**, **echm** and **hdcm** models. The gain and loss of benefit from irrigation to flood control are more nearly balanced in the **echo** and **pcm** models however.

Table 12 PE Model results, New Arrowrock storage with climate change. [1] Assume 20 fold increase in flood probability

Climate Scenario	Base Case	ccsm	cgcm	Echam	Echo	Hadcm	Hcm
Existing non-rival flood storage demanded	987,000	987,000	987,000	987,000	987,000	987,000	987,000
100 year flood probability without new storage (from Table 8)	0.01	0.19	0.18	0.10	0.05	0.10	0.05
Rival demands for new flood storage space, (AF) (621,000 AF constraint)	0	220,175	281,960	171,422	29,615	168,369	76,676
Rival demand for irrigation natural flow (AF) (water right constraint)	357,382	254,151	297,620	290,035	236,035	286,386	271,403
Flood control benefit with existing and new storage (millions)	$6.24	$122.78	$118.52	$64.17	$31.27	$64.14	$31.65
Boise Project irrigation benefit with existing and new storage (millions)	$94.54	$72.74	$79.08	$86.77	$81.47	$86.70	$72.00
Change in flood control benefit with new rival flood storage (millions)	$0.00	$116.54	$112.29	$57.93	$25.04	$57.90	$25.41
Change in Boise Project benefit with new rival flood storage (millions)	$0.00	$(21.80)	$(15.46)	$(7.77)	$(13.07)	$(7.84)	$(22.54)

The equilibrated demand for flood control is not constrained by the New Arrowrock supply of 317,000 AF in any of the Riverware climate scenarios. Therefore the flood control storage constraint cost is zero and additional Twin Springs flood storage is unnecessary. However irrigation demand for natural flow is constrained in all the scenarios (including the base-case, where it is constrained by water rights). Any further reduction in natural flow due to increased demand for flood control storage space means increased irrigator reliance on Project storage, an outcome of both Riverware climate and PE model scenarios.

In contrast to models which assume new storage to eliminate flood risk is a requirement, the redistribution of benefits that occurs when New Arrowrock storage is added to the Boise River/reservoir system can be traced back to differences in demand-price elasticity for irrigation water (mostly for low value crops) and flood control storage.

New Storage Net-Benefit and Benefit-Cost Ratio

The net annual benefit of new reservoir storage (Table 13, column 3) is calculated by subtracting the reduction in Boise Project irrigation benefit that results from reduced natural flow (Table 12, column 9) from the increase in flood control benefit derived from new storage (Table 12, column 8). Recall that the flood control benefit (consumer surplus) of a New Arrowrock reservoir is defined as the reduction in annually expected flood damage as a result of meeting the demand for flood control storage space.

The annual cost of new Arrowrock reservoir storage is based on the previous undiscounted USACOE construction cost estimate of $2700/AF of storage, along with the assumption of a 100 year reservoir life span and an annual O&M cost of $1.60/AF. The annual cost of new Arrowrock storage ($28.60/AF x 317,000 AF) is therefore about $9.1 million.

A ratio of net reservoir benefit to reservoir construction and O&M costs (Table 13, column 4) that is greater than 1.0 is an indicator that the cost of new storage may be a good investment; a ratio less than 1.0 is an indicator that it may not be a good investment. Riverware climate scenarios which project greatly increased probabilities of 100 year flooding such as **ccsm** and **cgcm**, shift the marginal utility function for flood storage outward (Figure 23), thereby greatly increasing the benefit-cost ratio of both existing and new storage. Scenarios which project only modest increases in flood probabilities, such as **echo** and **pcm** generate smaller outward shifts in marginal utility and smaller increases in benefit-cost ratios. The **pcm** climate model projection is the only one to produce a benefit-cost ratio less than 1.0.   The base-case model benefit-cost ratio is zero because with historic probability of 100 year flooding, there is no demand for new flood control storage.

Table 13 PE Model results, New Arrowrock storage benefit-cost ratio with climate change.

1. Climate scenario	2. 100 year flood probability without new storage (from Table 3)	3. Net annual benefit from New Arrowrock storage (in millions)	4. Annualized construction cost for New Arrowrock storage (in millions)	5. Benefit-Cost ratio of New Arrowrock storage
base-case	0.01	0	$9.1	0.0
ccsm	0.19	$ 94.74	$9.1	10.4
cgcm	0.18	$ 96.83	$9.1	10.6
echam	0.10	$ 50.16	$9.1	5.5
echo	0.05	$ 11.97	$9.1	1.3
hadcm	0.10	$ 50.06	$9.1	5.5
pcm	0.05	$ 2.87	$9.1	0.3

By shifting the marginal utility function for flood storage, the PE model new storage scenarios assume that the magnitude of a one in 100 year Boise River flood event is fixed (16,600 cfs), but the probability of its occurrence can change depending on climate. This is functionally equivalent to the underlying assumption of Look ahead forecasting (Raff et. al., 2009), in which a particular flood flow with an exceedence probability of 0.01 this year may have a different exceedence in future years due to climate change. In an application of Look ahead forecasting in the Boise River system, Raff estimated that as a consequence of future climate change one in 100 year flood flows in the Boise River could range between 40,000 and 48,000 cfs.[16]

Increase in flood probability is not the only climate model result influencing net benefit and benefit-cost ratio of new storage. Model projections of timing of runoff to reservoirs (before or after April 1) further constrain the availability of natural flow for irrigation (Table 12, column 5), which determines in part the reduction in irrigation consumer surplus as demonstrated in the difference between **echo** and **pcm** benefit-cost ratios and between **ccsm** and **cgcm** benefit-cost ratios. Also, since Riverware climate scenarios assume perfect runoff forecasting, the Table 13 results should be viewed as providing the best possible benefit-cost outcomes of New Arrowrock storage.

Summary and Conclusions

Depending on the climate scenario, basin-wide water shortages projected by the Riverware model range from just over 66,000 AF to almost 340,000 AF. However PE modeling indicates that these shortages have comparatively little impact on the economic benefit that Boise Project irrigators derive from Project water. Project irrigators growing high-value cash crops experience

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[16] The Boise River flood flow measurement location in the Raff study is described as “above Lucky Peak dam”. Flows at the Glenwood Bridge gage which are downstream from the dam would reach these levels only if Lucky Peak reservoir were full and no canal diversions were made upstream of the Glenwood Bridge gage.

a reduction in consumer surplus from the base-case that is no more than about 4 percent, and in most cases less than 2 percent. The relatively small reduction in benefit can be attributed to availability of storage water in place of reduced natural flows. The shortages of natural flows do however force a greater reliance on storage.

Non-Project irrigators experience a somewhat greater reduction in benefit as a result of Project shortages, a maximum of about 11 percent for groundwater irrigators and up to 35 percent, for non-Project drain water irrigators in the Boise Project drain return and groundwater response zones. The reductions are confined mostly to irrigators growing low value field crops however. This is true in all scenarios whether water constraints arise because of climate induced shortages, new conservation measures, or new rival demands for storage water.

Base-case Arrowrock Division canal seepage averages 327,000 AF annually. PE model results indicate that new canal lining conservation measures sufficient to reduce Arrowrock canal seepage losses by 65 percent would increase the Arrowrock Division water supply at head gates by an additional 214,000 AF, reducing the basin-wide impacts of the most extreme of the six Riverware climate scenario shortage projections, and reversing them entirely for the Arrowrock Division. With 113,000 AF of Arrowrock canal seepage remaining, the constraint on return flow in the drain return response zone would continue to be non-binding.

The reduced level of canal seepage does affect supply prices in the groundwater response zone, although the impact is relatively small. The average depth to water in the zone increases from 234 feet in the base-case to 259.7 feet, and the average supply price of groundwater increases about 6 percent, from $45.31 to $48.16 per acre foot

The canal lining conservation scenarios demonstrate that there is a level of Project conservation response to climate change that can reduce or eliminate the impact of irrigation shortages on Project irrigators with minimal impact on irrigators who have come to rely on the positive conjunctive-use externalities that result from Boise Project canal seepage.

The marginal utility of flood control storage is defined as the reduction in annually expected flood damage that results from the availability of each additional AF of flood storage space. Altered timing of runoff to the Boise River reservoir system reduces the availability of natural flows for irrigation while increasing the probability of flooding in the lower basin. The increase in flood probability thereby increases the marginal utility of flood control storage, which is represented by an outward shift in the marginal demand-price function.

Flood flow-damage estimates and flood flow probability data specific to the Lower Boise River basin were used to generate marginal demand-price functions for new flood control storage assuming three different projections of flood probability due to climate change.

New storage scenarios indicate that the benefit-cost ratio of new Boise River flood control storage is greater than 1.0 only if the probability of flooding in the lower basin as a result of climate change is significantly greater than what is indicated by the historical record. Given the uncertainties in PE model inputs a benefit-cost ratio of five or greater is not an unreasonable standard to apply in this analysis. This standard is met only by climate scenarios which project and increase in one in 100 years Boise River flood events by a factor of ten or more.

While most of the benefits of water Projects accrue regionally, most of the cost is borne nationally. Calculation of net basin-wide benefit and benefit-cost ratio of new water conservation and new reservoir storage are therefore fundamentally important to decision making by water managers at the federal level.

By incorporating elasticity of demand for irrigation and flood control, and by including the externalized costs and benefits resulting from conjunctive use of Reclamation Project water, hydro-economic modeling represents an application of best available science in the evaluation of Federal Investments in Water Resources. By monetizing the basin-wide costs and benefits of these and other potential supply management and demand management responses to climate change Reclamation is better able to determine which of these approaches is more cost-effective, an objective consistent with recently revised, Principles and Requirements for Federal Investments in Water Resources (2013).

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Appendix A - Partial Equilibrium Modeling Theory and Application to Water Supply and Demand

Leroy Stodick

Partial Spatial Equilibrium Theory

Partial equilibrium models, following the example of Takayama and Judge, have traditionally been cast in the form of optimization problems. The modeler derives a quasi-welfare function or a net social payoff function which is maximized subject to various constraints and the equilibrium position is assumed to occur at the optimal point of the optimization problem. Few if any modelers attempt to explain why the optimum point is the equilibrium point and in some cases it may that this assumption is not justified. When Takayama and Judge published their book in the early 1970's, numerical optimization techniques were well understood but mixed complimentary programming was just beginning to be studied. With the advent of GAMS and the accompanying solvers, it is now possible to directly solve the equilibrium equations set up as complementary slackness equations or as a mixed complementary problem, instead of setting up an artificial optimization problem and assuming (in some cases wrongly) that the Kuhn-Tucker conditions for the problem coincide with the equilibrium conditions. It is now possible to define equilibrium conditions as a mixture of equations, inequalities, and complementary slackness equations and solve them using mixed complementary programming. It is no longer necessary or, in some cases, even possible to equate these equilibrium conditions to the Kuhn-Tucker conditions of an optimization problem.

The basic partial equilibrium model developed by Takayama and Judge (1971) involved spatially distributed trading entities that have both supply functions and demand functions, and included the following assumptions:

1. One homogeneous product is traded.
2. Linear supply and demand functions are defined for each entity (see Figure 1).
3. A fixed per unit transportation charge is applied to all exchange paths between trading entities.
4. No monopoly behavior exists.
5. No import or export taxes exist.

A quasi-welfare or net social payoff function was defined as the sum, over all trading entities, of consumer and producer surplus, less transportation costs. This function was maximized subject to two sets of conditions:

1. There is no excess demand.
2. Excess supply is possible

Definitions

Q_A is economic output of canal water user A

Q_B is the economic output of groundwater pumper B.

f_A is the production function for canal water user A .

f_B is the production function for groundwater pumper B

W_A is the water demand by canal water user A.

W_B is the water demand by groundwater pumper B

The Meade Externality for Canal Diverters and Groundwater Pumpers

Water demand by canal water user A enters into the production function of groundwater pumper B since water that is available to user B (via canal loss) depends partly on the water demand of user A.

$$\begin{tikzcd}
Q_A = f_A(& W_A, \arrow[dr] & X_A) \\
Q_B = f_B(& W_B, X_B, & W_A)
\end{tikzcd}$$

This is a positive Meade externality for groundwater pumper B

The Cheung Externality for Canal Diverters and Groundwater Pumpers

Water demand by canal user A enters into the production function of groundwater pumper B since water that is available to user B (via canal losses) depends partly on the water demand of user A. In addition, when the canal is in contact with the watertable surface, water demand by user B enters in to the production function of user A, since groundwater pumping induces additional losses from the canal.

$$\begin{tikzcd}
Q_A = f_A(& W_A, \arrow[drr] & X_A, & W_B) \\
Q_B = f_B(& W_B, & X_B, & W_A) \arrow[u]
\end{tikzcd}$$

The Chung externality is positive for groundwater pumper B and negative for canal user A.

Partial Equilibrium Modeling with GAMS

In order to explicitly state the Kuhn-Tucker conditions for what Takayama and Judge call a quasi-welfare function (or net social payoff function), define the following variables:

Exogenous variables:

λ_i – intercept of the inverse of the linear demand function in region i

ω_i –absolute value of the slope of the inverse of the linear demand function in region i

γ_i – intercept of the inverse of the linear supply function in region i
η_i – slope of the inverse of the linear supply function in region i
t_{ij} – per unit transportation cost from region i to region i

Endogenous variables:

y_i – amount demanded in region i
x_i – amount supplied in region i
X_{ij} – amount exported from region i and imported into region j
ρ_i – market demand price in region i
ρ^j – market supply price in region j (subscript for ρ means market demand price, superscript for ρ means market supply price)

The Kuhn-Tucker conditions (and coincidentally the equilibrium conditions) are:

1. $\lambda_i - \omega_i y_i - \rho_i \leq 0$ and $(\lambda_i - \omega_i y_i - \rho_i)y_i = 0 \ \forall \ i$
2. $-\gamma_i - \eta_i x_i + \rho^i \leq 0$ and $(-\gamma_i - \eta_i x_i + \rho^i)x_i = 0 \ \forall \ i$
3. $\rho_j - \rho^i - t_{ij} \leq 0$ and $(\rho_j - \rho^i - t_{ij})X_{ij} = 0 \ \forall \ i,j$
4. $\sum_{j=1}^{n} X_{ji} - y_i \geq 0$ and $(\sum_{j=1}^{n} X_{ji} - y_i)\rho_i = 0 \ \forall \ i$
5. $x_i - \sum_{j=1}^{n} X_{ij} \geq 0$ and $(x_i - \sum_{j=1}^{n} X_{ij})\rho^i = 0 \ \forall \ i$

where it is understood that these equations hold only at the optimum point (the equilibrium point).

The economic interpretation of each of these equations is as follows:

Equation 1: when the consumption in the ith region (y_i) is positive, then the regional demand price
($p_i = \lambda_i - \omega_i y_i$) is equal to the market demand price ρ_i. When $y_i = 0$, the market demand price (ρ_i) must be greater than or equal to the regional demand price (p_i). This essentially results in a kinked demand function. As long as consumption in a region remains positive, the market demand price can be found along the demand curve. When consumption is 0, the market demand price may be above the demand curve on the vertical axis. In this case, the market demand price has risen so high that consumption in the ith region is driven to 0.

Equation 2: when the supply in the ith region (x_i) is positive, then the regional supply price ($p^i = \gamma_i + \eta_i x_i$) is equal to the market supply price ρi. When $x_i = 0$, the market supply price (ρ^i) must be less than or equal to the regional supply price (p^i). This results in a kinked supply function. As long as supply in a region remains positive, the market supply price can be found along the supply curve. When supply is 0, the market supply price may be below the supply curve on the vertical axis. In this case, the market supply price has dropped so low that supply in the ith region is driven to 0.

Equation 3: this is the so-called price linkage equation. When X_{ij} is positive (positive transfer of goods from region i to region j), the difference between the market demand price in region j and the market supply price in region i must be the per unit-cost of transporting the goods from region i to region j. If X_{ij} = 0, then the difference between the market demand price in region j and the market supply price in region i must be less than or equal to the per unit-cost of transporting the goods from region i to region j.

Equation 4: this equation insures that demand is met in all regions (no excess demand). If the market demand price in the ith region (ρ_i) is greater than 0, then consumption (y_i) is exactly equal to the quantity imported into the region (X_{ji}). (X_{ii} is the amount produced in region i that is consumed in region i.) If the market demand price is 0, then the amount imported into the region (including the amount produced locally which is consumed locally) is greater than or equal to the amount consumed in the region.

Equation 5: this equation allows for excess supply. If the market supply price in the ith region (ρ^i) is greater than 0, then the amount produced in region i (x_i) is exactly equal to the amount exported to all other regions as well as the amount that is consumed locally (X_{ij}). If the market supply price is 0, then the amount supplied must be greater than or equal to exports plus local consumption.

The Boise Valley Partial Equilibrium Model

The water allocation model developed for the Boise Valley Project differs from the model described above

(Subscripts refer to demand quantities, prices, and functions.)

(Superscripts refer to supply quantities, prices, and functions.)

Model 1: The basic model with no externalities.

Exogenous variables:

1. For each region with a demand function, the functional form and parameters of a monotonically decreasing demand function must be specified. $q_i = f_i(p_i)$.
2. For each region with a supply function, the functional form and parameters of a monotonically increasing supply function must be specified. $q^i = f^i(p^i)$. (Horizontal supply functions ($p^i = \text{constant}^i$) are allowed.
3. For each allowed path between regions, the per-unit conveyance cost must be specified. t_{ij} = cost of transporting one unit of the commodity from region i to region j.

Endogenous variables:

1. x_{ij} = amount of commodity exported from region i and imported into region j.
2. q_i = amount of commodity consumed in region i.
3. q^i = amount of commodity produced in region i.
4. p_i = locally determined demand price.
5. p^i = locally determined supply price.
6. ρ_i = globally determined demand price.
7. ρ^i = globally determined supply price.

p_i is the price determined by the inverse demand function. $p_i = f_i^{-1}(q_i)$. This is the price that consumers in region i are willing to pay in order to consume quantity q_i. p_i is determined by the consumer's utility function and budget constraints. ρ_i, on the other hand, is the price that consumers must pay in order to purchase quantity q_i on the global market. This price is determined by how much other regions are willing to supply and how much demand exists in other regions. p_i does not necessarily equal ρ_i.

Similarly, p^i is the price determined by the inverse supply function $p^i = f^{i(-1)}(q^i)$. This is the price that suppliers must receive in order to supply quantity q^i. p^i is determined by the producer's profit function and production constraints. ρ^i, on the other hand, is the price that producers will receive if they sell quantity q^i on the global market. This price is determined by the demand and supply conditions in all regions. p^i does not necessarily equal ρ^i.

Equilibrium conditions for spatial price equilibrium:

A variable printed in boldface denotes the value of that variable at equilibrium.

1. $\boldsymbol{\rho}_j - \boldsymbol{\rho}^i - t_{ij} \le 0$ and $\mathbf{x}_{ij}(\boldsymbol{\rho}_j - \boldsymbol{\rho}^i - t_{ij}) = 0$, $\mathbf{x}_{ij} \ge 0$.
2. $\mathbf{p}_i - \boldsymbol{\rho}_i \le 0$ and $\mathbf{q}_i(\mathbf{p}_i - \boldsymbol{\rho}_i) = 0$, $\mathbf{q}_i \ge 0$.
3. $\boldsymbol{\rho}^i - \mathbf{p}^i \le 0$ and $\mathbf{q}^i(\boldsymbol{\rho}^i - \mathbf{p}^i) = 0$, $\mathbf{q}^i \ge 0$.
4. $\sum_j \mathbf{x}_{ji} - \mathbf{q}_i \ge 0$ and $\boldsymbol{\rho}_i(\sum_j \mathbf{x}_{ji} - \mathbf{q}_i) = 0$, $\boldsymbol{\rho}_i \ge 0$.
5. $\mathbf{q}^i - \sum_j \mathbf{x}_{ij} \ge 0$ and $\boldsymbol{\rho}^i(\mathbf{q}^i - \sum_j \mathbf{x}_{ij}) = 0$, $\boldsymbol{\rho}^i \ge 0$.

Model 2: A model with interactions which look like externalities but which have prices assigned to them by the model:

We start with the basic model and add the following endogenous variables for each externality to be incorporated into the model:

1. $EX_{i,j,k}$ – the quantity of the externality accruing at node k from the quantity shipped from node i to node j.
2. $R_{i,j,k}$ – the price to be assigned to $EX_{i,j,k}$.

We also need the following exogenous variables:

1. $c_{i,j,k}$ – the cost of transferring the externality from the route i,j to the node k.

We also need the following function for all nodes with positive externalities:

$F_{i,j,k}(X_{i,j})$ – this function describes the relationship between the quantity shipped from node i to node j and the quantity available to node k as an externality. It must have the property that. $F_{i,j,k}(0) = 0$ and must be continuous with continuous first derivatives and must be monotonically increasing.

The model now becomes:

1. $\boldsymbol{\rho}_j - \boldsymbol{\rho}^i - t_{ij} + \sum_k \mathbf{R}_{ijk} \frac{\partial F_{ijk}(x_{ij})}{\partial x_{ij}} \le 0$

   and $\mathbf{x}_{ij}(\boldsymbol{\rho}_j - \boldsymbol{\rho}^i - t_{ij} + \sum_k \mathbf{R}_{ijk} \frac{\partial F_{ijk}(x_{ij})}{\partial x_{ij}}) = 0, \mathbf{x}_{ij} \ge 0$.

2. $\mathbf{p}_i - \boldsymbol{\rho}_i \le 0$ and $\mathbf{q}_i(\mathbf{p}_i - \boldsymbol{\rho}_i) = 0, \mathbf{q}_i \ge 0$.

3. $\boldsymbol{\rho}^i - \mathbf{p}^i \le 0$ and $\mathbf{q}^i(\boldsymbol{\rho}^i - \mathbf{p}^i) = 0, \mathbf{q}^i \ge 0$.

4. $\sum_j \mathbf{x}_{ji} + \sum_k \sum_j \mathbf{EX}_{kji} - \mathbf{q}_i \ge 0$ and $\boldsymbol{\rho}_i(\sum_j \mathbf{x}_{ji} + \sum_k \sum_j \mathbf{EX}_{kji} - \mathbf{q}_i) = 0,\ \boldsymbol{\rho}_i \ge 0$.

5. $\mathbf{q}^i - \sum_j \mathbf{x}_{ij} - \sum_j \sum_k \mathbf{EX}_{ijk} \ge 0$ and $\boldsymbol{\rho}^i(\mathbf{q}^i - \sum_j \mathbf{x}_{ij} - \sum_j \sum_k \mathbf{EX}_{ijk}) = 0, \boldsymbol{\rho}^i \ge 0$.

6. $\boldsymbol{\rho}_k - \boldsymbol{\rho}^i - c_{ijk} - \mathbf{R}_{ijk} \le 0$ and $\mathbf{EX}_{ijk}(\boldsymbol{\rho}_k - \boldsymbol{\rho}^i - c_{ijk} - \mathbf{R}_{ijk}) = 0,\ \mathbf{EX}_{ijk} \ge 0$.

7. $\mathbf{F}_{ijk}(\mathbf{x}_{ij}) - \mathbf{EX}_{ijk} \ge 0$ and $\mathbf{R}_{ijk}(\mathbf{F}_{ijk}(\mathbf{x}_{ij}) - \mathbf{EX}_{ijk}) = 0, \mathbf{R}_{ijk} \ge 0$.

In order to make EX into a true externality, we must remove any price attached to the quantity. We do that by removing equation 6 from the model described above and changing equation 7 from a complementary slackness equation into equality.

Model 3: a model with true externalities.

1. $\boldsymbol{\rho}_j - \boldsymbol{\rho}^i - t_{ij} + \sum_k c_{ijk} \frac{\partial F_{ijk}(x_{ij})}{\partial x_{ij}} \le 0$

   and $\mathbf{x}_{ij}(\boldsymbol{\rho}_j - \boldsymbol{\rho}^i - t_{ij} + \sum_k c_{ijk} \frac{\partial F_{ijk}(x_{ij})}{\partial x_{ij}}) = 0, \mathbf{x}_{ij} \ge 0$.

2. $\mathbf{p}_i - \boldsymbol{\rho}_i \le 0$ and $\mathbf{q}_i(\mathbf{p}_i - \boldsymbol{\rho}_i) = 0, \mathbf{q}_i \ge 0$.

3. $\boldsymbol{\rho}^i - \mathbf{p}^i \le 0$ and $\mathbf{q}^i(\boldsymbol{\rho}^i - \mathbf{p}^i) = 0, \mathbf{q}^i \ge 0$.

4. $\sum_j \mathbf{x}_{ji} + \sum_k \sum_j \mathbf{EX}_{kji} - \mathbf{q}_i \ge 0$ and $\boldsymbol{\rho}_i(\sum_j \mathbf{x}_{ji} + \sum_k \sum_j \mathbf{EX}_{kji} - \mathbf{q}_i) = 0,\ \boldsymbol{\rho}_i \ge 0$.

5. $\mathbf{q}^i - \sum_j \mathbf{x}_{ij} - \sum_j \sum_k \mathbf{EX}_{ijk} \ge 0$ and $\boldsymbol{\rho}^i(\mathbf{q}^i - \sum_j \mathbf{x}_{ij} - \sum_j \sum_k \mathbf{EX}_{ijk}) = 0, \boldsymbol{\rho}^i \ge 0$.

6. $\mathbf{F}_{ijk}(\mathbf{x}_{ij}) - \mathbf{EX}_{ijk} = 0$

Notice that the six equilibrium conditions do not correspond to the Kuhn-Tucker conditions of an optimization problem. No net social payoff function is constructed and it is not possible to determine the total social welfare of the system. Total consumer surplus in particular cannot be calculated although it may be possible, although not necessary, to determine the net benefits of trade in terms of change in consumer and producer surplus.

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Appendix B – IDEP Demand Function Calculator

(Irrigation Demand from Evapotranspiration Production Functions)

Bryce Contor

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:

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

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:

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

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

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

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

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

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:

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

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:

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

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:

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

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:

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

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:

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

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

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:

$$ET_d = \left(\frac{Y_d}{Y_m}\right) ET_m \qquad (11)$$

$$B = \frac{(ET_m - ET_d)}{I_m} \qquad (12)$$

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

$$K = {}^{1}/_{I_m}$$ no italics (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

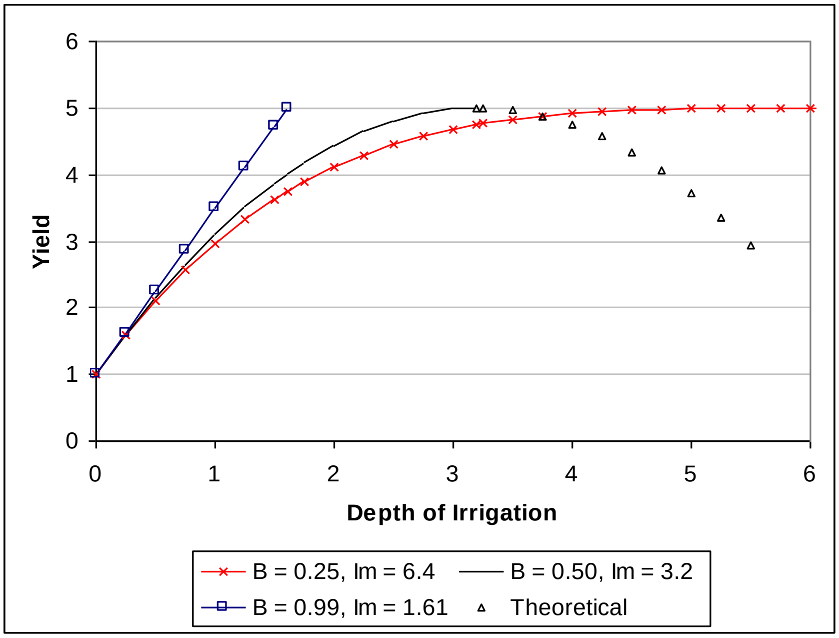

Figure 1. Yield/Irrigation relationship from production function equation.

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.

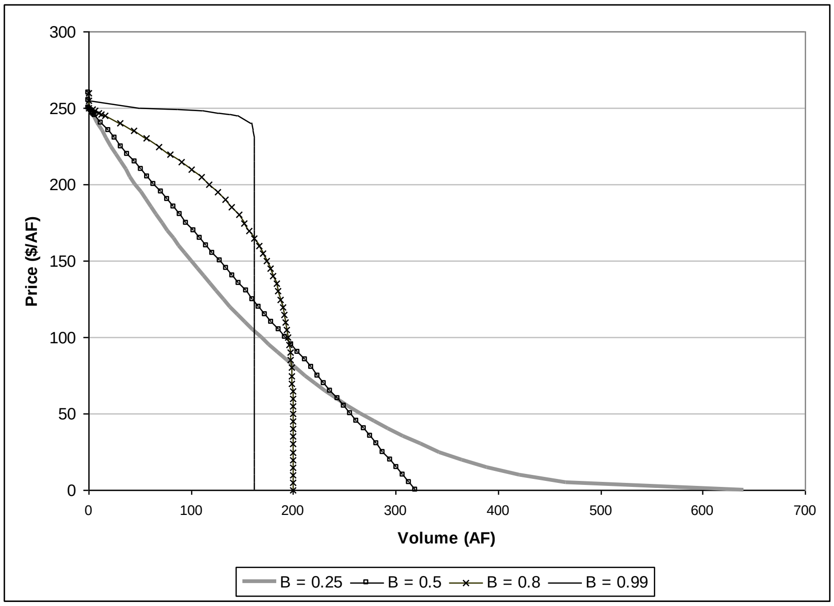

Figure 2. Demand for irrigation water at different values of B.

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.

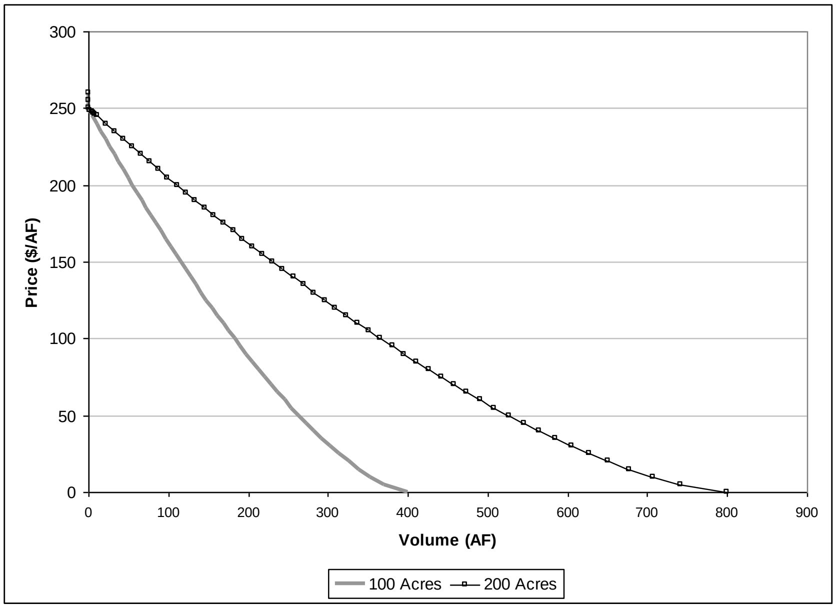

Figure 3. Demand curves for identical crops on different size parcels.

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.

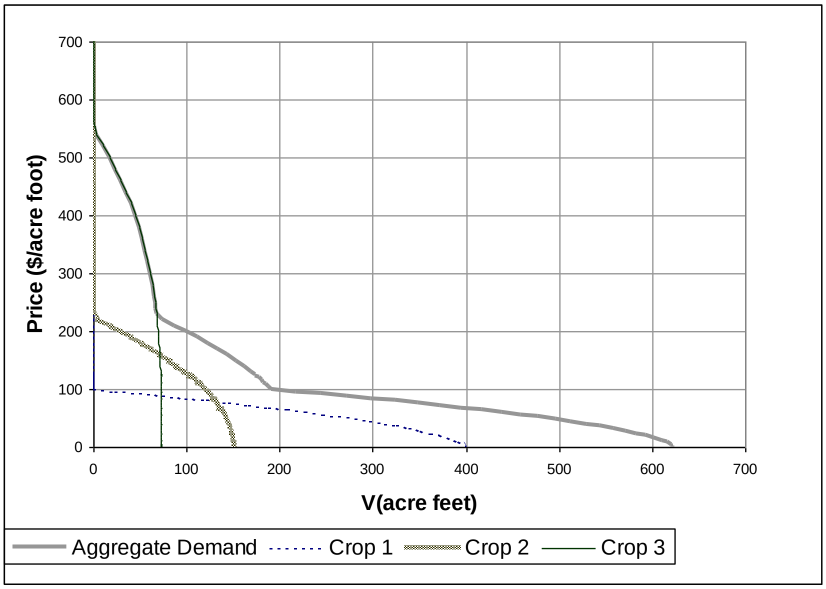

Figure 4. Aggregate demand by horizontal summation.

DERIVATION OF EQUATIONS WITH INDEPENDENT VARIABLES

Equation (6) from above is repeated:

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

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:

$$Y_m = K_1 \, ET_m \tag{15}$$
$$Y_d = K_1 \, ET_d \tag{16}$$

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:

$$ET_d = Re \tag{17}$$
$$Y_d = K_1 \, Re \tag{18}$$

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:

$$I_m = a(ET_m - Re) \tag{19}$$

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):

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

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):

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

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

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

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

Appendix C - Average versus Marginal Demand Price for Agricultural Water Users

RG Taylor

Residential water demand is often specified with the marginal price observed from a rate schedule (Howe 1998). Despite theory and empirical evidence, average price has been championed, in both early (Foster and Beattie 1981a) and recent research (Neiswiadomy and Cobb 1993; Michelsen, McGuckin, and Stumpf 1999), as the behaviorally relevant price perceived by consumers (Howe 1998). Espey et al. (1997) conducted a meta-analysis on 124 observations on the price elasticity of residential water demand. They found that the use of average price in place of marginal price resulted in higher price elasticities. If price elasticity estimates differ systematically when average price is used in place of marginal price then different methodological and policy implications ensue.

Marginal price specification in demand can be empirically equivalent to average price in two cases: (1) when firms are competitive price takers, average price equals marginal price (Edmonds 1977) and; (2) when the data result from a single equation demand function which is double log, price elasticity's are invariant to marginal or average price specification (Halvorsen 1975).

As opposed to the equivalency argument in the two cases above, average price has been specified in water demand based on the assumption that consumers perceive price to be average price. Foster and Beattie (1981b) submit that the fixed charge is perceived as a marginal cost:
"...consumers view their choices in the fixed charge block not as a fixed cost (minimum charge) with associated zero-marginal cost for some range of water used, but as a variable cost associated with the desired level of consumption in the first block. Thus, a positive "marginal cost" is perceived in this block. If so perceived, marginal and average cost would be the same for the amount consumed ..." (pages 258-259)

Average price replaces marginal price so that the demand function becomes:

$$W = f\left(P_{Avg}, P_x, M\right) \qquad [1]$$

where, P_{Avg} is computed as a utility's average revenue (total revenue divided by total water sales). The perception argument justifies average price because consumers are alleged to ignore the details of the rate schedule when water represents a small portion of their expenditures (Foster and Beattie 1981b). At issue in the marginal price versus average revenue specification is the consumer's knowledge and decision mechanism. Utility bills inform customers of total expense and in many instances marginal price. Whether, on a widespread basis, consumers convert billing information to an average price to judge cost of water consumption is an empirical question. Except for the special cases described earlier, average revenue is not marginal price but average revenue could be a proxy or measure upon which water consumption decisions are mistakenly based.

Specification of average price in demand poses serious estimation difficulties when utilities charge a constant monthly fee sometimes in combination with either flat or block rates. Taylor's (1975) study hinted at the average price specification problem:

"Also, there is the problem that when average price is defined ex post as the ratio of total expenditures to quantity consumed, as is the usual procedure, a negative dependence between quantity and price is established that reflects nothing more than arithmetic." (p. 78).

Consider the customer bill derived from a rate schedule that includes a fixed charge coupled with a generic variable water rate;

$$TR_{it} = K_i + R(W_{it}), \qquad [2]$$

where, TR is total receipts, K is revenue derived from a monthly fee fixed by each water utility, and R(W) is revenue derived from the variable portion of the rate schedule; indexed over utilities (i), and time periods over which revenues are collected (t). By definition, the fixed fee charged by the i^th^ utility is fixed over all quantities consumed. Average price based on average revenue is thus;

$$P_{Avg_{it}} = \frac{TR_{it}}{W_{it}} = \frac{K_i}{W_{it}} + \frac{R(W_{it})}{W_{it}} \qquad [3]$$

Equation (3) shows that average revenue is composed of average fixed revenue and average variable revenue components when fixed fees are included in the utility rate schedule. The average revenue definition of the price is substituted into the demand function (equation 1). However, for utilities charging only a fixed fee, the average variable revenue in equation (3) equals zero, and the demand function as shown in (4) becomes an identity with W_{it} on both sides of the equation:

$$W_{it} = f\left(P_{Avg_{it}}, P_x, M\right) = f\left(\frac{K_i}{W_{it}}, P_x, M\right) \qquad [4]$$

When the only charge is a fixed fee, the price quantity relationship is average fixed revenue, which is a rectangular hyperbola with unitary price elasticity. Taylor's "arithmetic" is thus an identity. A perfect fit ($R^2 = 1$) results when this identity is "properly" estimated. For example, assume a linear demand model is estimated for equation (4), $W = b_0 + b_1\left(\frac{K}{W}\right) + b_2 P_x + b_3 M$. If ordinary least squares (OLS) was capable of returning the identity the estimated coefficients would be: $b_0 = 0$, $b_2 = 0$, $b_3 = 0$, and $b_1 = -\frac{W^2}{K}$.

Price elasticity is defined as $E_p = \left(\frac{\partial W}{\partial P}\right)\left(\frac{P}{W}\right) and \frac{\partial W}{\partial P} = b_1 = -\frac{W^2}{K}$, when price is average fixed revenue. Thus, price elasticity is $E_p = -\left(\frac{W^2}{K}\right)\left(\frac{P}{W}\right) = -\frac{WP}{K}$, but both WP and K are total revenue and therefore price elasticity must always be minus one. The embedded identity is easily detected by OLS for a double log demand function. The double log demand equation is shown in (5) where for ease of illustration the nuisance parameters (other prices and income) are omitted:

$$W_{it} = \beta_1 \left[\frac{K_i}{W_{it}} + \frac{R(W_{it})}{W_{it}}\right]^{\beta_2} \qquad [5]$$

For the i^{th} utility, charging only a fixed fee (i.e., average variable revenue = $R(W_{it}) = 0$), the observed time series of price-quantity data again is a rectangular hyperbola. The estimated price elasticity (β_2) will equal minus one and β_1 will equal a constant k representing the fixed fee. If all utilities choose the same value for their fixed fee then the fit of quantity demanded on average price will be perfect and no other explanatory variables should enter the regression. If the value of the fixed fee varies across utilities then there is a set of rectangular hyperbolas whose distance from the origin varies with the magnitude of the fixed charge. (If variations in the fixed charge across the utilities could be explained, data would again fall on a single rectangular hyperbola.) The presence of variation in the fixed fee across utilities or over time may tend to obscure the existence of the embedded identity.

The crux of the argument is that when average fixed revenue (fixed fee) is high, relative to the average variable revenue portion of the rate structure, the change in total revenue over time, will be nearly invariant to water consumption. Thus, the effect of a rate schedule that is dominated by the fixed fee is to dampen any price effects on quantity demanded. When the variance of K_i is small relative to W_{it}, the major source of variation in the average price data originates from variation in water usage, W_{it}. Thus, as average variable revenue tends to zero, estimated demand tends to a unitary elasticity identity and measures of fit will increase and price elasticity will approach minus one.

Short run substitutes for water are virtually nonexistent. Our data are cross sectional and thus portray long run consumer water consumption decisions. Expensive water-saving appliances, irrigation systems, and landscaping are long-run substitutes for water. Utility bills are notoriously vague in detailing water costs and usage. Yet, knowledge of total water costs at different points on the rate schedule and projections of costs over time is essential in making capital investment decisions. Be it from their own experience, talking with neighbors, or contacting the utility, consumers do make long run adjustments to increasing water costs.