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Water Management Policies for Streamflow Augmentation in an Irrigated River Basin

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The value of maintaining a minimum streamflow objective on average is lessened when there is considerable dispersion around the average. An integrated economic and hydrology model is presented which provides water policy planners with a way to accurately measure both the economic cost and hydrologic consequences of maintaining a minimum streamflow level in an irrigated river basin at alternative probabilities of maintaining the target flow level. Water markets for streamflow augmentation are shown to be the most cost-effective policy in the study area.

Key words: hydrology, minimum flows, stochastic supply, water policy analysis

Introduction

The competition for water in many western irrigated river basins is reaching critical levels, raising questions about alternative water management policies. For example, will reducing irrigation diversions increase streamflows as anticipated to preserve riparian habitat, or will they only increase seepage? What impact do conservation and/or efficiency measures, conjunctive surface- and groundwater management, upstream storage, or basinwide water markets have on streamflow levels? What economic cost is imposed on irrigated agriculture?

These and other complex questions can be resolved with basinwide planning models. Such models must address important economic, environmental, and hydrologic concerns, yet have sufficient spatial and temporal disaggregation to allow a comprehensive subbasin evaluation of the economic and biophysical impacts of potential water policies. The modeling framework should explicitly consider the stochastic parameters in water resource systems. A policy which achieves a monthly streamflow standard on average may have little value if there is considerable dispersion around the average, particularly for fishery enhancement. This article presents a temporally and spatially disaggregated model to provide decision makers with the economic and hydrologic information required to establish credible instream flow standards.

The need for comprehensive water policy models is self-evident after reviewing the limited success of Washington State in implementing an effective instream flow program even though the Revised Code of Washington State declared in 1949 "that a flow of water sufficient to support game fish and food fish population be maintained at all times in the streams of the state" (p. 218). Despite this stated goal, statewide policy

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has moved little beyond the conceptual planning stage in the intervening 48 years due to a lack of information about the economic, biologic, and hydrologic tradeoffs of alternative water allocations. Lacking this crucial information, policy makers have been unable to achieve viable political compromises between instream and out-of-stream interests (Washington State Department of Ecology 1987).

In an effort to overcome technical and political barriers, the state subsequently implemented the two-tiered Chelan Agreement planning process (Washington State Department of Ecology 1992). This agreement requires the state to establish a framework for water policy development, but leaves policy development and implementation to regional (basinwide) planning committees. To date, the decentralized planning process has failed to produce a comprehensive water management plan for any of the state's 62 water resource inventory areas, partly because local decision makers lack information about the hydrologic and economic consequences of potential plans (Nelson). A recent study of Washington State's Walla Walla River Basin concluded that an accurate analysis of the cost effectiveness of alternative streamflow augmentation programs required a better understanding of the hydrologic, environmental, and economic consequences of alternative water allocations within the basin (Gettenger). The model developed here can provide these much needed data.

Study Area

The Walla Walla River Basin study area, shown in figure 1, is situated in southeastern Washington (73%) and northeastern Oregon (27%). Before irrigation development began in the late 1800s, the basin supported annual runs of spring chinook salmon (*Oncorhynchus tshawytscha*) and summer steelhead (*Oncorhynchus mykiss*) averaging about 4,900 for each species (Chapman). Irrigated agriculture hurt spring chinook because adult upstream migration and juvenile outmigration coincide with heavy irrigation diversions in late April through June. The last significant run was in 1925, and by the 1950s the run was lost (Van Cleve and Ting). Summer steelhead still survive, but with numbers far below historical levels. Their migration occurs between December and March, which is outside the major irrigation season (Confederated Tribes of the Umatilla Indian Reservation et al.). Reestablishing the spring chinook will require diverting some water from irrigated agriculture to streamflows.

Annual precipitation ranges from seven inches near the basin's western edge to over 40 inches in the Blue Mountains at the basin's eastern perimeter. Rainfall and snowpack melt from the Blue Mountains is the primary streamflow source. Streamflows are greatest in early spring, and dry stream beds are common in late summer due to low precipitation and high irrigation demand. A basalt aquifer system ranging in depth from 125 to 2,000 feet below the surface underlies the entire basin. A 120,000-acre, unconfined gravel aquifer overlays the basalt system in the central basin. The gravel aquifer is used intensively by irrigated agriculture, has an average thickness of 200 feet, and is recharged by precipitation, irrigation return flow, and stream and irrigation canal seepage (Barker and MacNish). MacNish, Myers, and Barker estimate the gravel aquifer's economically manageable reservoir reserve capacity to be one million acre-feet.

More than 20 irrigated crops are grown on the Washington side of the basin, with alfalfa seed, wheat, and alfalfa hay having the largest acreage. Washington's irrigated

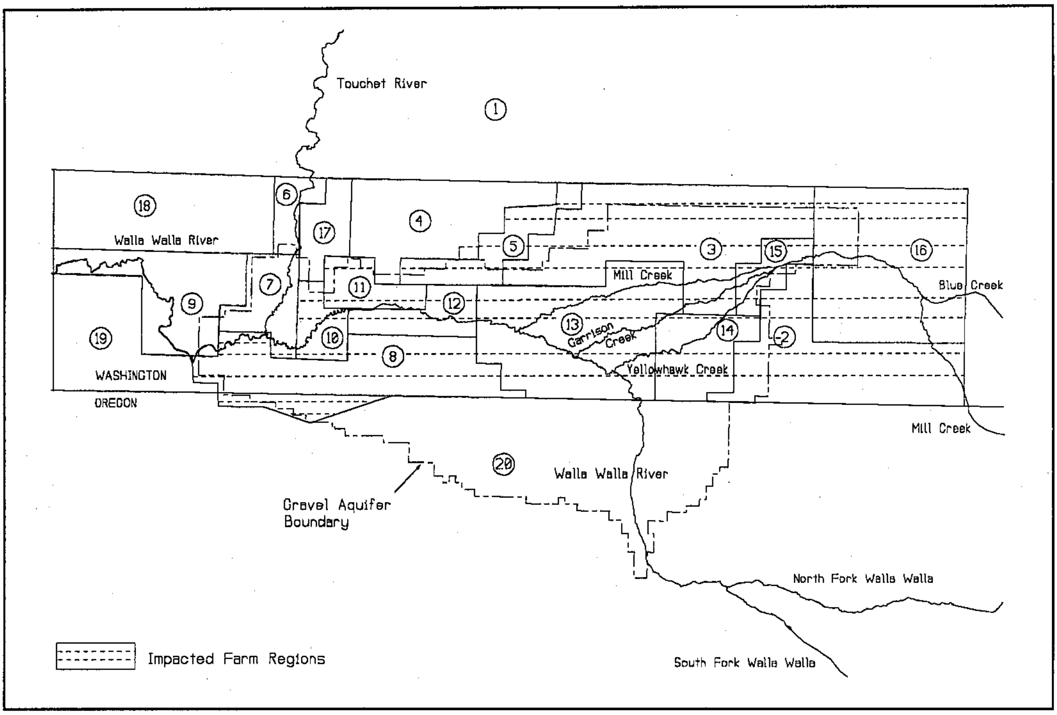

Figure 1. Walla Walla Basin study area and representative farm regions

crop acreage was 37,861 acres in 1989 [U.S. Department of Agriculture (USDA)]. Ten irrigation districts service 14,600 of these acres with diverted streamflow. These districts are located in the western half of the basin and have a water right junior to all upsteam diverters (Nevee). Except for 1,300 acres of flood irrigated pasture, most on-farm irrigation systems are side-roll or handline sprinkler systems. Dryland crops are concentrated in wheat, green peas, grass, barley, and dry peas.

In 1989, surface water accounted for 49% of all agricultural diversions, while the gravel aquifer accounted for 77% of groundwater use (Willis). Under current institutional arrangements, Oregon irrigators annually exercise their right to dam the Walla Walla River each June through early October just south of the Washington State line for purposes of irrigation. Small streams and spring discharge partially recharge the river after it crosses into Washington.

Modeling Approach

A two-stage modeling procedure was developed to analyze a variety of hydrologically viable streamflow augmentation policies. The first-stage economic submodel determines optimal on-farm response to a specific instream flow policy. The second-stage hydrology model subsequently employs the optimal water use pattern as determined by the economic model to monitor policy effects on monthly streamflow levels and groundwater levels.

Economic Submodel

The economic submodel is a chance-constrained programming (CCP) model consisting of farm models for each of the basin's 20 homogeneous farm regions, 15 of which contain irrigated acreage (figure 1). Information on basin hydrology, sources and location of irrigation diversions, irrigation practices, and cropped acreage was used to designate the farm regions. The CCP formulation explicitly recognizes the probabilistic nature of streamflow supplies and substitutes right-hand-side deterministic equivalent values for the maximum monthly surface diversions which satisfy the monthly instream flow standard at the specified probability level (Charnes and Cooper). As shown in the figure 2 flowchart, the economic submodel has four major components, discussed in detail below.

Data Input Template. Model parameters for each representative farm region are entered into a data input template. The user is prompted for hydrologic, agronomic, and economic data, and crop-specific information on irrigation systems and efficiencies for each farm region. If all preprogrammed default parameter values are accepted, the current baseline situation is replicated.

Required hydrology data consist of monthly surface and groundwater diversions from each aquifer by farm region. Groundwater pumping capacity and average pump lift also are requested for each aquifer by farm region. Agronomic information consists of monthly net irrigation requirement (NIR) and expected crop yield under full irrigation. The maximum percentage that each crop can be deficit irrigated in a month and the associated yield reduction at the maximum allowed deficit also are specified. Economic data include revenue, itemized production cost, plus irrigation energy and labor requirements. The user selects one of five irrigation systems for each crop in each region. A default dryland rotation is specified for each region for use when water supplies are insufficient to meet irrigated crop demands. Irrigated pasture acreage can be prevented from returning to dryland agriculture in regions where marginal soils and/or irregular field shape would prevent such changes.

Matrix Generator. The matrix generator produces a CCP matrix consisting of 1,134 equations and 901 decision variables for each irrigated farm region. The technical coefficients, resource limitations, and product and input prices determine the scenario addressed. Global constraints link available monthly surface water supplies to the irrigated farm regions.

Optimization Model. The CCP model determines optimal producer response for each water management policy while maximizing farm gross margins. Water policies considered involve (*a*) the temporal and/or spatial change in the quantity of surface water and/or groundwater used, (*b*) increased on-farm irrigation or off-farm conveyance efficiency, (*c*) development of upstream storage, and (*d*) intrabasin water transfers. Potential on-farm responses to a specific policy include switching to alternative irrigated crops, deficit irrigation, increasing irrigation efficiency, increased groundwater use, and dryland crops. Crop yields, production cost, and irrigation efficiency are endogenously adjusted when a crop is deficit irrigated. Scaling functions continuously adjust these values over the prespecified deficit irrigation range. Forty-two years (1948–89) of monthly data on streamflow entering the basin, precipitation, and temperature were used to develop the monthly distributions for stochastic streamflow supplies and crop NIRs.

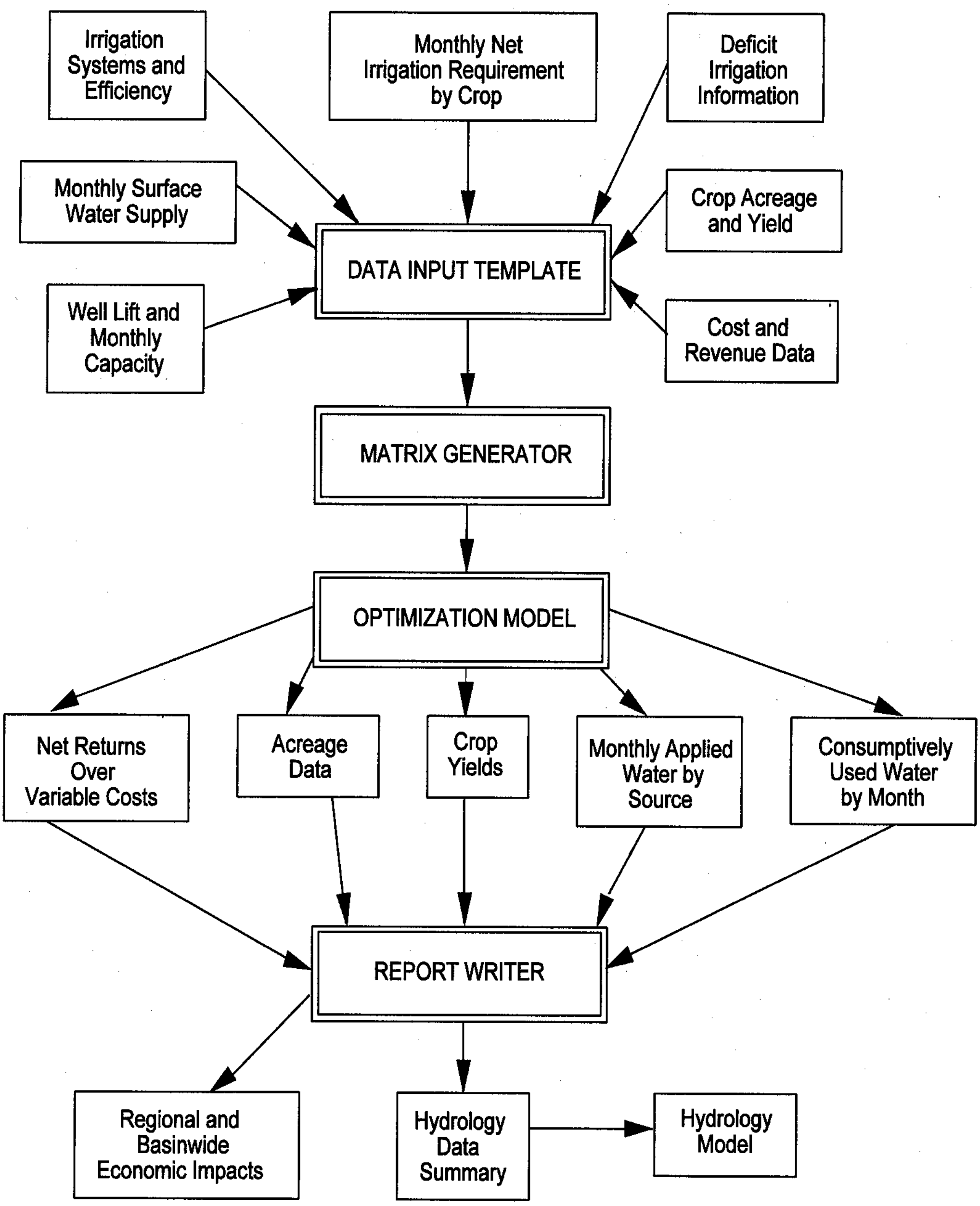

Figure 2. Flow chart of data flow and model structure for the economic submodel

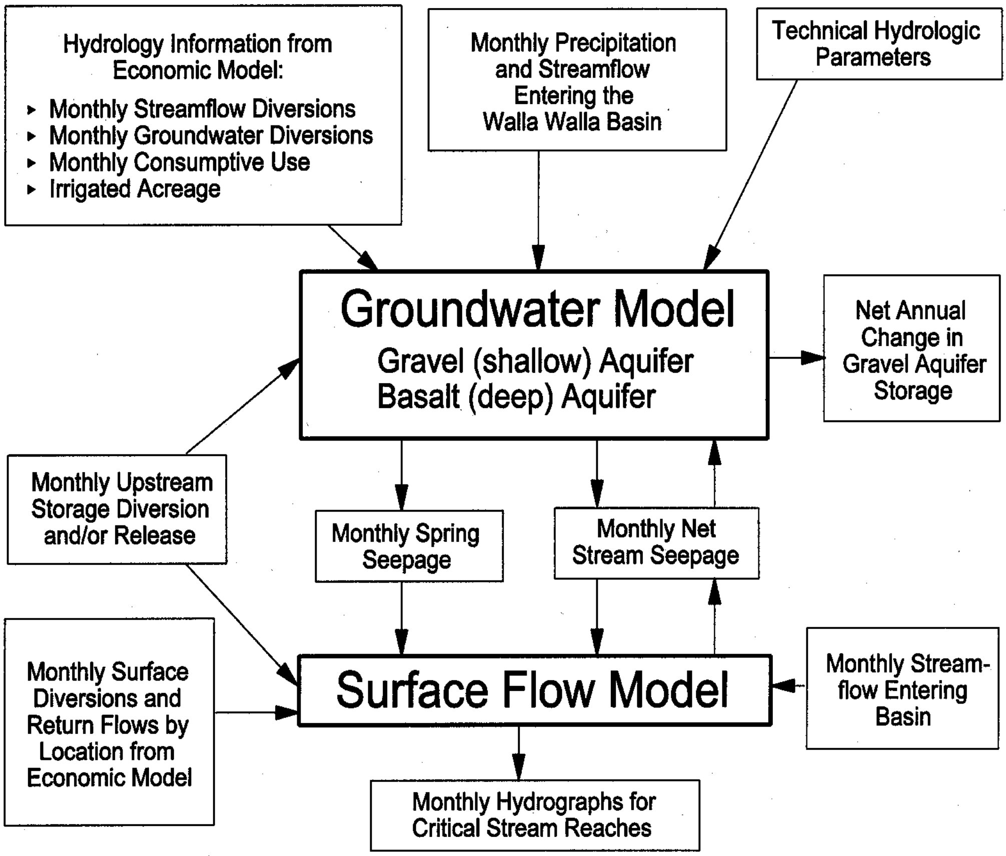

Figure 3. Data input, flow, and output for the hydrology submodel

Report Writer. A report writer summarizes economic and hydrology data generated by the optimization model for each representative farm, provides an aggregate basin-wide report for each instream policy, and outputs the water use data required by the hydrology model. The water use data set includes monthly data on irrigation applications, plus the quantity, source, and location of irrigation diversions, and irrigated acreage by crop and farm region.

Hydrology Submodel

The hydrology submodel consists of two linked computer models: a surface flow model and a groundwater model. Model linkages and data flow are illustrated in figure 3.

Groundwater Model. The groundwater model is a modified version of Barker and MacNish's 1976 digital model of Walla Walla's unconfined gravel aquifer and monitors changes in groundwater elevation resulting from natural recharge and groundwater pumping (Willis). The finite difference procedure used to monitor groundwater elevation required a grid to be constructed on the land over the aquifer.

Surface Flow Model. The surface model tracks monthly streamflow for the basin's five perennial streams. The gravel aquifer grid serves as the basis for defining a stream reach and provides the means to link the surface flow model to the groundwater model. The permanent streams are divided into 193 stream reaches corresponding to the gravel aquifer's grid system. Monthly surface flow for each reach is modeled by a simple continuity equation which states that reach outflows equal reach inflows less reach diversions and seepage, plus reach return flows and spring recharge.

Data Sources

Detailed 1989 acreage data for the Washington portion of the basin were provided by the USDA Walla Walla County Agricultural Stabilization and Conservation Service (ASCS) office and local commodity groups. The legal description accompanying the ASCS data allowed each irrigated field to be located within a section. Yield data were collected in a series of farmer interviews and cross-checked against the ASCS proven yield records. Monthly NIR was calculated using the Blaney-Criddle method (James et al.). Monthly rainfall levels and average monthly temperature data were obtained from the National Oceanic and Atmospheric Administration for seven basin weather stations for the 1948–89 water years.[1]

Irrigation diversion locations were identified to the nearest tenth of a mile using power record data for each of the 1,735 agricultural pumps in the basin. Monthly diversion quantities were estimated for each location using the power data in combination with available information on pump efficiency, system pressure, and pump lift for 110 pressurized basin irrigation systems (Henderson). Gravity surface diversion data were used to augment the energy-based estimates and provide the comprehensive estimate of total monthly diversion by farm region and water source.

Based upon historical records provided by ASCS personnel (Miller), commodity groups, and farmer interviews, 1989 was determined to be a representative year in terms of irrigated acreage by crop and farm region. Examination of monthly weather and streamflow data for the years 1948–89 also revealed that average monthly temperatures, precipitation, and streamflow supplies were near long-run averages in 1989. This formed the basis for using the 1989 condition as the baseline situation for evaluating alternative basin water management policies.

Model Calibration

Calibrating and linking the economic model with the hydrology model was a two-step process. The first step involved achieving a monthly water balance between a demand-based estimate of irrigation water use and a supply-based estimate of irrigation water use by farm region. Each regional demand-based estimate was derived from regional data on average irrigation efficiency by crop and system, and monthly NIR for baseline irrigated acreage. The supply-based estimates were computed from data on irrigation pump energy use, size, efficiency and lift, and known gravity surface diversions. The

[1] A water year encompasses the calendar period October 1 through September 30.

supply and demand water use estimates never differed by more than 4% in any region or month and provide strong evidence that the spatial and temporal use of water is accurately accounted for in the baseline calibration year.

Basinwide model calibration was verified in the second step by simulating baseline water use conditions and comparing the simulated monthly streamflow levels with those recorded at four continuous U.S. Geological Survey (USGS) gaging stations located within the basin. This comparison found the simulated and actual average monthly flow levels were always within 9% at each station. An additional calibration check revealed that the simulated monthly flow level in each of the 193 modeled stream reaches was always nonnegative after accounting for baseline diversion use. The simulated near-zero flow levels for the central basin reaches in the months of June through September also corresponded to baseline year records maintained by the local watermaster. Collectively, these comparisons establish that the economic and hydrology models were accurately linked and calibrated. Under baseline conditions, gravel aquifer withdrawals exceeded recharge by 22,681 acre-feet, representing an annual drawdown of about six inches.

Model Details

May and June streamflow levels in the central basin limit the reestablishment of spring chinook run in Mill Creek, the largest Washington tributary of the Walla Walla River. A 1983 U.S. Fish and Wildlife Service (USFWS) study determined a minimum flow of 75 cubic feet per second (cfs) must be maintained in the Walla Walla River from March through June to successfully reestablish the chinook salmon along Mill Creek. A reach located in region 10 (figure 1) was chosen to evaluate the economic cost and hydrologic consequence of policies designed to maintain the 75 cfs flow level. Maintaining a 75 cfs flow in this reach assures all river reaches below Mill Creek satisfy the monthly minimum flow target given the hydrologic linkages and surface diversion rights of upstream appropriators.

Baseline Situation

The baseline cumulative probability distribution for the critical reach flow level was established by simulating the model over the 42 years of monthly weather and streamflow data under baseline surface and groundwater use to measure the frequency and amount by which the streamflow target is violated in any given month. This simulation serves as the standard for evaluating the effectiveness and cost of alternative streamflow management policies.

The historical simulation revealed that sufficient surface supplies existed over time to completely satisfy baseline surface irrigation demand in all months except June and July. Simulated surface flow levels completely satisfied June and July baseline surface demands 55% and 69% of the time, respectively. Thus, there often would be no water left for streamflows. However, at least 90% of baseline surface demand is met 88% of the time in June, and 95% of the time in July. Moreover, under baseline groundwater use, sufficient groundwater pumping capacity exists to compensate for surface supply shortages in all low flow years.

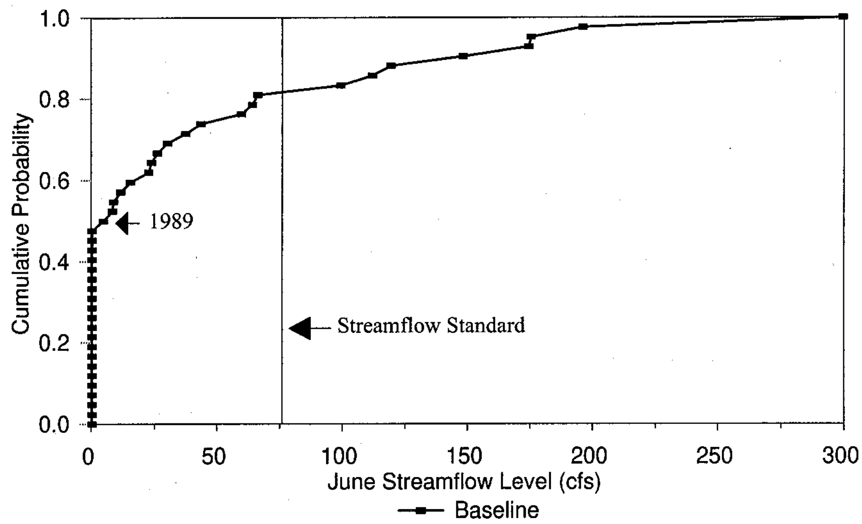

Figure 4. Cumulative probability distribution for June streamflow level in lower Walla Walla River under baseline practices

Under baseline conditions, 97% of all surface diversions are upstream of the selected reach and the 75 cfs target is violated about 15% of the time in May. In June, as shown in figure 4, the flow target is violated more frequently, with 80% of the years falling below the target flow, and zero flow levels occurring about 50% of the time.

Management Policies

Four management policies were evaluated for their ability to maintain the streamflow target over the critical spring chinook migration period:

(1) *Restricted Agricultural Diversion.* The restricted agricultural diversion policy (RD) seeks to maintain the minimum streamflow level by reducing surface diversions in those Washington farm regions (hatched regions in figure 1) that affect the critical reach flow level.
(2) *Storage.* One structural option is to build 6,000 acre-feet of storage in upper Mill Creek at a cost of $28 million (U.S. Army Corps of Engineers). Water would be stored during the high flow months of November to March for release into Mill Creek in May and June to meet the minimum flow standard.
(3) *Storage and Lining.* Another structural option is the storage and lining (SL) policy which combines upstream storage with lining 2-1/4 miles of lower Mill Creek, a major tributary of the Walla Walla River (see figure 1) where seepage losses average 22 cfs. The U.S. Army Corps of Engineers estimates the lining cost to be $2.5 million. The lining reduces losses to seepage.
(4) *Market.* The water market policy assumes a contractual agreement is reached with Oregon irrigators for release of 40 cfs down the Walla Walla River each June. Oregon irrigators would have to be compensated for lost farm income under this arrangement.

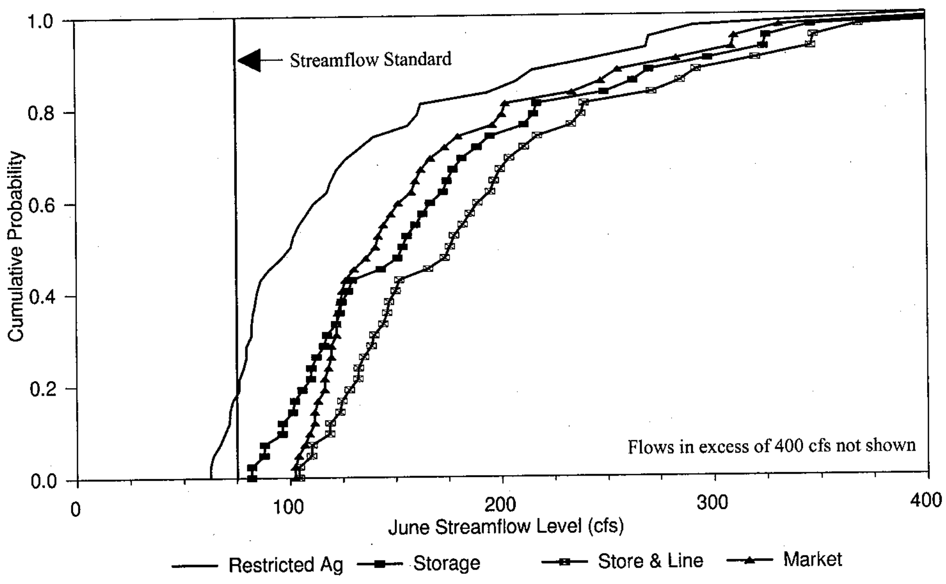

Figure 5. Cumulative probability distribution of June streamflow level in lower Walla Walla River for three blended policies and the restricted agricultural diversion policy

Policy Simulations

The empirical cumulative density functions (CDFs) for the June flow level in the critical reach, for each proposed policy, are illustrated in figure 5. The maximum quantity of water available for diversion under the RD policy was determined by eliminating all agricultural diversions in those Washington farm regions which affect the critical reach flow level, while all other basin regions continue to divert at monthly baseline levels. As shown in figure 5, this most extreme form of the RD policy fails to satisfy the 75 cfs flow goal 35% of the time in June.

The CDFs for the June flow level for the three other policies graphed in figure 5 were derived by simulating each policy under the assumption of being blended with the extreme variant of the RD policy that eliminates agricultural diversions in the regions affecting the streamflow level in the critical reach. Thus, the three "blended" CDFs represent the probability distribution of the maximum flow level attainable under each policy when agricultural diversions are eliminated in a subset of the farm regions. All three blended policies maintain the streamflow standard 100% of the time. The lowest June flow realized under any blended policy is 83 cfs for the storage policy.

The water management policies used to generate the CDFs in figure 5 are not politically acceptable since they completely eliminate irrigated agriculture in some regions. However, the simulated CDFs provide a means to determine the maximum irrigation diversion quantity that can be collectively diverted by the hydrologically linked regions at each probability level of maintaining the flow standard. Reference to figure 5 reveals that when the storage policy is blended with the extreme form of the RD policy, the June flow level exceeds 117 cfs 70% of the time. Thus, a maximum of 42 cfs can be diverted by agriculture in the linked regions if the 75 cfs target is satisfied at the 0.70 probability level. This quantity is the deterministic equivalent diversion value the CCP model optimally allocates to the impacted farm regions in June to satisfy the June flow target under the storage policy at the 0.70 probability level. May surface diversions are similarly adjusted downward from baseline levels, when necessary, to maintain the 75 cfs standard at higher probability levels.

Basinwide Analysis

The aggregate economic and hydrologic consequences of each blended policy are presented in this section. The economic analysis is limited to the Washington side of the basin, but Oregon water use is accounted for in the hydrology model and directly influences the quantity of water available to Washington for instream flow and diversion use. Oregon farms are assumed to divert surface supplies at monthly baseline levels, except for the market policy. Washington and Oregon municipal water use is also maintained at baseline levels. The pure RD policy is not considered because it did not maintain the monthly flow standard at a satisfactory probability level. Each policy is evaluated under three alternative scenarios.

Scenario 1

In Scenario 1, monthly surface diversions are restricted to the excess streamflow quantities available at a given probability level. The CDFs presented in figure 5 for June and corresponding CDFs for May were used to determine the excess flow levels. Key to this scenario is the fact that groundwater can be substituted for reduced surface diversions up to monthly baseline pumping capacity in each affected region.

Value of lost agricultural production, median May and June streamflow, changes in surface- and groundwater use, and average annual change in gravel aquifer reserves are reported in table 1. February, March, and April surface flows are not reported because the flow target is always met in these months under current use. Median May and June streamflows are 294 cfs and 5 cfs, respectively, under baseline use. Only the SL policy meets the flow target at the 0.50 probability without reducing baseline surface diversions. In fact, the SL policy augments June surface flows to the extent that the median June flow is 86 cfs at baseline diversion levels and exceeds the 75 cfs target. All policies satisfy the May flow target at the 0.50 probability level at baseline diversion levels.

Reducing June surface diversions at higher probability levels increases the median June flow level. The median May flow remains at the baseline level, except with the SL policy, until the flow target is satisfied at the 0.90 or higher probability level—at which point May surface diversions must be reduced below the baseline. The increase in the median May flow level under the SL policy at low probability levels results from less seepage, and not from reduced surface diversions.

The maximum average annual cost to Washington agriculture under all policy/probability combinations is $211,400, a relatively small cost given that baseline annual net return over variable cost to irrigated agriculture is $11.7 million in the impacted regions. Policy costs are small because most impacted regions can substitute groundwater for lost surface diversions. However, the substitution is generally not 100%,

Table 1. Agricultural Cost and Hydrologic Impact of Instream Flow Policies at Four Probability Levels: Groundwater Pumping Capacity Scenario (Scenario 1)

Policy	Probability Level	Agriculture Cost ($)	Median Streamflow (cfs)		Applied Irrigation Water Washington State Side of Basin (acre-feet)			Gravel Aquifer Mining[a] (acre-feet)
			May	June	Surface	Gravel	Basalt	
Baseline	N.A.	0	294	5	43,251	37,565	17,711	22,681
					------ Change Relative to Baseline ------			
Storage	0.50	5,997	294	75	-932	730	202	-1,564
Storage	0.70	32,102	294	108	-3,182	1,717	616	-887
Storage	0.90	132,568	348	123	-8,293	4,447	1,240	1,210
Storage	0.95	211,400	360	131	-9,426	4,431	1,240	1,188
SL	0.50	0	315	86	0	0	0	7,069
SL	0.70	12,932	315	109	-1,853	1,219	458	7,942
SL	0.90	52,777	346	130	-5,668	3,505	1,238	9,610
SL	0.95	83,560	365	138	-7,119	4,510	1,240	10,151
Market[b]	0.50	12,704	294	75	-1,825	1,219	458	726
Market[b]	0.70	23,091	294	89	-2,922	1,672	559	1,121
Market[b]	0.90	86,054	348	100	-7,394	4,788	1,241	2,491
Market[b]	0.95	107,784	360	103	-8,385	5,455	1,244	2,891

[a] A negative value for average annual mining of the gravel aquifer implies a reduction in the average annual drawdown of reservoir reserves relative to the baseline condition.

[b] Agricultural cost of this policy is limited to the Washington side of the basin.

especially at higher probability levels, as constraints on monthly pumping capacity and/or additional pumping costs make complete substitution either physically impossible or economically unprofitable. In these situations low-value grain crops receive less water and yield is reduced. Except for the storage policy, the ability to pump additional groundwater and/or deficit irrigate allows all baseline irrigated acreage to remain in production at all probability levels. Under the storage policy, 225 acres of irrigated pasture acreage is lost at the 0.95 probability level.

Under the storage policy, average annual aquifer drawdown is less than for the baseline because a significant portion of storage released for flow augmentation seeps into the aquifer. When the storage policy is combined with lining the porous reaches to form the SL policy, surface flows increase over the storage policy. However, aquifer drawdown is greater under the SL policy than under the storage policy because the policy reduces aquifer recharge over the entire year, not just the critical low flow months, which increases aquifer drawdown over the baseline. This crucial finding would not be measurable without an integrated model approach.

From a social perspective, the cost-effective choice for achieving the streamflow standard would couple the market policy with increased groundwater use. This conclusion is based on the fact that lining ($2.5 million) and storage construction ($28 million) costs have an amortized annual cost of $2.45 million assuming a 75-year project life and 8% interest rate, while the purchase of 2,400 acre-feet of water from Oregon (40 cfs in June) has a maximum annual value of $120,000 to Oregon agriculture (Willis).

Scenario 2

In Scenario 2, seasonal groundwater use cannot exceed baseline seasonal use in each region, but baseline groundwater can be redistributed over the growing season. This scenario would help preserve the aquifer in the long run.

Table 2 shows that each Scenario 2 policy/probability combination has a higher agricultural cost than in Scenario 1, except for the SL policy at the 0.50 probability level. At low probability levels, the cost increase is small because all baseline acreage continues to remain in production through the increased use of deficit irrigation. Relative to Scenario 1, at the 0.50 and 0.70 probability levels, storage policy cost is increased by $690 and $10,751, respectively, due to additional yield losses on pasture, wheat, and hay. At higher probabilities, irrigated wheat acreage is lost, and irrigated pasture losses increase—significantly raising policy cost over Scenario 1. The additional restriction on groundwater use increases storage policy cost by $64,098 and $59,938 at the 0.90 and 0.95 probability levels, respectively.

The additional groundwater restriction decreases aquifer mining relative to Scenario 1 for each policy/probability combination. Relative to the baseline drawdown level, drawdown is less for the storage and market policies, but greater for the SL policy due to lower recharge rates. A benefit of reduced aquifer drawdown is smaller stream seepage losses. With more flow staying instream, and not lost to seepage, the quantity of surface water that potentially can be diverted relative to Scenario 1 is increased. Reduced stream seepage does not affect the median streamflow level at the 0.50 probability level when the monthly probabilistic constraint is binding because the conserved surface supplies will be diverted to the point where the stochastic 75 cfs flow constraint is exactly satisfied at the 0.50 probability level. At higher probability levels,

Table 2. Agricultural Cost and Hydrologic Impact of Instream Flow Policies at Four Probability Levels: Baseline Seasonal Groundwater Use Scenario (Scenario 2)

Policy	Probability Level	Agriculture Cost ($)	Median Streamflow (cfs)		Applied Irrigation Water Washington State Side of Basin (acre-feet)			Gravel Aquifer Mining[a] (acre-feet)
			May	June	Surface	Gravel	Basalt	
Baseline	N.A.	0	294	5	43,251	37,565	17,711	22,681
					------------------ Change Relative to Baseline ------------------			
Storage	0.50	6,687	294	75	-828	0	0	-1,921
Storage	0.70	42,853	294	110	-2,973	0	0	-2,005
Storage	0.90	196,666	355	130	-7,914	0	0	-2,304
Storage	0.95	271,338	365	138	-9,026	0	0	-2,452
SL	0.50	0	315	86	0	0	0	7,069
SL	0.70	14,509	316	112	-1,803	0	0	7,026
SL	0.90	81,913	351	136	-5,610	0	0	6,837
SL	0.95	142,549	370	145	-7,007	0	0	6,818
Market[b]	0.50	14,229	295	75	-1,721	0	0	-1,317
Market[b]	0.70	30,781	296	94	-2,774	0	0	-1,393
Market[b]	0.90	154,608	355	108	-7,183	0	0	-1,620
Market[b]	0.95	199,743	367	112	-8,117	0	0	-1,685

[a] A negative value for average annual mining of the gravel aquifer implies a reduction in the average annual drawdown of reservoir reserves relative to the baseline condition.
[b] Agricultural cost of this policy is limited to the Washington side of the basin.

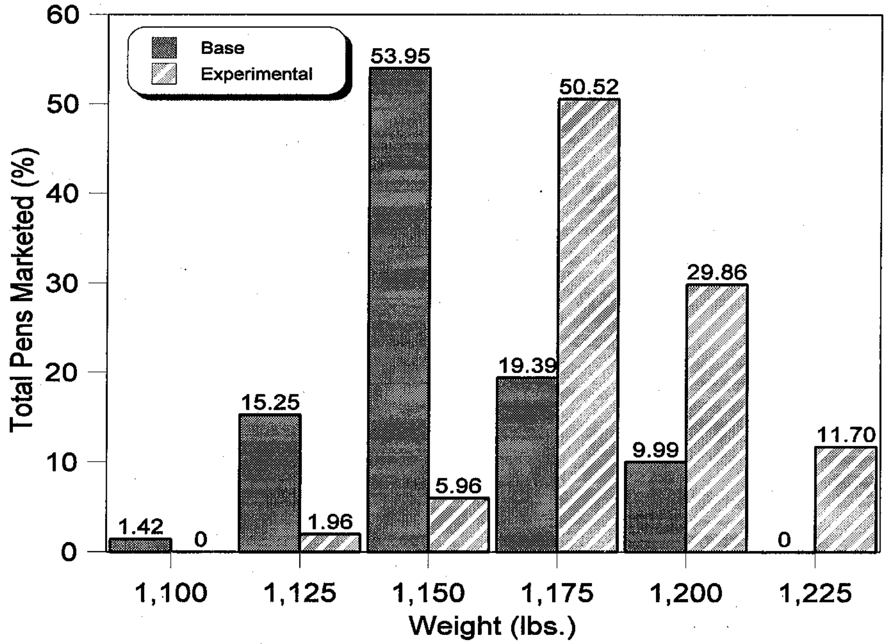

Figure 6. Monthly distribution of baseline seasonal groundwater use for the baseline and the market policy at the 0.95 probability level

median flow levels increase slightly relative to Scenario 1 because the cumulative long-run effect of pumping less groundwater translates into smaller stream seepage losses.

Though seasonal groundwater diversions are maintained at baseline diversion levels in Scenario 2 for each policy/probability combination, economic efficiency requires changing monthly groundwater use. In figure 6, monthly baseline groundwater use is compared with the market policy at the 0.95 probability level. Baseline use in July, August, and September is reduced and reallocated to May and June to partially compensate for reduced surface diversions in these months. Earlier use of groundwater reduces policy cost because all high-value crop acreage is fully irrigated and remains in production at the cost of deficit irrigating and/or losing some low-value irrigated crop acreage.

Scenario 3

In Scenario 3, increased irrigation efficiency is considered. Irrigation specialists familiar with the Walla Walla Basin affirm irrigation efficiency can be increased by 10 percentage points for the handline, wheel line, and rill technologies by increasing the number of irrigations by 50% and using less water per irrigation (Stockle and James). This increase in irrigation efficiency is achieved through a 50% higher irrigation labor cost. Irrigation energy cost is slightly less at the higher efficiency because less water is applied.

The Scenario 3 baseline solution presented in table 3 reports the agricultural cost and hydrologic consequence of a 10 percentage point increase in irrigation efficiency on the

Table 3. Agricultural Cost and Hydrologic Impact of Instream Flow Policies at Four Probability Levels: Efficiency Increase Scenario (Scenario 3)

Policy	Probability Level	Agriculture Cost ($)	Median Streamflow (cfs)		Applied Irrigation Water Washington State Side of Basin (acre-feet)			Gravel Aquifer Mining[a] (acre-feet)
			May	June	Surface	Gravel	Basalt	
Baseline	N.A.	0	294	5	43,251	37,565	17,711	22,681
					------------------ Change Relative to Baseline ------------------			
Scenario 3 Baseline[b]	N.A.	6,611	296	8	-1,120	-5,958	-1,337	-3,720
Scenario 3 + SL	0.50	6,611	317	89	-1,120	-5,958	-1,337	3,467
Scenario 3 + SL	0.70	18,754	317	110	-2,884	-4,700	-832	4,018
Scenario 3 + SL	0.90	42,553	349	132	-5,891	-2,261	-263	5,983
Scenario 3 + SL	0.95	55,347	368	138	-7,271	-1,061	-84	6,441
Scenario 3 + Market[c]	0.50	18,676	296	75	-2,874	-4,706	-835	-3,115
Scenario 3 + Market[c]	0.70	28,491	296	91	-3,954	-3,744	-718	-2,488
Scenario 3 + Market[c]	0.90	58,803	351	100	-7,618	-744	-54	-971
Scenario 3 + Market[c]	0.95	68,719	363	102	-8,537	-102	127	-793

[a] A negative value for average annual mining of the gravel aquifer implies a reduction in the average annual drawdown of reservoir reserves relative to the baseline condition.
[b] Scenario 3 baseline is the farm income and water use pattern that results if irrigation efficiency is increased by 10 percentage points in all regions on the Washington side of the basin.
[c] Agricultural cost of this policy is limited to the Washington side of the basin.

Washington side of the basin. The higher irrigation efficiency increases Washington production cost by only $6,611 over the original baseline as the labor cost increase is nearly offset by reductions in irrigation energy use and irrigation system maintenance cost. Under the Scenario 3 baseline, crop consumptive use remains at the original baseline level, but surface diversions decline by 1,120 acre-feet and groundwater diversions are reduced by 7,295 acre-feet. Because of the reduced groundwater withdrawals, annual aquifer drawdown is 3,720 acre-feet less than under the current baseline. Groundwater mining is not completely offset by the reduction in groundwater use, because less applied water is lost to aquifer recharge from deep percolation and return flow seepage. The higher irrigation efficiency increases the median streamflow level in the critical reach by 2 cfs in May and 3 cfs in June when consumptive use remains constant. This finding supports research by Frasier, Whittlesey, and Hamilton which found that irrigation efficiency increases will not substantially increase streamflow levels if the quantity of water consumptively used by crops remains constant.

Though increased irrigation efficiency contributes little to instream flows, it may reduce on-farm policy costs. The CDFs for the monthly flow levels in the critical reach at the higher irrigation efficiency were derived by the same procedure used in establishing the CDFs for Scenario 1 and Scenario 2. For brevity, the basinwide results for only the market and SL policies are reported in table 3. Agricultural cost is as much as one-third less with higher efficiency because less groundwater must be diverted to compensate for surface supply reductions and/or deficit irrigation levels can be reduced relative to Scenario 1. Higher irrigation efficiency also reduces the per acre energy cost of applying irrigation water as less water needs to be applied to satisfy crop irrigation requirements. In general, the private economic incentive to increase irrigation efficiency increases as water scarcity becomes more acute and/or at high energy cost levels. While increased irrigation efficiency does not appreciably increase median streamflow levels when crop consumptive use remains constant, it does reduce groundwater mining.

Distributional Impacts

Though small in total, policy cost varies considerably across regions due to regional differences in crops, water supply sources, groundwater pumping capacity, and pump lift. The percentage reduction from baseline net income levels under the storage policy for each impacted region is presented in table 4 for Scenarios 1 and 2. The reported results are limited to the 0.70 and 0.95 probability levels. These results should be viewed from the perspective of a social planner seeking to minimize basinwide agricultural policy cost because economic efficiency, and not surface water right priority, determines the quantity of baseline surface diversions each affected region must sacrifice to satisfy the monthly flow target. However, regions are prevented from diverting surface water in excess of their monthly appropriative right, even if such diversions would minimize basinwide policy cost.

Under Scenario 1, regional policy cost as measured by percentage net income loss is smallest for regions 13 and 14 due to a high marginal value for surface water in these regions, a result of an acreage concentration in high-value vegetable and orchard production, and high groundwater costs due to deep well lifts. Region 12 has the lowest

Table 4. Agricultural Cost of the Storage Policy Under Two Scenarios Evaluated at Two Probability Levels for Policy Impacted Regions

			Monthly Groundwater Capacity (Scenario 1)				Baseline Seasonal Groundwater Use (Scenario 2)			
			0.70 Probability		0.95 Probability		0.70 Probability		0.95 Probability	
Impacted Farm Region	Baseline Irrigated Acres	Baseline Income ($)	Policy Cost ($)	Income Loss (%)	Policy Cost ($)	Income Loss (%)	Policy Cost ($)	Income Loss (%)	Policy Cost ($)	Income Loss (%)
5	1,788	554,911	1,437	0.26	22,112	3.98	12,154	2.19	32,662	5.89
8	12,746	4,843,264	13,113	0.27	156,332	3.23	5,834	0.12	183,874	3.92
10	1,643	438,139	1,997	0.46	4,387	1.00	2,543	0.58	9,486	2.17
11	2,052	655,401	3,175	0.49	6,318	0.96	3,285	0.50	9,050	1.38
12	1,658	461,773	7,240	1.59	13,859	3.00	7,912	1.74	16,069	3.48
13	6,004	3,427,874	2,767	0.08	5,568	0.16	7,395	0.22	14,879	0.43
14	1,445	1,086,958	782	0.07	1,162	0.11	1,153	0.11	1,923	0.18
15	318	155,714	1,310	0.85	1,310	0.85	2,098	1.37	2,915	1.87
16	48	26,019	282	1.09	352	1.35	480	1.88	480	1.88
Total	27,702	11,650,072	32,102	0.28	211,400	1.81	42,853	0.37	271,338	2.33

Note: Baseline income represents regional return to baseline irrigated acreage. Baseline dryland crop acreage exceeds irrigated acreage in all regions except regions 8 and 13 (refer to figure 1).

marginal value of surface diversions because a high proportion of its acreage is in low-value pasture under inefficient gravity irrigation. Thus, relative cost to region 12 is higher and this region sacrifices about 1.6% of net farm income (table 4) at the 0.70 probability level, compared to losses of less than 0.1% for regions 13 and 14. At the 0.95 probability level, the percentage income reduction becomes greatest for regions 5 and 8 because these regions primarily grow low-value small grains and dry beans, and have shallow pump lifts—providing a good opportunity to substitute groundwater for forfeited surface diversions. All policy costs under Scenario 1 arise from yield losses due to deficit irrigation of low-value crops and/or increased groundwater use.

Besides increasing basinwide policy cost, the seasonal restriction on groundwater use in Scenario 2 also affects the relative ability of individual regions to adjust to a given policy. For example, at the 0.70 probability level, region 5 has the third smallest percentage net income loss under Scenario 1, but the highest percentage loss under Scenario 2. Region 5 costs markedly increase because the region is concentrated in low-value agriculture and loses a disproportionate share of its total water supply when groundwater use cannot be increased over baseline seasonal use. The groundwater use restriction increases the relative value of scarce surface supplies in favor of other regions to the detriment of region 5, and this region forfeits nearly three times more surface supplies than it did in Scenario 1.

Conclusions

Linking economic and hydrology models permits the benefits and costs of potential water policies to be more accurately examined. Such models are especially valuable when developing minimum streamflow polices where stochastic streamflows complicate the analysis. Policies which provide inadequate streamflow in some years could prevent maintaining a valuable anadromous fish stock. The integrated modeling approach provides water policy planners with a technique to accurately measure both the economic cost and hydrologic consequences of maintaining a minimum streamflow level at alternative probability levels.

The modeling approach allows a thorough analysis of the benefits and costs of alternative storage policies. For example, the costly storage policy was shown to be ineffective since nearly 40% of June reservoir releases were lost to seepage. Augmenting the storage policy with the lining policy solved the seepage problem, but at the expense of increasing annual aquifer drawdown. Water markets for streamflow augmentation were shown to be the most cost-effective policy in the study area. Markets allow water to be derived from cost-effective sources within the limits of institutional and technical constraints. Increased irrigation efficiency might be in the farmer's economic self-interest, but will not increase streamflows over the long run. Basinwide streamflow levels can be increased only if crop consumptive use is decreased or additional water is provided through increased storage.

Agricultural policy cost can rapidly increase as the probability of maintaining the minimum streamflow goal is increased. For one storage policy scenario, the agricultural cost of maintaining the minimum streamflow target is $6,687 at the 0.50 probability level, but increases 40-fold (to $271,338) when the flow target is maintained at the 0.95 probability level.

The disaggregated modeling approach provides policy makers with a tool to target low-cost water providers. Factors such as groundwater depth and availability, crop type, and irrigation system all affect the marginal value of water to an agricultural region. The ability to alter the temporal application of stored irrigation water supplies, including groundwater, over the irrigation season is an important factor in minimizing streamflow policy cost. Coordinated ground- and surface water management strategies should be actively pursued in irrigated river basins with functional groundwater supplies to minimize the basinwide cost of streamflow augmentation policies.

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