Economic Implications of Winter-run Chinook Salmon Conservation through Water Management in the Southern Delta

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Abstract

Recent legal restrictions on water exports in the Southern Delta to protect listed fish populations have brought public attention to the trade-off relationship between fish conservation and agricultural economy. The restrictions may result in losses of agricultural returns in the Central Valley. This paper aims to examine the economic costs of conserving the endangered Winter-run Chinook salmon for two water year assumptions: one without environmental correlations and the other with the environmental correlations. The combination of a modified statewide agricultural production model and a multistage Winter-run Chinook salmon model allows me to assess the economic costs per age 3 and 4 adult for two cases. The estimated costs range from $1,304 to $114,966 for the first case and from $864 to $721,120 for the second case. They generally increase at an increasing rate as the pumping cuts back from 10% to 100%. The consideration of environmental correlations does not change the order of cost estimates: critical, dry, wet, above normal, and below normal. The results provide policy-makers with economic data on the tradeoffs in water management for the Southern Delta. One important factor in determining the agricultural losses is a climatic condition and the corresponding dependency of the farms on water exports.

Keywords: Statewide Agricultural Production Model; Multistage Winter-run Chinook Salmon Population Model; Water Export; Economic Cost; Ecological Benefit; Trade-off; Water Management

About 70 percent of people in California use water from the Sacramento-San Joaquin Delta as drinking water and approximately four-fifths of the water exports from the Delta are used for agriculture and the rest for urban areas in California (USGS 2000). Furthermore, the Delta provides the habitat for a wide variety of species. Recently, several species in the Delta have been listed under the Federal and State Endangered Species Act. Public attention has been focused on the operation of Central Valley Project and State Water Project pumping plants in the Southern Delta, which is one of the potential factors that affect these species. A significant decline in delta smelt population caused Federal Judge Oliver Wanger to impose legal restrictions on both pumping plants (Wanger, 2007). Another restriction followed in order to protect the listed Winter-run and Spring-run Chinook salmon and Steelhead (Wanger, 2008). Due to water supply shortages by these decisions, the Central Valley farmers and urban water users are suffering economic losses, resulting in the potential trade-off relationship between fish conservation and agricultural production.

This controversial trade-off relationship raises several research questions. 1) What are the economic costs of water export reductions in terms of the foregone agricultural returns to the Central Valley? 2) What are the ecological benefits of water export reductions on the listed species? 3) What are the economic costs to increase the listed species? For simplicity and clarity, I limit the focus of this study in several ways. The economic cost analysis focuses on the losses of agricultural returns to the Central Valley by excluding the economic losses to urban water users. The ecological benefit analysis focuses on the Winter-run Chinook salmon, which was listed as threatened under the Endangered Species Act (ESA) in 1989, changed to be endangered in 1994 and became a significant object of conservation (USFWS 2009)[1]. Despite a variety of

[1] The Winter-run Chinook salmon is the number one ranked listed species in terms of the Federal conservation expenditures in 2011, which is $80,004,247 (USFWS 2011).

potential water export reduction scenarios, I consider only two uncertain features of water exports: weather conditions and corresponding environmental correlations. Environmental correlations are defined as correlations among the environmental factors including water export, river temperature, salinity, and flow over the water years. Two cases of water export reduction scenarios are therefore used for these analyses: one without environmental correlations and the other with environmental correlations. The first case has 10% steps of water export reduction scenarios for five water years and the second case has only five water years.

To answer the above research questions, I combine a number of different model components. First of all, I modify a statewide agricultural production model (SWAP) that has applied a positive mathematical programming (PMP) to agricultural and environmental policy issues for several decades. Using a modified SWAP along with the base year economic data, the losses of agricultural returns in the Central Valley are calculated under different water export scenarios. Second, I develop the multi-stage Winter-run Chinook population model over its life cycles by incorporating the environmental impacts[2] during the juvenile stage into existing fish population models. Using the historical abundance and environmental data sets, the environmental impacts and the survival rates are estimated under the same water export scenarios. These estimated parameters are used to estimate salmon population increases. The combination of both economic and ecological models permits an assessment of the opportunity cost of conserving Winter-run salmon under different pumping scenarios in terms of the foregone agricultural returns[3]. The results of this study will provide policy-makers with guidance on the opportunity costs of

[2] The environmental impacts include the effects of water export, river temperature, flow, and salinity on juvenile Winter-run Chinook salmon. They will be described in detail in Section 3.
[3] This paper uses the agricultural returns (gross revenues minus variable costs) in the calculation of economic costs instead of the agricultural profits since fixed costs are excluded.

managing water in the Southern Delta under uncertain weather conditions in order to meet two conflicting objectives: robust Winter-run Chinook salmon and a reliable water supply.

The remaining paper is organized as follows. The framework of economic cost analysis in the Central valley is illustrated in the first section. The second section discusses the framework of ecological benefit analysis on the Winter-run Chinook salmon. The third section then presents the results on economic costs, ecological benefits, and economic costs per age 3 and 4 adult salmon for two cases. Final section has conclusions and caveats.

Economic Cost Analysis Framework

In order to calculate the economic costs of water export reductions in the Southern Delta, I modify an existing SWAP model by changing the amount of water supply under different water export scenarios. A SWAP model follows four stages of PMP calibration procedures (Howitt, 1995a, 1995b; Howitt et al, 2001, 2010). The first stage sets up a linear programming that maximizes total agricultural returns subject to resource and calibration constraints with base year average data. In the second stage, parameters of non-linear production and land cost functions are calibrated using data, optimal solutions, and shadow prices from the first stage. The third stage specifies a non-linear programming using data and the calibrated functions from the second stage. The fourth stage uses the calibrated non-linear programming model from the third stage for various environmental and agricultural policy analyses (Howitt et al, 2009a, 2009b, 2009c; Lund et al, 2007, 2008). The following subsections highlight the mathematical structures of a SWAP model.

Linear Programming

The first step of a SWAP maximizes the farm returns subject to resource constraints and calibration constraints over g regions, i crop groups, and j inputs in a linear programming (LP) framework. The LP is mathematically defined as:

$$\text{Max}_{x_{g,i,1}} \sum_g \sum_i \{v_{g,i}\bar{y}_{g,i} - \sum_j c_{g,i,j} a_{g,i,j}\} x_{g,i,1} \quad (1)$$

$$\text{s. t. } \sum_i a_{g,i,1} x_{g,i,1} \leq b_{g,1} \ \forall g \quad (2)$$

$$\sum_i a_{g,i,2} x_{g,i,1} \leq b_{g,2} \ \forall g \quad (3)$$

$$x_{g,i,1} \leq \tilde{x}_{g,i,1} + \epsilon u \ \ \forall \ g,i \quad (4)$$

$$\tilde{x}_{g,i,1} - \epsilon l \leq \ x_{g,i,1} \ \forall \ g,i \quad (5)$$

where $v_{g,i}$ is a regional crop price per ton, $\bar{y}_{g,i}$ is an average yield per acre in ton, $c_{g,i,j}$ is an average input cost per unit, $\tilde{x}_{g,i,j}$ is a realized input use, $a_{g,i,j}$ is a normalized input use per acre ($a_{g,i,j} = \tilde{x}_{g,i,j}/\tilde{x}_{g,i,1}$), $x_{g,i,1}$ is a decision variable for land use, $b_{g,j}$ is an input supply, ϵu and ϵl are respectively small disturbances of upper bound and lower bound constraints.

Resource constraints in Equation 2 and 3 have their own shadow prices, respectively $\lambda_{r,g,1}$ and $\lambda_{r,g,2}$. The shadow prices are the imputed marginal agricultural costs of restraining one unit of resource supply. The LP needs to include upper bound calibration constraints in Equation 4 in order to prevent it from having degenerate solutions and to approximate data on land use (Howitt, 1995a). This paper, however, adds the lower bound calibration constraints in Equation 5 in order to accurately calibrate 37 cases of negative returns with positive land uses. In these cases, farmers do not rationally grow crops from a short-run economic perspective but data show that they are still observed doing so[4].

Data Description and LP implementation

A recent SWAP model (Howitt et al, 2010) expands an original 21 region Central Valley Production Model (Howitt et al, 2001) by adding 10 more regions. The SWAP defines California crops into 20 groups using a representative crop for each group consistent with DWR land use survey data.[5] The crop prices and yields are obtained by calculating their weighted averages for the SWAP regions since data on crop prices and yields from the U.S. Department of Agriculture in 2005 are based on the Detailed Analysis Unit and the California County Agricultural Commissioner's reports. Input costs are collected from the regional cost and return studies of the UC Davis Extension Crop Budgets in 2005 dollars to be consistent with data on input uses for land, labor, water, and fertilizers. Regional water supplies are separated into six sources: five sources of surface water and ground water (GW). The surface water is categorized into five sources: three types of Central Valley Project delivery[6], a State Water Project water delivery (SWP), and local surface water delivery (LOC). Data on six sources of water are obtained from the DWR water use data. Regional crop acreages are obtained from the 2005 DWR Data. The base year data are adjusted for practical and economic reasons in several ways. Crop prices per ton and crop yields per acre are adjusted to match total output value agricultural commissioners' report. Land costs are averaged over the regions and crops for eight years (2003-2010). Average water costs are calculated by multiplying the price of water over the regions and six water

[4] There may be different reasons for farmers to produce crops with negative returns, for example, rotational benefits to land. This paper, however, does not consider different objectives of the farmers to simplify the analyses.

[5] For more details on the SWAP regions and crop groups, refer to Howitt et al (2010).

[6] The Central Valley Project delivery includes the water service contracts both from Friant Class 1(CVP1) and Friant Class 2 (CL2) and water rights settlement and exchange delivery (CVPS).

sources by regional water proportion. In cases of no land use, I set prices, yields and costs equal to zero so that optimal land uses is zero in these cases.

Using the base year data, I derive optimal land uses ($x^*_{g,i,1}$) and the shadow prices ($\lambda^*_{r,g,1}$, $\lambda^*_{r,g,2}$, $\lambda^*_{u,g,i}$, and $\lambda^*_{l,g,i}$) of each constraint from the LP in Section 2.1[7]. Since all of the optimal land uses are within the range between -1% and 1% in the deviations from realized land uses, the derived optimal land uses and the shadow prices can be used in the calibration of production and cost functions.

Parameter Calibration

Before proceeding with the parameter calibration procedures, the form of the production function and PMP land cost function has to be decided. Different forms of the production and cost function have been used in the literature[8]. This paper uses a constant elasticity of substitution (CES) production function that allows a potential resource substitution under different water export scenarios[9] and nests Leontief and Cobb-Douglas production functions and an exponential land cost function that provides reasonable marginal costs in any production level.

Howitt (1995a) describes the parameter calibration procedure of CES production function with one crop and three inputs. This procedure is applied to the case of 20 crops, 37 regions, four inputs, and lower bound calibration constraints in this paper. A four-input CES production function over 37 regions and 20 crop groups is defined as:

$$y_{g,i} = \alpha_{g,i}\left[\sum_j \beta_{g,i,j} x^{\rho}_{g,i,j}\right]^{1/\rho} \tag{6}$$

[7] This paper sets ϵl at 0.01 and ϵu at 0.000001 after several trials since at those values, the number of binding calibration constraints (511) is equal to the total number of calibration constraints (703) minus the number of zero land use solutions (192).

[8] In the literature, the Leontief, Cobb-Douglas, CES, and quadratic function have been used for a production function whereas the linear, Leontief, quadratic, weighted-entropy, and exponential function for a land cost function.

[9] If water export is reduced, farmers may substitute it for different inputs such as labor, land, and fertilizer. CES production function in a SWAP can incorporate this substitution effect.

where $\alpha_{g,i}$ is a scale parameter, $\beta_{g,i,j}$ is a share parameter ($\sum_j \beta_{g,i,j} = 1$), σ is the elasticity of substitution, and $\rho = (\sigma - 1)/\sigma$.

This production function has g*i*j unknown parameters to calibrate: g*i*(j-1) share parameters and g*i scale parameters. The first order optimization conditions (FOCs) of all inputs set the value marginal product of each input equal to its opportunity cost, which is its cash cost plus shadow price. After several manipulations, the share parameters are sequentially calibrated in terms of input cost ratios and input use ratios:

$$\beta_{g,i,1} = \frac{1}{1+\sum_{j=2}^{4}\left(\frac{\omega_{g,i,j}}{\omega_{g,i,1}}\right)\left(\frac{x^*_{g,i,1}}{x^*_{g,i,j}}\right)^{-1/\sigma}} \tag{7}$$

$$\beta_{g,i,2} = \beta_{g,i,1}\left(\frac{\omega_{g,i,2}}{\omega_{g,i,1}}\right)\left(\frac{x^*_{g,i,1}}{x^*_{g,i,2}}\right)^{-1/\sigma} \tag{8}$$

$$\beta_{g,i,3} = \beta_{g,i,1}\left(\frac{\omega_{g,i,3}}{\omega_{g,i,1}}\right)\left(\frac{x^*_{g,i,1}}{x^*_{g,i,3}}\right)^{-1/\sigma} \tag{9}$$

$$\beta_{g,i,4} = \beta_{g,i,1}\left(\frac{\omega_{g,i,4}}{\omega_{g,i,1}}\right)\left(\frac{x^*_{g,i,1}}{x^*_{g,i,4}}\right)^{-1/\sigma} \tag{10}$$

where $\omega_{g,i,j}$ is an opportunity cost in region g, crop i, and input j.

Using data on yield per acre ($\bar{y}_{g,i}$) and land use ($\bar{x}_{g,i,1}$), calibrated share parameters ($\beta_{g,i,j}$), and LP optimal inputs ($x^*_{g,i,j}$), scale parameters ($\alpha_{g,i}$) are then calibrated as[10]:

$$\alpha_{g,i} = \frac{\bar{y}_{g,i}\bar{x}_{g,i,1}}{[\sum_{j=1}^{4}\beta_{g,i,j}x^{*\rho}_{g,i,j}]^{1/\rho}} \tag{11}$$

The percentage differences between value marginal products and marginal opportunity costs are calculated to check whether the calibrated production function closely replicates the optimality

[10] This paper assumes that σ is assumed to be fixed at 0.22 (Howitt et al, 2010). For the complete descriptions on the CES production parameter calibration procedures, refer to the appendix of Howitt (1995a).

criteria. Because all of the percentage differences range between -1% and 1%, all of the calibrated share and scale parameters can be used for later water policy scenario analyses.

An exponential land cost function has two advantages over a quadratic land cost function more often used in the literature (Howitt et al, 2011). A quadratic cost function can have a negative marginal cost for a low level of land use whereas an exponential cost function always has a positive marginal cost. In addition, the latter can fit a desired elasticity of supply while the former can result in an unrealistic elasticity. An exponential land cost function is defined as:

$$\boldsymbol{TC}(\boldsymbol{x}_{g,i,1}) = \boldsymbol{\delta}_{g,i}\mathbf{exp}(\boldsymbol{\gamma}_{g,i}\boldsymbol{x}_{g,i,1}) \tag{12}$$

where $\boldsymbol{\delta}_{g,i}$ and $\boldsymbol{\gamma}_{g,i}$ are respectively an intercept and an elasticity parameter.

Two conditions should be met to calibrate exponential land cost parameters. The first condition is an equality condition in which the value average product of land should be equal to the value marginal product of land by equating the FOCs of land use in a LP to the FOCs of land use in a non-linear programming (NLP). From the LP, the FOCs of land use are:

$$v_{g,i}\bar{y}_{g,i} = c_{g,i,1} + \lambda_{r,g,1} + \lambda_{u,g,i} - \lambda_{l,g,i} \;\; \forall\, g,i \tag{13}$$

The FOCs of the NLP for land use are as follows,

$$v_{g,i}\frac{\partial y_{gi}}{\partial x_{g,i,1}} = \delta_{g,i}\gamma_{g,i}e^{\gamma_{g,i}x_{g,i,1}} + \lambda_{r,g,1} \;\; \forall\, g,i \tag{14}$$

The first condition, called a PMP condition, is derived from Equations (13) and (14) as:

$$c_{g,i,1}a_{g,i,1} + \lambda_{u,g,i} - \lambda_{l,g,i} \;\; = \delta_{g,i}\gamma_{g,i}e^{\gamma_{g,i}x_{g,i,1}} \; \forall\, g,i \tag{15}$$

The second condition is found using prior information on the short run acreage supply elasticity. It is therefore called an elasticity condition. The acreage supply elasticity ($\eta_{g,i}$) is defined as:

$$\eta_{g,i} = \frac{\partial x_{g,i,1}}{\partial MC_{g,i}}\frac{p_{g,i}}{x_{g,i,1}} \tag{16}$$

where $\eta_{g,i}$ is a short run acreage supply elasticity, P is a crop price per acre, and MC is a marginal land cost.

The first term of the supply elasticity can be derived from the first derivative of marginal land cost function with respect to land use from Equation (12):

$$\frac{\partial MC}{\partial x_{g,i,1}} = \delta_{g,i}\gamma_{g,i}^{2}e^{\gamma_{g,i}x_{g,i,1}} \quad (17)$$

After inserting the reciprocal of Equation (17) into Equation (16) and replacing $P_{g,i}$ by $v_{g,i}\bar{y}_{g,i}$, the elasticity condition is derived as follows:

$$\eta_{g,i}\delta_{g,i}\gamma_{g,i}^{2}x_{g,i,1}e^{\gamma_{g,i}x_{g,i,1}} = v_{g,i}\bar{y}_{g,i} \quad (18)$$

Among two methods, a least squares estimation method (Howitt et al, 2010) and a direct method, the direct method is chosen to calibrate exponential land cost parameters because a least squares method provides greater discrepancy between the marginal land cost and its opportunity cost. After several manipulations of two conditions using the direct method, the land cost parameters are calibrated as:

$$\gamma_{g,i} = \frac{v_{g,i}\bar{y}_{g,i}}{\eta x_{g,i,1}^{*}(c_{g,i,1}a_{g,i,1}+\lambda_{u,g,i}-\lambda_{l,g,i})} \quad (19)$$

$$\delta_{g,i} = \frac{c_{g,i,1}a_{g,i,1}+\lambda_{u,g,i}-\lambda_{l,g,i}}{\gamma_{g,i}e^{\gamma_{g,i}x_{g,i,1}^{*}}} \quad (20)$$

Non-linear Programming Specification

Using the calibrated production and land cost functions in Section 2.3, the NLP is defined as:

$$\text{Max}_{x_{g,i,j}} \sum_g \sum_i \left[v_{g,i}y_{g,i} - \sum_{j=2}^{4} c_{g,i,j}x_{g,i,j} - \delta_{g,i}\exp(\gamma_{g,i}x_{g,i,1})\right] \quad (21)$$

$$\text{s. t. } \sum_i x_{g,i,j} \le b_{g,j} \quad \forall g, j = 1,3,4 \quad (22)$$

$$\sum_i x_{g,i,2} \le \sum_{ws}\sum_i \tilde{x}_{g,i,2}\frac{\tilde{x}_{g,ws}}{\sum_{ws}\tilde{x}_{g,ws}} \quad \forall g \quad (23)$$

$$x_{g,corn,1} \geq \tilde{x}_{g,corn,1} \; \forall g \qquad (24)$$

where $\tilde{x}_{g,ws}$ is data on water supply over the regions and six water sources, $\tilde{x}_{g,corn,1}$ is the regional minimum corn silage acre, and $\lambda_{silage,g,1}$ is the shadow price of silage constraint. Equation (21) is an objective function of the NLP that replaces a linear production and land cost function of the LP with the calibrated CES production and exponential land cost functions. Two more resource constraints are added for labors and supplies in Equation (22). The water resource constraint is modified to consider different sources of water supply in Equation (23). The final additional constraint in Equation (24) is a regional silage constraint for dairy herd feed, which requires corn production to meet the minimum silage requirement to feed the California dairy herd for each region. The minimum silage requirement for cows in that region is calculated by multiplying the silage acres per cow per year by the number of cows in each region. The NLP closely approximates the base year data on four resources since all of the solutions have less than 2% deviations from the data. This base NLP will be used for economic cost analyses in Section 4.

Ecological Benefit Analysis Framework

In order to examine the Winter-run population increases due to water export reductions, I develop a multi-stage Winter-run Chinook population model that incorporates the environmental impacts and its life cycle. Section 3.1 builds a theoretical model based on a conceptual model of the Winter-run life cycle. Section 3.2 then describes abundance data on juvenile and adult salmon and environmental factors that affect juveniles. Section 3.3 describes the estimation procedures on the survival rates over the life cycle and environmental impacts during juvenile stage. After the prediction of Winter-run population increases using the developed Winter-run salmon model, the model specification that results in lowest simulation errors is selected for water export scenario analyses in Section 3.4.

Multi-stage Winter-run Chinook population Model

Maturing Winter-run Chinook female adults (S_{2ft}, S_{3ft}, and S_{4ft}) return from the ocean to the Sacramento River from December to July and spawn from late April to early August (Fisher, 1994). Most of the spawning adults are 3 year old fish (67%) with a small portion of age 2 (25%) and age 4 fish (8%) (Hallock and Fisher, 1985). Eggs reside in the gravel between April and May (Hendrix, 2008). Between July and October eggs emerge as fry and migrate down past RBDD from August to October (Fisher, 1994; Poytress and Carrillo, 2010). The fry grow to be juveniles (J_t) as they migrate down to the ocean through the lower Sacramento River and Delta from October to May (Fisher, 1994; Hendrix, 2008). The juveniles migrate through Knight's Landing during December, through the lower Sacramento River between December and March, and through the Central Delta from March to May (Hedgecock, 2002). The immature juveniles survive to the second year in the ocean and return to the freshwater as age 2 mature adults (S_{2mt+2} and S_{2ft+2}) or stay in the ocean one more year (O_{2mt+2} and O_{2ft+2}) to return as three year old adults (S_{3mt+3} and S_{3ft+3}). Some age 3 adults stay in the ocean (O_{3mt+3} and O_{3ft+3}) to become age 4 returning adults (S_{4mt+4} and S_{4ft+4}). The returning adults enter into the San Francisco Bay starting in November (Hendrix 2008). This paper focuses on environmental factors ($X'\gamma$) during juvenile outmigration period in the Delta under the assumption that there are no major environmental impacts from other stages[11]. In measuring the effects of water exports only the juvenile stage is used since data on some of the environmental factors for other stages

[11] This assumption is unlikely because environmental factors of other stages may also have significant effects on the Winter-run Chinook salmon population. Other major environmental factors include hatchery fish releases at Coleman and Livingston Stone Hatchery (Hendrix, 2008), the water temperature during incubation (Cramer et al, 2004; NMFS, 1997), Delta Cross Channel gate position (Hendrix, 2008; Newman and Rice, 2002; Newman, 2003), ocean commercial and recreational catch and recreational sport fishery in the freshwater (Cramer et al, 2004; Grover et al, 2004). Especially, I do not include the harvest rate due to the endangered status of the Winter-run and the corresponding stricter harvest regulations.

are unobtainable at this point. The factors that affect juveniles are Sacramento River flow, water export, river temperature, and salinity.

Founded upon the conceptual framework of Winter-run Chinook salmon life history along with environmental factors in Figure 1, I develop the multi-stage Winter-run Chinook population model in Table 1. The highlights of the theoretical model are to incorporate the environmental impacts on juvenile Winter-run salmon in a logistic function (Hendrix, 2008; Newman, 2003)[12] and to use different models throughout life stages in order to consider model uncertainty in the estimation of survival rates. I calculate the total number of eggs by summing the product of the number of eggs and the number of adult females over age 2, 3, and 4. In order to consider model uncertainty and density-dependence, all of the Winter-run life stages are assumed to have three different models: a linear model and two non-linear stock recruitment (Beverton-Holt and Ricker) models[13]. Using three models and abundance data in the following sections, I estimate the survival rates to test the empirical relationship. In order to analyze the impact of water export reductions on the Winter-run population, the survival rate from juveniles to age 2 adult is assumed to be a logistic function of environmental factors.

Data Description

To estimate the survival rates of the Winter-run Chinook salmon in each stage and the environmental impacts on the juveniles, it is necessary to collect abundance data on juveniles and age 2, 3, and 4 adults and data on environmental factors. Juveniles have been monitored by the United States Fish and Wildlife Service (USFWS) at the Red Bluff Diversion Dam (RBDD) since 1994 using rotary-screw traps. The rotary-screw traps sample the juveniles 24 hours daily.

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[12] Neman and Lindley (2006) use a complex Bayesian hierarchical modeling framework to consider environmental impacts and parameter uncertainty.

[13] Newman et al (2006) and Newman and Lindley (2006) assume only a Beverton-Holt model for the stage from eggs to juveniles and a linear model for later stages. This study also adds more years (2005-2007) to the model years of their studies (1996-2004).

A Fry-equivalent Juvenile Production Index (JPI) is calculated using these rotary-screw trap data. The JPI can be used as the recruitment data for the first stage and is used as the stock for the later stages[14]. There are two sources of adult salmon data: the Winter-run Chinook salmon carcass survey and RBDD ladder count[15]. I selected the carcass survey data to calculate a female spawning stock for each age due to the more detailed information on gender. The Winter-run Chinook salmon carcass survey has been jointly conducted by the California Department of Fish and Game (CDFG) and the USFWS from late April to early September since 1996[16]. Data on both juveniles and adults in Figure 2 show that after listing as an endangered species in 1994, the winter-run population significantly increased for a while, probably due to conservation efforts, but recently it has regressed to the level shown before the listing. This trend brought my attention to factors that may have caused a recent reduction in the Winter-run population, one of which is the level of water exports, a potential factor connected with an agricultural economy in California.

Environmental factors that affect the survival rate from juvenile to age 2 adults in the Delta include Sacramento River flow, SWP and CVP water exports, river temperature, and salinity. The Sacramento River flow is measured at Freeport in cfs, which is 75 km from Sacramento-San Joaquin confluence. Water export is measured in cfs at the State Water Project and Central Valley Project pumping plants. X2, which is an estimated distance in km from Golden Gate to the place of a salinity level of 2ppt, is used as a proxy variable for salinity[17]. Water temperatures have been monitored in different locations and times throughout the Sacramento River. To match

[14] For more details on JPI, refer to Poytress and Carrillo (2010).
[15] For more details on RBDD ladder counts, refer to annual reports by the Red Bluff Sacramento River Salmon and Steelhead Assessment Project (SRSSAP) (Killam, 2004-2007, 2009).
[16] The detailed descriptions on the survey location are in Killam (2006) and on different methods of estimating the Winter-run escapement are in Snider et al (2000).
[17] Data on flow, water export, and X2 are from the Environmental Planning and Information Branch Dayflow Program at the Department of Water Resources (http://www.water.ca.gov/dayflow).

with the time frame of other environmental factors, I choose to use water temperatures at RBDD[18]. Since juveniles pass through RBDD from August to November and reach Knight's Landing close to the pumping plants from November to March (Cramer et al, 2004)[19], data on Flow, CVP, SWP, and X2 are annualized by averaging them on a daily basis during that period. Data on water temperature at RBDD is averaged daily from August to November during 1996-2007. Hydrological data on flow, water exports, and X2 are correlated with each other and to the weather conditions. For instance, during wet years, river flow is at a higher level, CVP and SWP water exports are at a lower level, and X2 is at a closer distance from the Golden Gate than during dry or critical years, because the Central Valley farmers are more likely to meet their water demand from other sources during wet years than during dry years. Flow and X2 have a high negative correlation (-0.9766) since the greater the river flow, the lower the salinity. The second highly correlated variables are CVP and SWP (0.6828) since both pumping plants are operated in a similar manner depending on weather conditions and hydrological conditions. The correlation among all other factors is lower than 0.5 in an absolute value. These environmental correlations are considered in the second case of water export scenarios.

Estimation Procedures over the Life Stages

Using data collected in Section 3.2 and three different models, all the survival rates over the life stages and the environmental impacts during juvenile outmigration stage are estimated to examine the relationships among life stages. Three different relationships are assumed among all life stages: linear and stock-recruitment relationship (Beverton-Holt and Ricker).

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[18] Data on water temperature are from the Sacramento River Temperature Report by Central Valley Operations Office of Bureau of Reclamation at the Department of Interior (http://www.usbr.gov/mp/cvo/temp.html).

[19] Cramer et al (2004) show the mean length and the timing of juvenile passage in four sampling stations in the Sacramento River in Figure 18(p 36) from data on 1998 and 1999 brood year Winter Chinook Juveniles.

The total number of eggs is calculated by summing the number of eggs that age 2, 3 and 4 females spawn over ages. The most recent average number of eggs is 3,205 for age 2 females ($\bar{E}_2$) and 6,304 for age 3 and 4 females ($\bar{E}_{3,4}$) (Newman and Lindley, 2006). Abundance data on female adults at each age and the number of eggs cover the same period from 1996 to 2010.

For the stage from eggs to juveniles, a linear model and two density dependence models are assumed to check the empirical relationship between eggs and juveniles. Since I have only 10 observations due to unavailability of juvenile data for two years (2000 and 2001), I calculate 95% confidence intervals for each parameter. All of three models are chosen for the simulation analyses because the estimated survival parameters from all of the models are statistically significant (Table 2).

This stage is the most important stage of this paper since it is the stage that is influenced by both SWP and CVP pumping plants along with other environmental factors. In the literature, however, researchers have estimated the survival rates mostly for the Fall-run Chinook, not for the Winter-run Chinook (Kjelson et al, 1989; Newman, 2003; Newman and Rice, 2002). I therefore, start out with estimating the survival rates of the juvenile Winter-run using data on environmental factors and abundance through the ordinary least square method[20]. This method however does not provide the expected negative water export impact. I then use two alternative methods: 1) use the prior estimates of all the environmental impacts of Newman (2003) 2) use only prior water export impact from Newman(2003) to estimate other environmental impacts using a Monte Carlo simulation method, therefore called two-stage Monte-Carlo method[21]. Since Newman (2003)

[20] After estimating three models (a linear, Beverton-Holt, and Ricker) without environmental factors in order to check the true relationship between juveniles and age 2 adults, I adopt a linear model that only provides the significant survival rates from juvenile to age 2 adult. A linear model, therefore, is used for the estimation of the environmental impacts.

[21] Both methods assume that the environmental impacts on the Fall-run are applicable to the Winter-run as in Cramer et al (2004) and Cramer Fish Sciences (2008).

contains the estimation results of the first method in more detail, here I only describe the second method. A new dependent variable is generated by subtracting the prior water export impact from log transformation of juvenile survival rate. The impacts of other environmental factors (logflow, x2, and river temperature) are estimated by regressing of the new dependent variable on the explanatory factors. Since the prior water export impact estimate is normally distributed with mean -0.32 and standard deviation 0.09, a new dependent variable is assumed to be equal to $y^* = \log(\varphi_{2t}/1 - \varphi_{2t}) + \beta_{export} * export$, where export is a standardized variable for water export and $\beta_{export} \sim N(-0.32, 0.09^2)$. Using a Monte Carlo simulation method, thousands of β_{export} values are generated from a normal distribution of original water export impact. To obtain 10,000 values of y* (10 years times 1000 simulations), the following regression of y^* on logflow, x2, and water temperature is estimated 1000 times. Environmental impact parameters, t-values and confidence intervals in each regression are stored and reported in equation (25).

$$y^* = -6.9542 + 1.0857\ lflow + 0.9068\ X2 - 0.1080\ Temp \qquad (25)$$

(0.0055) (0.2115) (0.2397) (0.0035)

$R^2 = 0.1088$, n=10

where the numbers in the parenthesis are standard deviations of each coefficient.

Using all of the coefficients from two alternative methods that provide statistically significant negative water export impact, I calculate the survival rates from juveniles to age 2 adults in order to use them in the estimation of survival rates for later stages and simulation analyses.

Using the survival rates from Juveniles to age 2 adults in Section 3.3.3 from both methods, the survival rates from age 2 and 3 ocean-staying adults to age 3 and 4 returning adults are estimated using only a linear model with an ordinary least squares method[22]. The estimated survival rates

[22] I also consider three different models (linear, Beverton-Holt, and Ricker) for the estimation of survival rates in this stage but choose only a linear model that provide statistically significant survival rates. A linear model for this

from juveniles to age 4 returning adults do not make biological sense and are greater than one unlike the estimated survival rates from juveniles to age 3 returning adults less than one. I thus set the former survival rates to zero for simulation analyses because data also show a very small portion of age 4 returning adults (8%).

Simulations

To select a method and a model that provides lower simulation errors, I simulate abundance data using the estimated survival rates and environmental impacts from two alternative methods in Section 3.3. After the simulation of the Winter-run population data for each age class, the percentage simulation errors between simulated data and actual data for each age class and model are calculated in Table 3. I select a two-stage Monte Carlo method since it provides lower simulation errors for the stage from juveniles to age 2 adults. A Ricker model is then chosen because it provides the lowest simulation errors for most of the age class. The two-stage Monte Carlo method and a Ricker model will thus be used for economic implication analyses.

Economic Implications of Winter-run Salmon Conservation

The main factors that affect water exports in the Southern Delta are weather conditions and legal rulings on endangered species. I use 10% steps of water export reduction scenarios under different weather conditions unlike the literature that has heavily focused on the legal rulings on Delta Smelt (Howitt et al, 2009a; Sunding et al, 2008). A proxy variable for weather conditions is Sacramento River water years[23]. I thus start with 10% step water export reduction scenarios for five water years at historical average levels of other environmental factors (X2, logflow, and

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stage makes biological sense since the density-dependence may be an unimportant factor that affects the survival from juveniles to age 3 and 4 adult due to larger space in the ocean.

[23] The California Department of Water Resources (CDWR) uses two different water year classifications: Sacramento River and San Joaquin River. This paper uses the Sacramento River water years since the amount of water export pumped from the Federal and State pumping stations is from water stored from Sacramento River.

water temperature) (Case 1). I then add the case that all of the environmental variables are varying over the water years in order to consider the environmental correlations (Case 2)[24].

Case 1

The CDWR classifies the Sacramento River water years into five categories: wet (W), above normal (AN), below normal (BN), dry (D), and critical (C)[25]. I calculate the annual water exports in acre feet by first aggregating the daily average water exports in cfs and then converting them in acre feet[26]. I then calculate average annual water exports for five water years during the period 1996-2010, which is the same period as in the salmon model estimation. Annual water export cutbacks from 10% to 100% are calculated by subtracting winter water export cutbacks from annual water exports since water export cutbacks only during the salmon migration period from November to March may affect the Central Valley agricultural production (Table 4).[27] The order of annual exports from highest to lowest is below normal, above normal, wet, dry and critical for different reduction scenarios. In order to calculate the foregone agricultural returns under different pumping scenarios, the right hand side of Equation (23) in Section 2.4 is divided into two components: water supply from the CVP and SWP pumping stations and from other water sources. New water constraints are defined as,

$$\sum_i x_{g,i,2} \leq \sum_{ws=5}^{6} \sum_i \tilde{x}_{g,i,2} \frac{\tilde{x}_{g,ws}}{\sum_{ws} \tilde{x}_{g,ws}} + Export * \left(\frac{\sum_{ws=1}^{4} \sum_i \tilde{x}_{g,i,2} \frac{\tilde{x}_{g,ws}}{\sum_{ws} \tilde{x}_{g,ws}}}{\sum_g \sum_{ws=1}^{4} \sum_i \tilde{x}_{g,i,2} \frac{\tilde{x}_{g,ws}}{\sum_{ws} \tilde{x}_{g,ws}}} \right) \forall g \qquad (26)$$

where Export is an average annual water export for different pumping scenarios in Table 4.

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[24] For the second case, I do not consider 10% step water export reduction scenarios since I could not calculate different levels of environmental factors under 10% step water export reduction scenarios.
[25] For more details on water years, refer to California Cooperative Snow Surveys at the CDWR (http://cdec.water.ca.gov/cgi-progs/iodir/wsihist).
[26] The reason for conversion is that a SWAP model uses the amount of water in acre feet, not in cfs.
[27] Annual water exports from 10% to 100% cutback are calculated by $(1 - PR_i * WP_{WY})$ *Annual Water Export*, where Annual water export is an annual water export at no cutback (0%), PR_i is a pumping reduction ratio at each 10% step from 10% to 100%, and WP_{WY} is a proportion of winter export to total annual water export over water years, for example, WP_W=0.397, WP_{AN}=0.465, WP_{BN}=0.42, WP_D=0.45, and $WP_C = 0.372$.

More realistic economic cost analysis requires both varying water exports and varying local surface water for five water years since the local surface water may also change over the water years. However, I limit the case of only varying water exports due to unavailability of data on varying local surface water over the water years and SWAP regions.

The foregone agricultural return losses (economic costs) are computed by subtracting total agricultural return of each 10% cutback scenario from the "no cutback" scenario for the five water years[28]. The economic costs range from $0 to about $89 million for different scenarios[29]. Under a 10% reduction scenario, all of the water years have the lowest economic costs and the lowest difference in economic costs between water years (Figure 3). However, as the reduction in water exports increases from 10% to 100%, economic costs increase at an increasing rate and the difference becomes larger. In general, the order of economic cost from highest to lowest is critical, dry, wet, above normal, and below normal, which is, as expected, completely opposite to the order of annual average water exports, due to the scarcity value of water corresponding to the weather conditions. By comparison, the calculated annual economic costs are reasonable costs of conserving the endangered Winter-run salmon because the estimates are below 2011 Federal and State expenditures on the Winter-run Chinook conservation by U.S. Fish & Wildlife Service ($82,668,247)[30] except for the 100% cutback cases for dry and critical years.

The prediction of the Winter-run Chinook population increases for different water export reduction scenarios over the water years. Daily average water exports need to be calculated since the prior water export impact (Newman, 2003) is estimated using daily average water exports.

[28] Total agricultural returns for different water export scenarios are calculated by rerunning a SWAP program in GAMS with 55 iterations through inserting 55 levels of Exports in Table 6 into Equation (26).

[29] I also calculate economic costs per acre feet by dividing the foregone return losses by the change in amount of water export in order to examine whether the calculated economic cost is reasonable. The economic cost per acre feet ranges from $11 to $31 under wet year and from $49 to $68 under critical year, which shows a reasonable price of water in the literature.

[30] Refer to Table 1 and Table 3 in USFWS (2011).

The calculated daily average water exports for different water export scenarios in Table 5 have slightly different order from that of annual average water export in Table 4, switching the order between wet year and dry year.

I then recalculate the survival rates from juveniles to age 2 adult in 2008 and their 95% CIs under different scenarios of pumping, using standardized daily average export[31], standardized other environmental factors at their historical average from 1996 to 2010, and the estimated environmental impacts from two-stage Monte Carlo method. These new survival rates are used to predict point estimates and the 95% CIs of the Winter-run salmon population increases for different age groups[32] and different water export scenarios. The total Winter-run population is calculated by multiplying the number of age 3 and 4 adults by 3 since juveniles and age 2 adults become age 3 and 4 adults in their later life stage. The conversion into age 3 and 4 adult populations makes the economic cost of conserving one age 3 and 4 adult salmon comparable to the commercial price of age 3 and 4 adult salmon because age 3 and 4 salmon have sufficient size for harvesting and have commercial prices.

The salmon population increases are measured by subtracting the total population of each 10% water export cutback scenario from that of no pumping cutback for five water years. The point estimates of salmon population increases range from 57 to 1,188 (Figure 4). In general, as the reduction in pumping increases, the marginal change in salmon population increases at an increasing rate. The order of salmon population increases from highest to lowest is below normal, above normal, dry, wet, and critical, which is the same order of daily average water exports in Section 4.1.1 since salmon population increases as water export reduces. During above normal and below normal water years, the pumping reductions will be more beneficial to salmon

[31] I calculate the standardized daily average water export by subtracting mean value of export 4888.23 cfs from actual value and dividing it by standard deviation 2141.71 cfs from Newman (2003).
[32] Different age groups include juvenile (2008), age 2 adult (2010), and age 3/4 adult (2011).

population than during dry or critical or wet water years. Under a 10% reduction, the difference in salmon population increase among water years is smallest but as the reduction increases, the gap becomes greater.

I also estimate the economic costs of increasing one age 3 and 4 Winter-run Chinook adult salmon in terms of foregone agricultural returns under different water export scenarios. These costs may provide policy-makers with information on how to manage the water in the Southern Delta to optimize the trade-off between salmon conservation and reliable water supply to the agriculture under different weather conditions. These economic costs per age 3 and 4 adult salmon are calculated both in point estimates and the 95% CI estimates by dividing the foregone agricultural losses by the estimated Winter-run population increases under different water export scenarios. The point estimates range from $0 to $114,966 with wide 95% CIs from $0 to $915,006 (Figure 5). All of the economic cost estimates generally keep increasing at a 10% increment in water export. The order of economic costs per salmon for all 10% step reduction scenarios from highest to lowest is critical, dry, wet, above normal, and below normal, which is the same order of the economic cost in Section 4.1.1, since the economic cost estimates are dominantly higher than salmon population increase estimates. Increasing the Winter-run salmon through water export reductions is more costly under dry years than wet years since the scarcity value of water is higher in dry years than in wet years. However, above normal or below normal years have lower costs than wet years and the critical year has the highest economic cost.

These economic cost estimates, however, may be the upper bound of actual economic costs because this study does not consider potential decrease in the salmon population extinction risk due to water export reductions and excludes fixed costs in a SWAP model. The inclusion of both factors may significantly lower the economic costs.

Case 2

In order to consider the environmental correlations, which may potentially affect the order of economic cost estimates, this section assumes that all of the environmental factors are varying over the water years. The economic costs are calculated by subtracting total agricultural returns of each water year from that of a below normal water year. A below normal year is chosen as a criteria year since it is the year of highest agricultural return. The economic costs range from $0 to about $47 million (Table 7)[33]. The ordering of economic cost from highest to lowest is critical, dry, wet, above normal, and below normal. The environmental correlations do not change the order of economic cost estimates.

In order to incorporate the environmental correlations in salmon population prediction, I calculate daily average amount of water export, logflow, X2, and water temperature for each water year, standardize them, and use them in the salmon population prediction (Table 6)[34]. Using these standardized environmental variables over the water years, the new survival rates from juveniles to age 2 adults are calculated over the water years. Using new survival rates and estimated environmental impacts, the point estimates and 95% CIs of population increases are calculated by subtracting the total population of each water year from that of a below normal year.

The salmon population increases are highest in wet years and lowest in below normal years with above normal, critical, and dry years in order between two extremes (Table 7). For the case 1, dry years have higher salmon population increases than wet years because farmers may need more water during dry years than wet years. Yet, for the case 2, wet years have higher increase

[33] These cost estimates are again smaller than government expenditures on the Winter-run conservation (USFWS, 2011).

[34] Standardized variables for logflow, X2, and water temperature are calculated by subtracting a mean from an actual value and dividing it by its standard deviation during 1996-2010. Standardized water export is calculated by subtracting a mean (4888.23) and dividing it by a standard deviation (2141.72) in Table 2 of Newman (2003).

than dry years since the environmental correlations dominate the effect of seasonal water demand.

By combining the results on both Winter-run salmon increases and the agricultural return losses for the case 2, I calculate the point and 95% CI cost estimates per age 3/4 adult salmon over the water years. Point estimates of economic costs per salmon range from $0 to $721,120 with the still wide 95% CIs from $0 to $4,447,222 (Table 7). The ordering of economic costs per salmon from highest to lowest is critical, dry, wet, above normal, and below normal (Figure 6). The environmental correlations still do not change the order of the economic costs per salmon due to domination of economic costs over the salmon population increases.

Conclusions and Discussions

Due to the environmental concerns on the water management in the Southern Delta, I examine the economic implications of conserving the Winter-run Chinook salmon through measurement of the agricultural losses in the Central Valley. I use two scenarios of water export reductions: one without environmental correlations and the other with environmental correlations. Using a modified SWAP, I estimate the economic costs for two cases. The cost estimates range from about $0.22 million to about $89 million for the case 1 but from about $0.11 million to around $47million for the case 2. These estimates are reasonable costs since they are below the total government spending on the Winter-run conservation in 2011. I also estimate the survival rates and environmental impacts over the life cycle of Winter-run Chinook salmon using time series data on juveniles and adults and environmental factors. A two-stage Monte Carlo simulation method using a prior water export impact from Newman (2003) provides reliable salmon population increase estimates with lowest simulation errors for two cases, ranging from 57 to 1,188 for the case 1 but from 50 to 262 for the case 2. By combining these two models, I estimate the economic costs of increasing a single age 3/4 salmon adult for the two cases. The economic cost estimates per salmon range from $1,304 to $114,966 for the first case but from $864 to $721,120 for the second case. As the pumping reduction increases from 10% to 100%, the economic cost increases at an increasing rate. The order of economic costs per salmon over the water years does not change with the environmental correlations.

This study, however, could be improved in several ways due to data and modeling limitations. First of all, the Winter-run Chinook simulation model could be expanded to incorporate several uncertainties such as measurement errors and parameter uncertainty (Newman and Lindley, 2006). Second, more available data on environmental factors and abundance over the Winter-run life cycle will enable the more precise ecological benefit analysis. Potential environmental factors may include sea temperature and predators of Chinook salmon in the ocean. In addition, economic cost estimates may be upper-bound estimates because I do not consider the benefits of reducing extinction risk of endangered species under water export reductions and fixed costs in the SWAP model. The consideration of these factors may reduce the costs. I could estimate the former by using non-market valuation method that surveys the willingness to pay for conservation efforts under different scenarios. Lastly, a SWAP model can incorporate endogenous crop prices in order to examine the effect of changing crop price caused by water export reductions on the economic cost estimates.

Despite all of the above limitations, this study shows reasonable economic costs associated with conserving the endangered Winter-run Chinook salmon through the water management in the southern Delta. Furthermore, these costs vary significantly corresponding to climatic conditions. Policy makers need to consider weather conditions in their water management plans due to the changing scarcity value of water over the water years. Moreover, the approach of this study could be applied to other listed species in the Delta such as delta smelt or the ecosystem as a whole.

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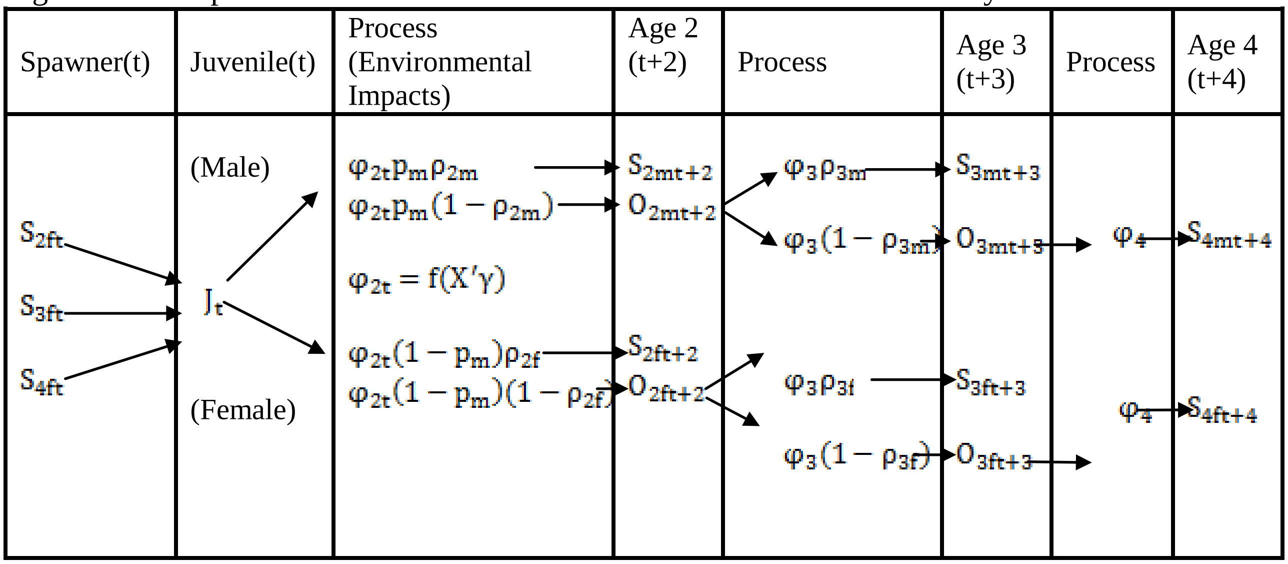
Figure 1. Conceptual Framework of Winter-run Chinook salmon Life History



Source: This Figure is slightly modified from Figure 2 in Newman and Lindley (2006).

Note: S_{agt}, J_t, and O_{agt} are respectively spawners, juveniles, and immature ocean-staying fish at age a, sex g, and time t. φ_{at} is age-specific survival rate(age 2 survival rate is an only time-varying parameter due to the environmental impacts), ρ_{ag} is sex and age-specific maturation rate, and p_m is the probability of a male fish. X_s are environmental variables and γ_s are the marginal environmental impacts.

Figure 2. Returning Abundance on Winter-run Chinook salmon

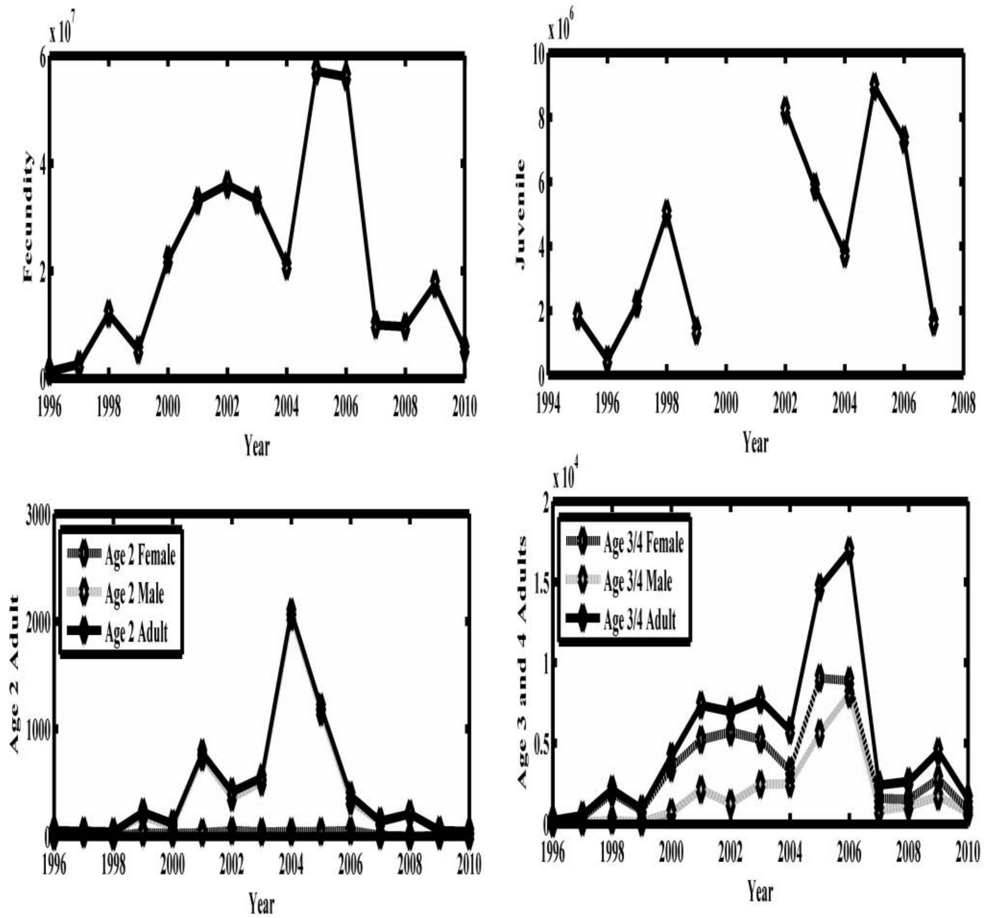


Figure 3. Economic Costs under different water export scenarios (Case1)

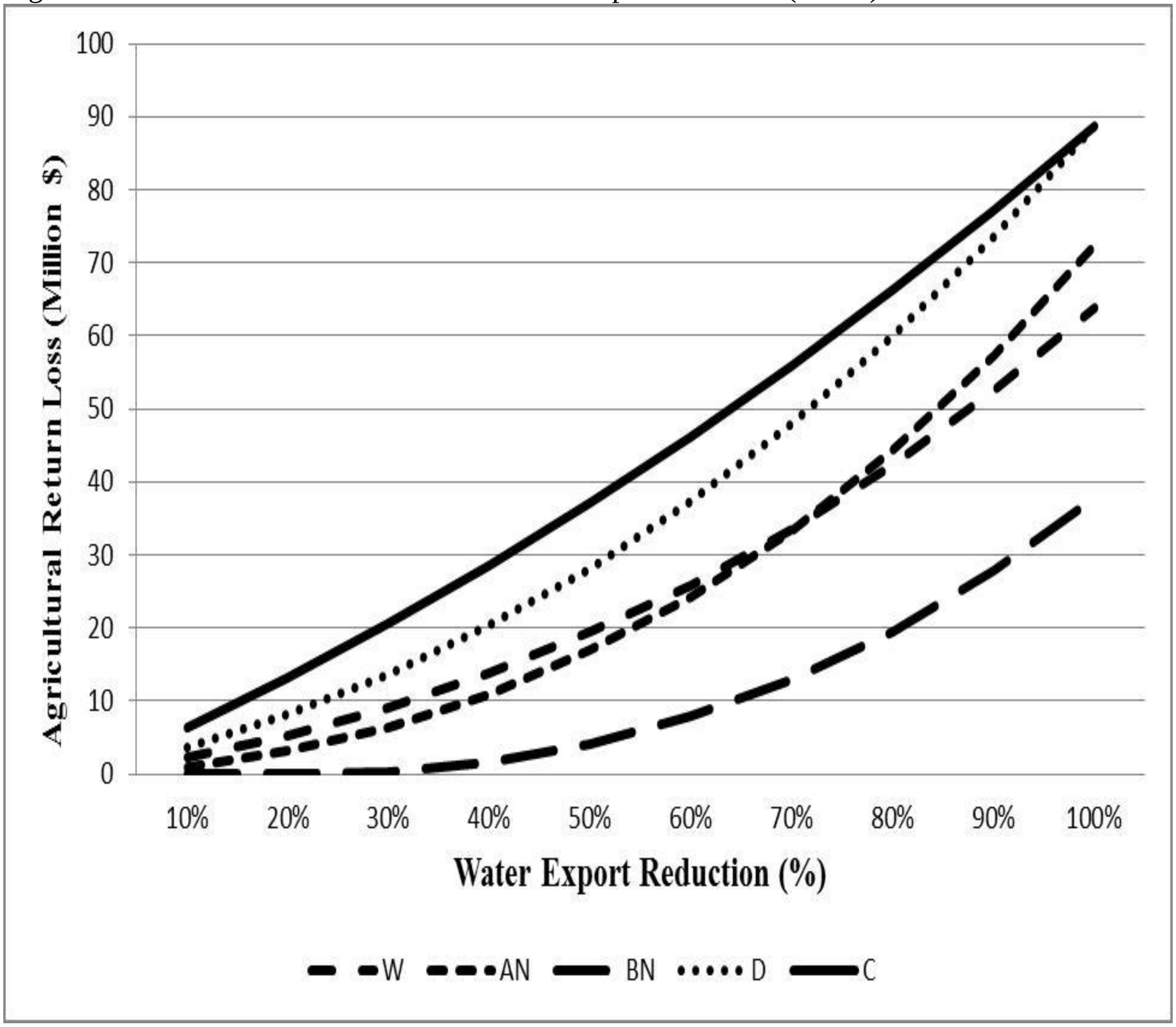


Figure 4. Winter-run Salmon Population Increases under different water export scenarios (Case1)

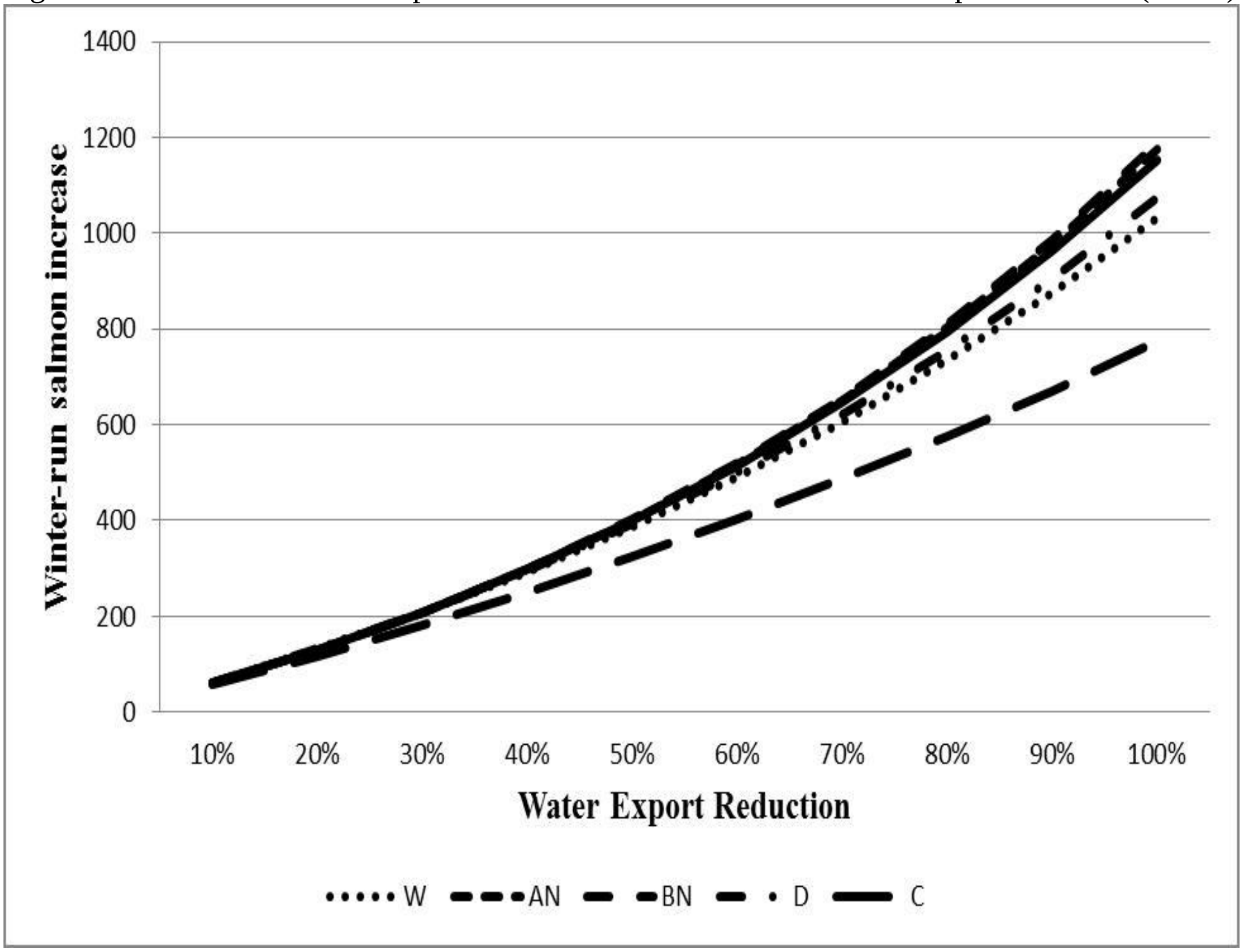


Figure 5. Economic Cost per Salmon under different water export scenarios (Case 1)

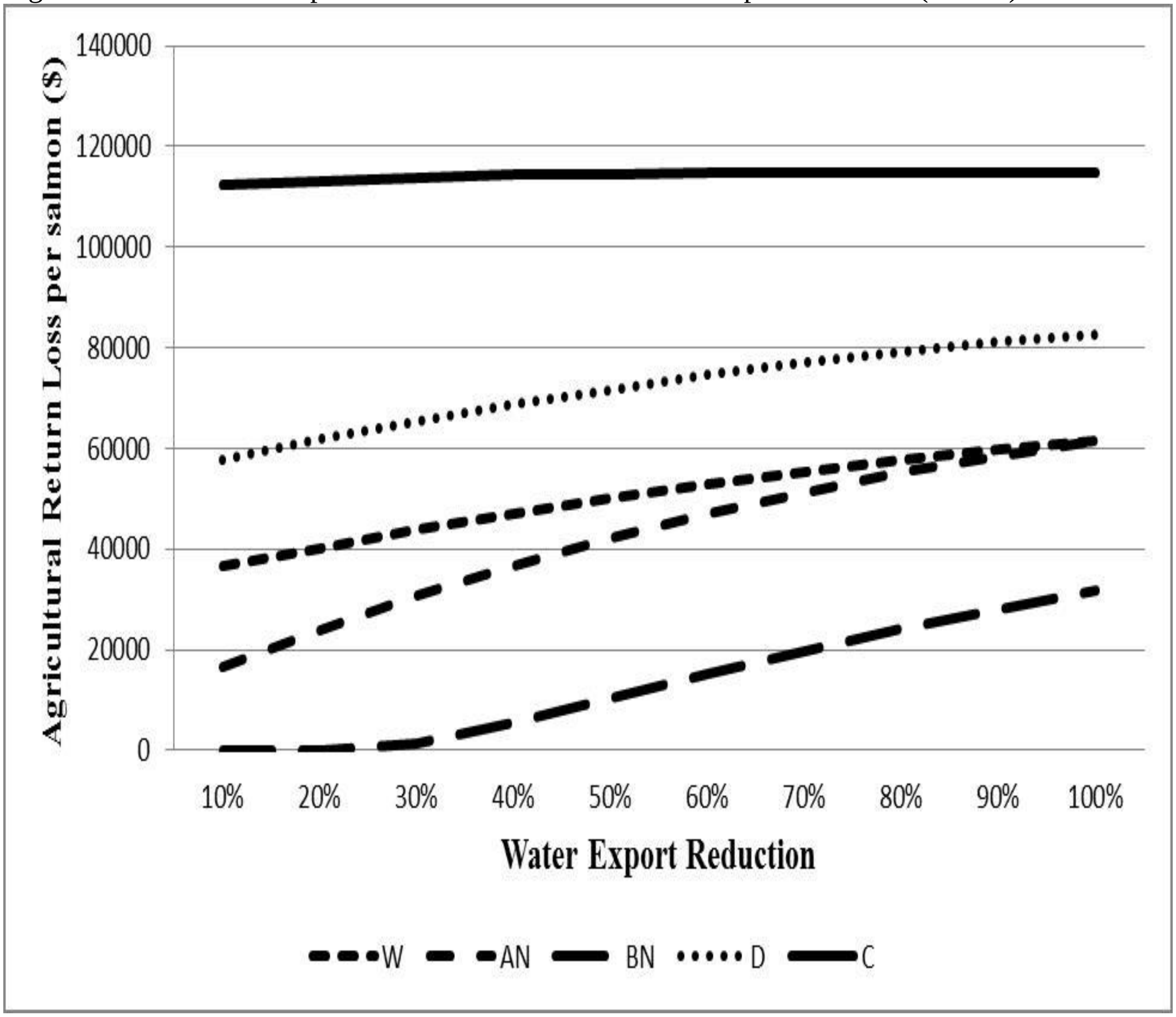


Figure 6. Economic cost per Salmon under different water years (Case 2)

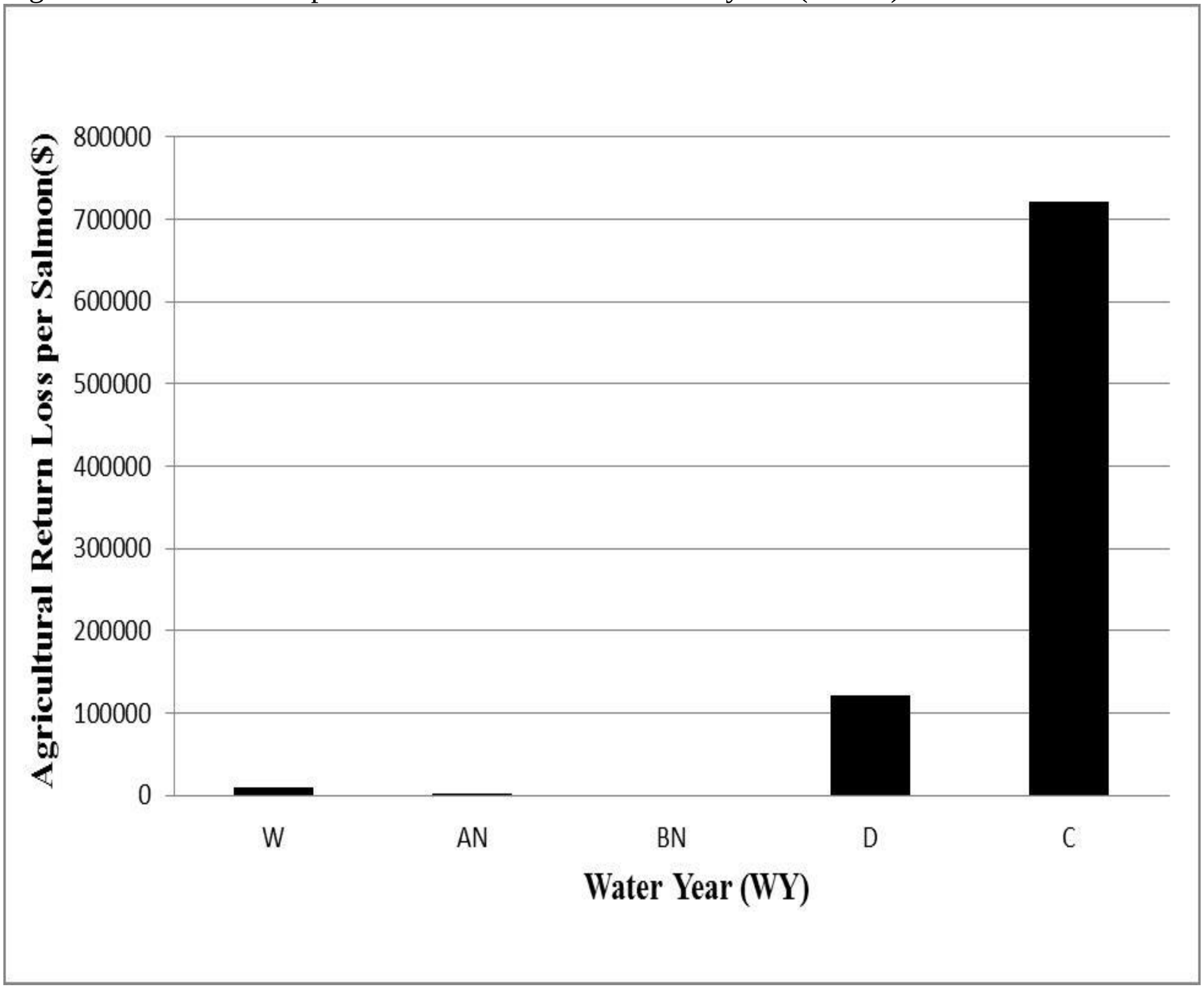


Table 1. Multi-stage Winter-run Chinook salmon population model[a]

Life Stages	State Processes
Eggs at t [b]	$F_t = \overline{E}_2 S_{2ft} + \overline{E}_{3,4}(S_{3ft}+S_{4ft})$
Juveniles at t [c]	$J_t = \alpha F_t$(Linear),$J_t = \frac{\alpha F_t}{1+\frac{\alpha}{\beta}F_t}$(B-H model),$J_t = F_t \exp(\alpha + \beta F_t)$(Ricker)
Age 2 adult at t+2[d]	$S_{2mt+2} = \rho_2 \varphi_{2t} p_m J_t$ $S_{2ft+2} = \rho_2 \varphi_{2t}(1-p_m)J_t$ $S_{2t+2} = \rho_2 \varphi_{2t} J_t$ $\varphi_{2t} = f(X'\gamma) = \frac{\exp(X'\gamma)}{1+\exp(X'\gamma)}$
Age 3/4 adult at t+4	$S_{3+4mt+4} = \rho_3 \varphi_{3m}(1-\rho_2)p_m \varphi_{2t+1} J_{t+1}$ $+\varphi_{4m}(1-\rho_3)\varphi_{3m}(1-\rho_2)p_m \varphi_{2t} J_t$ $S_{3+4ft+4} = \rho_3 \varphi_{3f}(1-\rho_2)(1-p_m)\varphi_{2t+1} J_{t+1}$ $+\varphi_{4f}(1-\rho_3)\varphi_{3f}(1-\rho_2)(1-p_m)\varphi_{2t} J_t$ $S_{3+4t+4} = \rho_3 \varphi_3(1-\rho_2)\varphi_{2t+1} J_{t+1} + \varphi_4(1-\rho_3)\varphi_3(1-\rho_2)\varphi_{2t} J_t$

a. Adjusted from Table 2 of Newman and Lindley (2006) by removing all types of uncertainties and including environmental impacts and time-varying survival rate from juvenile to age 2 adult.
b. $\overline{E}_2$ is an average fecundity rate for age 2 adult and $\overline{E}_{3,4}$for age 3,4 adult ($\overline{E}_2$=3205 and $\overline{E}_{3,4}$=6304 from Newman and Lindley(2006)), S_{agt}: Spawning adult at age a(2,3+4), gender g(f and m), and time t
c. J_t: Juveniles, F_t: The number of eggs, α: survival rate for B-H, Ricker, and linear models and β: B-H parameters
d. p_m is the male ratio (p_m=0.5 from Newman and Lindley(2006))
φ_{at} is the survival rate of age a fish(age 2 survival rate is an only time-varying parameter)
ρ_a is a maturity rate of age aadult salmon (ρ_2=0.08, ρ_3=0.963 from Cramer et al(2004))
γ: marginal environmental impacts, X: Environmental factors (river flow, water temperature, X2 and water export)

Table 2. Estimation Results of Linear, B-H, and Ricker Models from Eggs to Juveniles

Models	Estimation Results
Linear [a]	$Juv(t) = 0.1658\,\mathrm{Fec(t)}R^2 = 0.7367$ n=10 (10.3524)*** 95% CI (0.1296, 0.2021)
Beverton-Holt [b]	$Fec(t)/Juv(t) = 2.8228 + 7.4794e^{-8}\,\mathrm{Fec(t)} \quad R^2 = 0.5922$ n=10 (4.172)*** (3.4082)*** 95% CI(1.2625, 4.3830) (2.4188e-8, 1.254e-7) Point estimate: $\alpha_{1bh} = 0.3543, \beta_{1bh} = 1.337e^7$ 95%CI : α_{1bh} $(0.2282, 0.7921)$, β_{1bh} $(7.9745e^6, 4.1342e^7)$
Ricker [c]	$\log(Juv(t)/Fec(t)) = -0.9479 - 1.9115e^{-8}\,Fec(t)$ (-4.4404)*** (-2.7606)**$R^2 = 0.4879$ n=10 95% CI (-1.4402,-0.4557) (-3.5082e-8, -3.1476e-9)

Numbers in parenthesis are t-values *significant at 90% **significant at 95% ***significant at 99%

a. Linear regression model without intercept

b. $J_t = \alpha_{1bh}F_t/(1 + (\alpha_{1bh}/\beta_{1bh})F_t)$,

where J_t is juveniles, F_t is the fecundity rate, α_{1bh} is a productivity, and β_{1bh} is a carrying capacity.

c. $J_t = F_t\exp(\alpha_{1r} + \beta_{1r}F_t)$, where α_{1r} is an intercept and β_{1r} is a slope parameter for Ricker model.

Table 3. Percentage Simulation Errors for Two Alternative Methods

Age Class \ Models	Linear (%)		B-H (%)		Ricker (%)	
	a)	b)	a)	b)	a)	b)
Juveniles	1.9539e+7	765	1933	644	717	617
Age 2 females	1.2014e+11	1,015	1.4405e+7	1,691	4.3329e+6	2,174
Age 2 males	1.1967e+10	912	1.2102e+6	920	3.7494e+5	921
Age 2 Adults	2.1746e+10	967	2.1867e+6	959	6.5776e+5	951
Age 3/4 females	7.4291e+6	1,064	909	1,004	947	980
Age 3/4 males	5.8994e+6	1,046	802	978	841	953
Age 3/4 Adults	6.7383e+6	1,060	860	1,002	921	978

Simulation errors are calculated by 100*|simulated data-actual data|/actual data over the years.
a) Method that uses all of environmental impact estimates from Newman(2003)
b) Method that uses only the water export impact from Newman(2003)(two-stage Monte Carlo Method)

Table 4. Average Annual Exports under different water export scenarios

	Annual Exports (acre feet) under Sacramento River WYs (1996-2010)				
Pumping Reduction	W	AN	BN	D	C
0%	5,216,690	5,688,450	6,426,627	4,923,904	3,513,421
10%	5,009,384	5,423,806	6,156,718	4,702,399	3,382,602
20%	4,802,077	5,159,162	5,886,809	4,480,894	3,251,783
30%	4,594,771	4,894,517	5,616,900	4,259,389	3,120,965
40%	4,387,465	4,629,873	5,346,991	4,037,885	2,990,146
50%	4,180,159	4,365,229	5,077,082	3,816,380	2,859,327
60%	3,972,853	4,100,585	4,807,173	3,594,875	2,728,508
70%	3,765,546	3,835,941	4,537,265	3,373,371	2,597,689
80%	3,558,240	3,571,297	4,267,356	3,151,866	2,466,871
90%	3,350,934	3,306,653	3,997,447	2,930,361	2,336,052
100%	3,143,628	3,042,009	3,727,538	2,708,856	2,205,233

Five types of water years: wet (W), above normal (AN), below normal (BN), dry (D), and critical(C).
All types of water years come from Sacramento River water year classifications by CDWR data.
All of the average annual exports are calculated by averaging annualized water export for each water year type from 1996 to 2010. For example, wet years are 1996-1999 and 2006, above normal years are 2000, 2003, and 2005, below normal years are 2004 and 2010, dry years are 2001-2002 and 2007 and 2009, and a critical year is 2008.

Table 5. Daily average water exports under different water export scenarios

	Average daily export (cfs) under Sacramento WYs				
Pumping Reduction	W	AN	BN	D	C
0%	6,912	8,825	9,018	7,392	4,404
10%	6,221	7,943	8,116	6,653	3,964
20%	5,530	7,060	7,214	5,914	3,523
30%	4,839	6,178	6,312	5,175	3,083
40%	4,147	5,295	5,411	4,435	2,643
50%	3,456	4,413	4,509	3,696	2,202
60%	2,765	3,530	3,607	2,957	1,762
70%	2,074	2,648	2,705	2,218	1,321
80%	1,382	1,765	1,804	1,478	881
90%	691	883	902	739	440
100%	0	0	0	0	0

Average daily export is calculated by averaging daily export during salmon migration period from November to March from 1996 to 2010.

Table 6. Environmental Variables under different water years

WYs	Level Variables				Standardized Variables			
	Export(cfs)	Lflow	X2(km)	Temp(◦F)	Export	Lflow	X2	Temp
W	6912	4.557	66.92	55.64	0.945	0.610	-0.654	-0.721
AN	8825	4.483	71.05	56.66	1.838	0.213	-0.026	0.076
BN	9018	4.457	70.35	56.56	1.928	0.073	-0.133	0.000
D	7392	4.338	74.79	57.13	1.169	-0.561	0.541	0.445
C	4404	4.147	80.79	58.61	-0.226	-1.588	1.452	1.601

Correlation coefficients among variables are 0.739(Export and Lflow), -0.719(X2 and Export), -0.604(Temp and Export), -0.9896(X2 and Lflow) and 0.775(Temp and X2).

Table 7. Economic Costs per Salmon under different water years (Case 2)

Water Year	Winter run Increase	Agricultural Return Loss($)	Economic Cost per Salmon($)
W	262 (28~2,746)	2,656,228	10,146 (967~93,411)
AN	124 (10~1,738)	107,272	864 (62~10,566)
BN	0 (0~0)	0	0 (0~0)
D	50 (6~483)	6,079,770	122,225 (12,590~1,072,005)
C	65 (11~267)	47,130,443	721,120 (176,410~4,447,222)
Numbers in the parenthesis are 95% confidence intervals.			