Irrigation Development versus Hydroelectric Generation: Can Interruptible Irrigation Play a Role?

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Irrigation, under conditions where water has a high opportunity cost, could be interruptible with water use, only occurring when water is plentiful. Pacific Northwest case studies indicate interruption can substantially lessen the opportunity cost of new irrigation developments, although not enough to justify the particular case projects examined. Interruptible operation of existing projects in the case study areas appears desirable.

Key words: irrigation, risk, stochastic programming, water availability, welfare analysis.

Water demand and intersectoral competition are increasing in the Pacific Northwest (PNW) (Anderson, Whittlesey et al.). PNW streamflow competition involves irrigation, hydroelectric generation, transportation, fisheries, manufacturing, municipalities, and recreation. Whittlesey et al., Houston and Whittlesey, and McCarl and Ross have shown important economic dimensions to the irrigation/hydropower water use tradeoff; the per acre opportunity cost of irrigation water can be as high as $200 per year (equivalently, $75 per acre foot). Currently, there are efforts to expand regional irrigated acreage. In particular, the potential expansion of the East-Central Washington Columbia Basin Irrigation project was evaluated by several parties in the mid-1980s, and in these evaluations intersectoral water tradeoffs were an important issue as well as a key cost element. In total, Whittlesey et al. estimate that there are 2.2 million acres of potentially irrigable land in the PNW. This quantity of land coupled with an up to $200 annual opportunity cost per acre points out that large costs are potentially involved.

Whittlesey et al. have analyzed the tradeoffs between irrigation development and hydropower. Also, Houston and Whittlesey have examined the potential for water marketing between irrigation and hydropower. However, these analyses assume that acreage either will be fully irrigated or that permanent water sales will occur. But, water availability exhibits considerable year-to-year variability (fig. 1). This flow variability has led PNW power planners to rely only on the quantity of hydropower which can be generated in the lowest flow years and to satisfy the rest of the demand from thermal facilities. For example, Bonneville Power Administration (BPA) determines required thermal capacity by examining the projected demand for electricity minus the hydroelectric potential in a low flow period (1929–31). Irrigation strategies could be designed to complement power needs by not using water in critical periods. Whittlesey and Houston as well as McCarl and Ross investigated the desirability of such a strategy.[1] Whittlesey and Houston concluded that irrigation interruptions occurring 10%–15% of the time would

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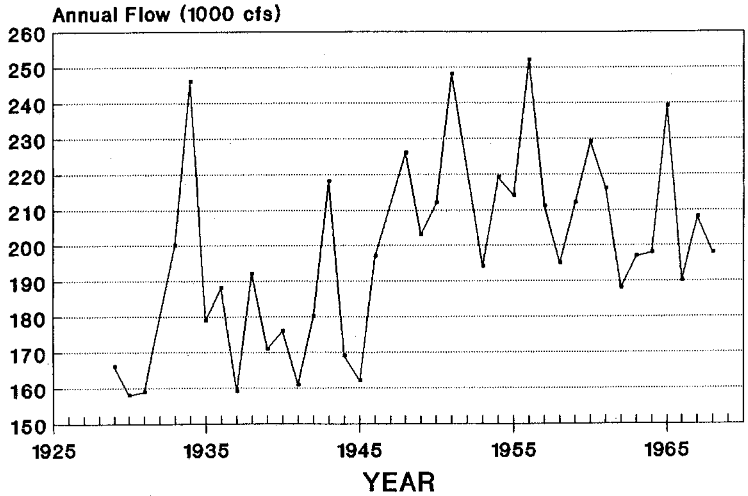
[1] Such a strategy would reduce the peak need for thermal generating capacity, thereby reducing cost of electricity generation and, following the theory of peak load pricing (Joskow), reducing consumer electricity cost.



Note: 1000 cfs equals 28.3 cu meter/sec

Figure 1. Annual flow at Bonneville Dam

be socially beneficial with power consumer gains offsetting farmer losses. Later, Whittlesey, Hamilton, and Halvorson concluded the same thing. McCarl and Ross, examining power consumers' welfare, concluded that irrigation interruptions 7.5% of the time would lead to an 87% reduction in the opportunity cost of water. The purpose of the study done herein is to examine further the frequency of irrigation interruption question considering the combined welfare of both power and agricultural interests and to examine whether interruptions provide additional economic justification for irrigation project development. Also interruptible operation of existing projects will be investigated.

Methods

The basic economic problem studied herein involves decisions about facility investment and subsequent facility operation under uncertainty. Land may be either equipped with irrigation facilities or farmed dryland. Power may be generated hydroelectrically or by using existing or newly constructed thermal facilities. Both irrigation and new thermal generation facilities must be developed in advance of their use. Such facilities, once developed, are available regardless of water availability. On the other hand, decisions to irrigate, pass water through the hydroelectric generators, and operate thermal powered generators can be varied in reaction to the water available, subject to capacity constraints. A programming model of this process may be developed using stochastic programming with recourse (Hansotia) or discrete stochastic programming (Cocks; Rae 1971a, b). This model is as follows:

Maximize

$$(1) \quad CPD*U - CID*V + \sum_k P_k [-CH(W_k) + \beta(Y_k) - CNH(Z_k)]$$

so that

$$
\begin{array}{llr}
(2) & V & \leq L \\
(3) & W_k + \alpha(Y_k) & \leq H_k \quad \text{for all } k \\
(4) & -W_k + X_k - Z_k & = 0 \quad \text{for all } k \\
(5) & -U + Z_k & \leq EC \quad \text{for all } k \\
(6) & -V + Y_k & \leq 0 \quad \text{for all } k \\
(7) & X_k - \gamma(Y_k) & \geq PD \quad \text{for all } k,
\end{array}
$$

where k identifies the water flow state, P_k the accompanying probability, and H_k the associated available hydropower. The variables are separable into two classes: (*a*) operational items which depend on state of nature (k) and (*b*) overall investment items. The operational variables are hydropower generation (W_k), total power generated (X_k), irrigated acreage use (Y_k), and non-hydropower generation (Z_k). The investment variables are new thermal generating capacity (U) and new irrigated acreage (V).

Equation (2) limits irrigated land developed (V) to irrigable land available (L). Equation (3) limits hydropower generation (W_k) and hydro precluded by irrigation ($\alpha(Y_k)$) to that available (H_k). Equation (4) equates power available for consumption (W_k) with hydropower (W_k) plus thermal generation (Z_k). Equation (5) limits thermal generation (Z_k) to existing capacity (EC) plus new construction (U). Equation (6) limits irrigated acreage use (Y_k) to developed irrigated acres (V); and equation (7) insures power generated (Y_k) is greater than power demand (U) plus irrigation pumping electricity use ($\gamma(Y_k)$). An inelastic specification for power demand is adopted here following the findings of McCarl and Ross.

The objective function involves the probabilistically weighted sum of the benefits and costs from operation under uncertain water flow less the costs of investments in thermal generating capacity ($CPD*U$) and irrigation facilities ($CID*V$). The uncertain state terms involve the net benefits from irrigating $\beta(Y_k)$, less the costs of hydropower generation ($CH(W_k)$), and the costs of thermal power generation ($CNH(Z_k)$).

All in all, this model will derive the optimal level of overall investment/development considering all water states and the optimal level of operation under each water state given the installed facilities. An empirical example of this model can be obtained by writing the authors.

Model Discussion

The model is a two-stage stochastic program (Dantzig) which also falls into the classes of discrete stochastic programs (Cocks; Rae 1971a, b) and stochastic programs under recourse (Hansotia). The two-stage context can be developed as follows. In the first stage, there are investment decisions which make facilities available regardless of water availability state. In the second stage, there are operating decisions which are made given knowledge of water availability and facility investments. Thus, the irrigation and hydropower operating decisions are made with knowledge of water availability, whereas the investment decisions are made with respect to the water availability probability distribution. This assumption is not terribly unrealistic because the Columbia system flow can be predicted fairly accurately before the irrigation season. See Glantz for discussion.

Additionally, the events are assumed independent. The Columbia system is assumed to begin every year in the same initial state. Occurrence of several low flow years in a row (e.g., as occurred in the late 1920s–early 1930s) would not satisfy this assumption. (Relaxation of this assumption would require a study with a complex hydrological component.)

The model has three uses for water: hydropower generation, irrigation, and slack—nonuse, which can be interpreted as spillage over the dams. Ordinarily, water will be used for hydropower generation unless power demand is saturated or the water is diverted for irrigation. Water will be used for irrigation if the returns exceed the development plus opportunity costs. The water opportunity cost will have three stages: (*a*) zero-valued water when the power demand is saturated and additional water goes into slack; (*b*) nonzero-valued water where water use in hydropower generation can be reduced by replacing hydropower generation with thermal generation from existing, not fully used thermal plants; and (*c*) yet higher-valued water where diversions from hydropower require construction and use of new thermal generation facilities. Irrigation development requires a positive probabilistically weighted sum of the net benefits less water opportunity costs. This model embodies a probabilistic form of the Kaldor-Hicks compensation principle; i.e., as long as the probabilistically weighted benefits exceed development costs plus the probabilistically weighted water opportunity cost, then the model will undertake irrigation construction regardless of to whom and when the benefits and costs accrue.

Generically, this problem involves the optimum level of investment in a stochastic environment. Howe and Cochran (HC) analyzed a similar problem considering the long-run investment and short-run operating decisions relative to snow removal. HC's basic analytical framework shows that (paraphrasing their results on p. 53) investment should be undertaken until marginal investment cost equals the probabilistically weighted benefits from the investment. This conclusion was inherent in the above discussion about when irrigation is profitable.

Finally, note that we do not have estimates of the costs of implementing the interruptions, thus we will only examine the potential net benefits from development and interruptions.

Empirical Specification

Two cases were examined involving projects potentially irrigated from the Columbia River. Project data were drawn from Whittlesey et al. The first project is the potential East High Project in the Columbia Basin of East Central Washington near Moses Lake, and the second is the potential Umatilla II project along the Columbia River near Umatilla, Oregon. Whittlesey et al. and McCarl and Ross give additional details on the study areas.

The East High Project involves 310,000 acres located on the upper Columbia River. This project draws water from above Grand Coulee Dam, which is the furthest up river of the U.S. hydroelectric dams diverting the largest kinetic head of potential hydropower. Thus, this project possesses a relatively high hydroelectric opportunity cost. East High was authorized in the 1930s and has water rights with that seniority. In the nearby area there are about 500,000 acres of currently irrigated land.

The Umatilla II project contains 40,000 acres along the Columbia River. This project is downstream from East High, involving less kinetic head and a lower hydropower opportunity cost. Further, the dams downstream from Umatilla are BPA-owned, and BPA to date has not chosen to challenge increases in upstream diversions. Thus, water may well be available for project development. In the Umatilla Region there are about 250,000 currently irrigated acres.

Data were developed using identical procedures for both case studies. The farm irrigation data (water requirements and pumping energy requirements) came from regional extension budgets and Whittlesey et al. Power plant operating and development costs were adapted from McCarl and Ross. The water flow data were taken from McCarl and Ross's table 3 (p. 1324), who in turn used data from a Bonneville Power Administration (BPA) simulation model for the water years 1929–68. Energy demand and existing thermal capacity data were drawn from PNW Utilities Conference Committee reports (1983a, b). Hydroelectric demand was calculated as 1985 total demand less existing thermal resources. Data on power diverted by irrigation were from McCarl and Ross's table 3.

The model requires an estimate of the net benefits from increased irrigated production. The East High Project is large, so use of a consumers' plus producers' surplus (CSPS) appeared desirable. Thus, an estimate was constructed of the annual CSPS consequences of increased fully irrigated acreage. This was done by using an auxiliary existing PNW agricultural sector model. This model was developed by BPA and Northwest Economics Associates (Northwest Economics Associates 1981, 1984) and is, hereafter, called the BPA/NEA model. The BPA/NEA model is a mathematical programming, agricultural sector model of the type explained in McCarl and Spreen. The model maximizes CSPS for the production of selected primary and processed products (see appendix) in ten PNW regions considering demands in the PNW, the rest of the U.S., and the rest of the world. Runs from the BPA/NEA model were used to develop benefit estimates under expanded irrigated acreage as follows.[2] Runs were obtained reflecting base acreage and an additional 150,000 fully irrigated acres in the East High area (reflecting an increase in regional irrigated land from 500,000 to 650,000 acres) with the appropriate pumping lift and reduction in dryland area. Thus, this model gave estimates of the value of converting dryland to irrigated acreage and operating that acreage. Comparing the runs revealed full utilization of the additional acreage with an increase in CSPS. The change in CSPS value was used as exogenous data in the model described herein. The benefits curve for the model herein was derived under two assumptions. First, demand for additional irrigated acres was assumed to be infinitely elastic at $84 per acre converted to irrigation (the per additional ir-

[2] Thanks to John Wilkens and Bob McKusick for making the runs available.

rigated acre change in CSPS from the BPA/NEA model).[3] This $84 estimates the annual net benefits of fully irrigating one additional acre in a year after paying the costs of all production inputs and the amortized development cost. Subsequently, the amortized cost of development ($130.92) assumed in the BPA/NEA model and the cost of pumping electricity (which is the only input explicitly modeled herein) were added to generate a point benefits estimate ($264/acre) for additional fully irrigated production.

Second, a price elastic model was assembled containing a linear demand curve for fully irrigated acres in a year. The curve was calculated so that it passed through $264 at 650,000 acres and so that the integral under it equaled $84 per acre when irrigated acres increase from 500,000 to 650,000. The resultant demand curve is $R = 358.96 - 0.000146I$, where R is the per acre price and I the acres irrigated. In this case, the irrigable land available was increased to 650,000.

The final data needed were an estimate of the irrigation development costs. The BPA model assumed annual development costs of $130.92 per acre. This estimate arises based on existing irrigated acreage development costs as well as Bureau of Reclamation cost sharing. The net present value of a $130.92 per acre cost paid over fifteen years at 4% real interest is $1,514. However, development costs for East High are estimated at more than $4,000 per acre, which amounts to an annual cost (under 15-year payback and 4% interest) of approximately $346 per acre. In turn, rather than development returning $84 per acre, these costs lead to a $131 net loss. The analysis below initially assumes the $264 benefits and the $130.92 per acre development cost. Later, alternative development costs are considered.

Experiments

The appraisal of the irrigation development options and water usage possibilities are examined using five model experiments for each case study area.

The first experiment uses the model as described in the previous section. This experiment simulates optimal construction and water use including the possibility of irrigation interruptions.

The second experiment precludes irrigation interruptions, assuming once irrigated acres are developed, they will be fully irrigated regardless of flow (assuming sufficient water for uses with prior water rights) but the amount of irrigated land development is optimized. This was done by converting equation (6) to an equality constraint.

The third experiment forces development of all irrigable land, i.e., equation (2) is an equality. However, irrigation is interruptible, i.e., equation (6) is an inequality. This experiment simulates the way water would be allocated if interruptions are possible, but all land is developed.

The fourth experiment forces full land development and irrigation in each water year, i.e., both equations (2) and (6) were converted to equalities. This experiment gives the returns to full development without interruption.

The fifth experiment prohibits land development and thereby allows no additional irrigation, i.e., the right-hand side on equation (2) was changed to zero, simulating what happens if the water remained in the hydroelectric system.

By comparing the objective function value of these experiments, the differences in CSPS arising under the various situations can be examined and the desirability of pursuing different operating policies can be examined.

Results

The five experiments were performed for each case study, first under perfectly elastic demand for irrigated production, then under the sloped demand. In addition, material will be presented regarding interruptions of existing acreage and alterations in power demand.

East High Project Results

Table 1 shows the East High results from the five experiments for the perfectly elastic demand case. When the model was allowed to develop as much irrigation as it wanted but did not have to operate it every year (experiment 1) all the potential irrigable land was developed ($V = 310{,}000$). However, irrigation was curtailed ($Y_k = 0$) in the water year 1930

[3] The distribution of this benefit is that aggregate consumers will gain by $415 per acre, while all producers lose the equivalent of $331 per acre. The difference amounts to the reported net $84 per acre increase in social benefits.

Table 1. East High Project (310,000 Acres): The Case of Perfectly Elastic Derived Demand for Irrigated Land

Experiment	Objective Value	Results
	($ mill.)	
(1) Less than full development permitted Interruptible irrigation	−385.55[c]	Full land development[a] Zero irrigation year 1930[b] Partial irrigation 1937, 1931 Full irrigation rest of years Zero nonhydro development
(2) Less than full development permitted Full irrigation required each year	−418.24	Zero land development Zero irrigation Zero nonhydro development
(3) Full development required Interruptible irrigation	−385.55	Same results as experiment (1)
(4) Full development required Full irrigation required each year	−435.23	Full development[d] Full irrigation Nonhydro development of 227.8 MW
(5) Zero development allowed Zero irrigation	−418.24	Same results as experiment (2)

[a] Development costs of more than $247.50 per acre would make case 5 optimal.
[b] Interruptible irrigation (as resulted in experiments 1 and 3) yields a $32.71 million (equivalently $105.77 per acre or $26.25 per acre foot) benefit over no agricultural development (result of experiments 2 and 5) and $49.68 million ($160.26/acre or $40.00/acre foot) benefit over full agricultural development and water use (result of experiment 4).
[c] This is the objective function value from the model and reflects thermal and hydropower generation costs as well as agricultural net benefits.
[d] Full land development with full irrigation (i.e., result of experiment 4) will cost society $16.99 million ($54.81/acre or 13.68/acre foot over zero development (experiment 2 or 5).

(the lowest water flow year in the 40) and only partially used for the years ($Y_k < V$) 1937 and 1931 (the next two lowest). Full irrigation was employed in the rest of the years ($Y_k = V$). This solution reflects operation without new thermal plant development ($U = 0$). Irrigated acreage was fully used only when there was excess total generating capacity relative to demand (considering existing thermal plus hydropower). When this was not the case, interruption occurred.

However, when new irrigation could not be interrupted (experiment 2), no new acres were irrigated. Water use in the critical water years was simply too expensive. When the model was forced to develop and irrigate the land all years (experiment 3) then, about 227 megawatts of new non hydro facilities (U) were required.[4] Comparison of experiment 2 and 5 results show that when interruptions are not permitted that society is better off by $16.99 million ($54.81/acre) by leaving the East High Project undeveloped. However, society does benefit from irrigation development under an interruptible regime assuming $130.92 amortized development costs (a key assumption as discussed below). A comparison of the experiment 1 and 5 results show this benefit amounts to $32.71 million ($105.77/acre) over no agricultural development and $49.68 million ($160.26/acre) over irrigation development which requires full water use in all years. This result arises because critical year irrigation causes hydropower loss that is replaced by costly new thermal generating facilities. Since irrigation is interrupted infrequently (7.5% of the time) society could afford to compensate farmers as much as $1,410 ($105.77/0.075) per acre during the interrupted years and still be as well off as without irrigation development.

Underestimation of the value of irrigated production is a possible reason for the model employing interruptible irrigation; thus, sensitivity analysis was done. This showed that the annual returns to irrigated land would have to exceed $7,000 per acre before full irrigation in all water years would be optimal (27.5 times our estimate). Such a figure is far too large for practical consideration. Underestimation of irrigated production value is not a plausible

[4] One megawatt equals 1,000 kilowatts, and 1 megawatt equals 8,760 megawatt hours or 8,760,000 kilowatt hours.

Table 2. Umatilla II Project (40,000 Acres): The Case of Perfectly Elastic Derived Demand for Irrigated Land

Experiment	Objective Value	Results
	($ mill.)	
(1) Less than full development permitted Interruptible irrigation	−413.73[c]	Full land development[a] Zero irrigation year 1930[b] Partial irrigation year 1937 Full irrigation rest of years Zero nonhydro development
(2) Less than full development permitted Full irrigation required each year	−417.19	Full development[d] Full irrigation Nonhydro development (15.9 MW) Nonhydro facilities are required for years 1930, 1937[e]
(3) Full development required Interruptible irrigation	−413.73	Same results as experiment (1)
(4) Full development required Full irrigation required each year	−417.19	Full development[d] Full irrigation[e] Nonhydro development (15.9 MW)
(5) Zero development allowed	−418.24	Zero irrigation development Zero nonhydro development

[a] Development costs of more than $246.76 per acre would make the no irrigation case better than this one.
[b] Interruptible irrigation (i.e., results of experiments 1 and 3) benefits society $4.5 million (equivalently $112.75/acre benefit or $41.26 per acre foot) over no irrigaton and $3.46 million ($36.66/acre foot or $86.50/acre) over full agricultural development.
[c] These objective function values include the cost of power generation plus the net benefits from agricultural development and thus are negative.
[d] Development costs above $157.17 would make the no-irrigation solution better than this one.
[e] Full land development with full irrigation (i.e., result of experiments 2 and 4) will benefit society by $1.05 million ($26.25/acre or $9.61/acre foot) relative to zero irrigation development (i.e., experiment 5).

explanation for the adoption of the interruptible policy.

The result on the value of irrigating relative to no development is sensitive to the development cost assumption. Any increase in the East High development costs to more than an amortized $236.70 cost causes the no irrigation alternative to be preferable. Based on these results, then, we may conclude two things relative to East High:

(*a*) Current real amortized development costs (approximately $346) do not render the East High Project socially profitable under either of the irrigation regimes studied. Development costs would have to fall below $236.70 per acre before benefits from interruptible irrigation would be realized and below $185.73 to obtain benefits from full irrigation. Thus, it would be socially optimal to not develop under current and most forseeable future conditions.

(*b*) If the East High Project is constructed, there is a considerable benefit from operating it in an interruptible fashion ($160.26/acre). These interruptions would occur infrequently (3 years out of 40), and farmers could be compensated quite substantially in the interrupted years with society still as well off.

Umatilla

Table 2 shows the results of the Umatilla II experiments. As mentioned before, Umatilla II is much smaller but requires more power per acre for pumping but involves less kinetic head (Whittlesey et al., McCarl and Ross). Because of these differences, the results differ somewhat.

Again, the optimal solution to the unrestricted model (experiment 1) is full land development with interruptible irrigation. Here there is no irrigation in 1930 and partial irrigation in 1937, with full irrigation the rest of the years. When all developed lands are fully irrigated (experiment 2), the project is still fully developed. In this case the hydropower opportunity cost is small enough that society benefits more from having the project than not. The benefit of interruptible versus full development and irrigation amounts to $3.46 million ($86.50/acre). Also, the comparative stat-

Table 3. Total Net Benefits from Currently Developed Acreage Under Varying Irrigation Regimes with Zero Development Cost Assumed

Pumping Electricity Use	Irrigation Operation Regime		Marginal Benefits to Interruptible		
	Full	Interruptible	Total	Per Acre	Per Acre Foot
	($ mill.)			($)	($)
East High					
Full	−344.63	−344.46	49.67[a]	160.22	40.00
50%	−380.93	−343.12	37.81[b]	121.98	30.44
Umatilla II					
Full	−411.75	−408.49	3.46[c]	86.48	31.62
50%	−410.10	−408.17	1.93[d]	48.15	17.61

[a] An increase in returns per acre to more than $7,000 per acre is required to make zero interruptions optimal. The optimal interruptible solution involves three interruptions in the forty years.
[b] An increase in returns per acre to more than $5,468 per acre is required to make zero interruptions optimal. The optimal interruptible solution involves three interruptions.
[c] An increase in returns per acre to more than $3,804 per acre is required to make zero interruptions optimal. The optimal interruptible solution involves two interruptions.
[d] An increase in returns per acre to more than $2,190 per acre is required to make zero interruptions optimal. The optimal interruptible solution involves one interruption.

ics show a net benefit of the interruptible project over no project amounts to $4.57 million ($112.75/acre) at $130.92 development cost. Therefore, although agricultural development brings benefit to society whether or not interruptions occur, it is worth $86.50 per acre for society to adopt a policy of interrupting irrigation in low water years. Again, there is potential for substantial compensation to farmers. Sensitivity analysis shows the returns need to be more than $3,804 per acre before full irrigation occurs in every year (14.4 times our estimate).

The development cost assumption is again critical and sensitivity analysis shows that development costs above $243.61 make the no development option optimal. Whittlesey et al. estimate actual development costs at $3,000 per acre, which amounts to approximately $259 in annual cost. Thus, the Umatilla project is not currently socially profitable, but if it is developed operating under interruptible irrigation leads to 86.50 per acre more in social benefits than noninterruptible irrigation.

Less Than Perfectly Elastic Demand

The results for the less than perfectly elastic demand curve case for both regions were qualitatively the same as those above. The amount of hydropower development for both regions are the same for both cases, and the social benefit estimates are within 0.1%. Therefore, these results are not presented in the interest of conserving space.

Existing Irrigated Acres

The enhanced economic returns under interruptible irrigation and the economic unattractiveness of the new irrigation development raise the question as to how existing irrigated acreage should be managed. Both projects are located in areas where parcels with similar characteristics are currently under irrigation (although the pumping lift may not be as great). Consequently, analysis was done on management of currently irrigated land. Here, the development cost was reduced to zero and pumping electricity use was held at current levels and reduced by 50%. The subsequent results are given in table 3. These results show benefits to interruptible operation of these existing irrigated acres. For example, operating existing East High region acreage with 50% of the above pumping electricity use still yields a $121.98 per acre benefit over the current practice of full irrigation. Also, the results show that a tenfold or more increase in agricultural returns are required before the current full irrigation in all years policy is optimal.

Altering Power Demand

Finally, investigations were done considering power demand increases. However, regardless of power demand, the same interruption frequency arose as in the base case. The increased power demand only led to increases in thermal construction. Interruption was still done such that no thermal construction was required because of diversions. Experimentation shows that interruption frequency only increases when the quantity of hydropower foregone by irrigation diversion increases.

Concluding Comments

Neither of the projects studied is socially profitable at current development costs though they may be regionally profitable (Findeis and Whittlesey). However, interruptible irrigation does lower project opportunity costs, so other projects may be justified if set up on an interruptible basis. The results also show that for existing projects it would be socially beneficial to interrupt irrigation either fully or partially in low water years such that the need for thermal power is reduced as power demand grows. The interruption result merits discussion from four aspects.

First, interruption frequency varied between 5% and 7.5%. Social welfare is best served when irrigation is interrupted in critical water years. Interruption frequency varied depending on project size but the determining factor remained that diversions should only occur when the lost hydropower can be replaced from existing, not fully utilized, thermal plants.

Second, the returns to interrupting irrigation are less the further downstream or the lower the opportunity cost of water (the lower the cumulative kinetic head of hydroelectric potential).

Third, there is potential for an infrequent temporary water market as argued in Whittlesey, Hamilton, and Halvorson. Electricity consumers should be willing to pay more in critical years than the water is worth in irrigation but not in all years. This willingness to pay occurs infrequently (2–3 years out of 40 in the case above), occurring only when irrigation diversions reduce the hydropower that can be relied upon. Analysis indicates the interruption frequency remains unchanged as power demand grows. Interruptions have occurred in the past; for example, in California and Colorado (Howitt, Watson, and Nuckton; and Howe et al.). Institutional mechanisms could be put in place to facilitate temporary water markets and interruptions when needed.

Fourth, the economic results indicate that society would gain by an average annual amount of $120–$160 per acre in the East High case or $48–$86 per acre in the Umatilla case by interrupting irrigation water on existing projects. These interruptions occur 7.5% of the time for East High and 2.5% or 5% of the time for Umatilla. This would imply that society should be willing to pay as much as $1,600–$2,133 per acre for East High or $1,720–$1,920 per acre for Umatilla in the years when interruptions are needed to avoid needing to build costly thermal power generators. On an acre-foot diverted basis this amounts to $400–$500 in East High and $628–$701 in Umatilla. Such economic returns would probably pay for any losses caused by curtailed water use.

Such an interruptible policy could be implemented not only through water markets, as mentioned above, but also through programs such as a "set aside" program where the consumers through utility companies could compensate farmers for diminished irrigation in critical years, through a regulatory system of water curtailments or by letting power producers challenge out of stream diversions based on rights to instream water coupled with the institution of junior water rights for East High.

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APPENDIX

A Brief Description of the Agricultural Sector Model

The model used to derive net benefits for expanded irrigation was the Bonneville Power Administration (BPA) Agricultural Model (Northwest Economic Associates). This model was designed to study the effects of change in irrigated acreage, electricity rate structures, and other economic parameters on agricultural activity, income, and energy usage.

The model depicts production of twenty raw (wheat, other grains, alfalfa, other hay, corn, potatoes, other field crops, apples, other fruits and nuts, vegetables, cull apples, cull potatoes, soybeans, silage, cull cows, 425-pound calves, 650-pound yearlings, other livestock, milk, and poultry) and ten processed products (frozen potatoes, dehydrated potatoes, canned apple juice, canned other fruits, frozen other fruits, canned vegetables, frozen vegetables, red meat, poultry meat, and processed milk) in eleven subregions within Washington, Oregon, Idaho, and western Montana. Land within these regions is disaggregated into five classes on which water is assumed to come from surface and groundwater sources disaggregated into seven pump lift classes. The model reflects, production, interregion transportation, feeding, processing, final transportation and consumption at PNW, rest of U.S., and rest-of-world levels. The model has been used operationally since about 1982 in constructing power forecasts.