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Water management in a far from equilibrium system

A model of the Columbia River

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40th Annual Conference of the
Australian Agricultural and Resource Economics Society
Melbourne, 13-15 February 1996

Alternative water resource allocation decisions may present a wide range of tradeoffs in terms of both financial and environmental goals. The aim of this paper is to examine the implications of imposing environmental flow requirements in a multiple use river system.

Water policy choices are likely to involve tradeoffs between externalities. Hence, it can be important to understand how policy change will affect the evolution of incentive structures and the externalities which may be created. Spatial and intertemporal equilibrium models of water systems fully internalise externalities. To explicitly model the externalities of a system it is necessary to represent the individual economic incentives generated by physical, biological and institutional constraints. The modelling approach adopted here embeds these incentives in a way which does not internalise existing resource use conflicts.

The modelling approach is used to examine resource tradeoffs on the Columbia River system in the United States. The reshaping of the Columbia River to meet environmental flow requirements for endangered salmon has significant implications for future investment in power generation. Increased spills from hydro dams promote fish survival but result in reduced power supply and higher prices, principally in winter. Higher prices in winter increase the rate of return and gas power generation at that time of the year. Nevertheless, power supply remains lower on average, even with additional investment in gas power generation and/or investment in wind power generation. Furthermore, greenhouse gas emissions rise as the power supply is increased through additional investment in gas power generation.

Introduction

The competing use of natural resources often presents complex and dynamic policy problems. The regulation and diversion of water resources alters the natural flow dynamics and ecology of river systems but also gives rise to a range of economic opportunities. The efficient use of water resources is both facilitated and constrained by institutional arrangements, such as trading rights, sharing arrangements for infrastructure and regulations.

The aim of this paper is to examine the implications of imposing environmental flow requirements in a multiple use river system. Of particular interest is the way in which externalities may influence the dynamics of resource use, specifically the adjustment to changes in resource access policy. The issues associated with environmental flows on the Columbia River discussed by Buchanan (1996) are considered in the context of a somewhat stylised example. This choice reflects an interest in the complexity of the issues on the Columbia, and the availability of existing research on which the physical and biological components of the example is based.

At present, the central issue surrounding the Columbia River is the management of regulated flows to meet power generation requirements and to maintain populations of anadromous fish which migrate to the ocean and return to spawn in the streams in which they were born. Existing infrastructure includes over one hundred storage and generation facilities which are capable of supplying in excess of 18 500 million watts of electrical power, meeting 75 per cent of regional power demand. The reshaping of the river to meet environmental flow requirements for fish may have significant implications for future investment in power generation throughout the west of the United States and in Canada. In particular, Buchanan (1996) indicates that with increased seasonality of hydro power generation, future investment may be directed away from continuous energy generation based on renewable resources, such as wind generation, to thermal generation with the consequent production of greenhouse gasses.

In physical terms, the scope of the issue is substantial. The Columbia River drains seven western US states and a part of western Canada — a total catchment area of around 670 000 square kilometres. Annual flows average around 7700 cubic metres per second at the river mouth. From an environmental perspective, the problem is complex. Individual fish species and sub-species may be highly dependent on local ecologies, and when these ecologies are degraded, the impediments imposed by downstream dams may present a greater threat to species survival. Migration survival rates are thought to be directly related to flow rates (Bonneville Power Administration, US Army Corps of Engineers and US Bureau of Reclamation 1991; Hydrosphere Resource Consultants 1991). In the case of dam passage, greater spill rates would reduce the number of fish passing through the turbines. Depending on the timing of flows, instream survival may also improve because high spring flows were a characteristic of the unregulated river in which the fish species evolved. However, high spring flows correspond to a period of relatively

low power demand, and operation of the dams to restore this flow pattern would reduce capacity to meet peak electricity loads in winter and, to a lesser extent, in summer.

In a dry continent such as Australia, river system problems are more focused on water availability and quality. However, the link between physical flows, stream ecologies and economic uses are no less complex. Alternative resource allocation decisions may present a wide range of tradeoffs in terms of both financial and environmental goals. While the specific objective of the model developed here is to examine the impact of environmental flow regulations for the Columbia River on future investment in power generation, the modelling approach provides a framework for examining tradeoffs associated with environmental flow regulations more generally.

Externalities and optimisation

The concept of an externality is central to economic theories of efficient resource allocation, arising when the incentives faced by individual agents are not equivalent to those generated by a global objective (commonly, the maximisation of social welfare). The notion of an externality is not limited to economic activity; externalities may be associated with specific environmental constraints which are out of alignment with a wider social goal. The economic problem of achieving the most efficient allocation of natural resources is often cast in a global optimisation or equilibrium framework. Frameworks may be a spatial and/or intertemporal equilibrium model, but share the common feature that at the optimal solution resource use tradeoffs are fully internalised. To preserve an externality an additional behavioural constraint on resource use must be imposed — that is, the externality is not a consequence of a dynamic behaviour of the system represented by the model.

Within a global optimisation framework, the removal of any binding constraint is guaranteed to yield an adjustment toward a global equilibrium and improvement in the objective function. This may still provide a reasonable representation, if the system being modelled is near to the equilibrium represented by the objective function. However, it is reasonable to expect, in a complex environment, that the removal of a constraint may lead to a worse outcome given that other physical or institutional arrangements in the system are not addressed. Such a system might be classified as far from equilibrium in that the dynamics of the system are largely determined by the interaction between isolated components of the system. These interactions are the process through which externalities are generated.

Economic incentive structures may be isolated spatially and temporally. Spatial isolation occurs through property rights which define spatial boundaries to various resource allocation decisions. Temporal isolation is exemplified by the potential problem of intergenerational equity with public goods. There can be other dimensions, such as exclusive rights to produce or market, which isolate firms from competition and trade. Creating trade is commonly put forward as an economic instrument for internalising an externality. However, trade involves transaction costs, of defining and enforcing property rights, which

can be prohibitively high. For example, consider the difficulty in defining rights which would effectively allow trade of commodities such as clean air. Where existence values are important, these rights may simply be undefinable.

While the objective of water policy may be to maximise social welfare from water resources through the realignment of economic and social incentives, institutional arrangements cannot fully address this objective. Given the difficulties of defining and enforcing adequate property rights to public resources the link between available policy instruments and social welfare may be weak. Consequently, resource policy choices are likely to involve tradeoffs between externalities, making it important to understand how policy change will affect the evolution of incentive structures and the externalities which may be created.

Consider an Australian example. Environmental flow restrictions are currently being considered in which access to water will be restricted during periods of low flow. Low flow periods are often associated with peak water demand and such restrictions may alter the risk profile for farmers of planting perennial versus annual pastures and crops. Perennial crops present a greater risk but may provide a means of increasing evaporation and transpiration to manage high saline watertables. Reduced stream access may generate a tradeoff between stream water and groundwater management in some regions, and may result in a shift in the incentives to plant different crops.

Another example is found in hydroelectric power generation by a single large scale utility exercising market power. Transfer of control of the dams to a number of utilities may break the monopoly and generate more competitive pricing. However, the incentive for individual firms to store water in a way which maximises the overall value of power generated from the system of dams is likely to be lost. For example, an upstream facility may release water at a time when it can be neither stored nor used for power generation by a downstream facility. It would seem that such a problem could be solved by allowing downstream firms to purchase storage from upstream firms. However, as the upstream firm supplies lower facilities with the water to compete with it, the upstream firm may take into account the potential impact of releasing water on its own level of profit and charge a higher price for water storage and release, effectively reducing or eliminating trade. The physical link between water flows from one dam and the next would appear to generate a potential negative externality under any market structure. The optimal solution may be a regulated monopoly, but this conclusion cannot be reached or disputed without an understanding of how the physical link shifts economic incentives under different institutional arrangements.

To model the externalities of a system does not require any fundamental shift in paradigm or methodology. It is simply necessary to identify and represent the isolated economic incentives generated by physical, biological and institutional constraints. These behavioural incentives must be embedded in a

way which does not internalise existing resource use conflicts, allowing for multiple and differing objectives to determine economic behaviour. The conceptual problem is largely one of design. The practical problem is one of solving a number of individual optimisation problems and allowing for a range of possible interactions between competing economic agents.

Modelling framework

Two aspects of the modelling framework are discussed below. First, the mathematical specification of model is presented in terms of its individual physical, biological and economic components. Second, the design of the modules is presented to illustrate how the components of the model interact in the context of the simulation.

Hydrological flows

The spatial structure of the model is determined by physical river flows which at any point may be minimally characterised by volume, velocity and pressure. The pressure of the flow is considered later in context of the hydraulic head for power generation. The objective here is to represent flow rates in a large scale river system, ignoring the hydraulics of instream flows. The spatial aspect of the problem is represented by a directional flow in one dimension. For a given water velocity, flow rates are determined by the cross-sectional area of the stream flow. This change in area is propagated according to an advective equation for a wave (Press, Teukolsky, Vetterling and Flannery 1992):

$$\frac{\partial area}{\partial t} = -velocity \frac{\partial area}{\partial z}$$

where t denotes time and z the spatial coordinate. This can be solved by finite differencing using a forward time centred representation:

$$area_j^{n+1} = \frac{1}{2} (area_{j+1}^n + area_{j-1}^n) - \frac{velocity \Delta t}{2 \Delta z} (area_{j+1}^n - area_{j-1}^n)$$

where j is a spatial subscript and n is a temporal superscript. Noting that flow rate is the product of the cross-sectional area and velocity, the equation may be rewritten in terms of the flow rate:

$$(1) \quad flow_j^{n+1} = \frac{1}{2} (flow_{j+1}^n + flow_{j-1}^n) - \frac{velocity \Delta t}{2 \Delta z} (flow_{j+1}^n - flow_{j-1}^n)$$

Equation 1 is the principal equation for the hydrological component of the model.

Fish populations

Biological relationships introduce a dynamic component to the model, with the temporal dependence of future populations on current and past populations. The fundamental recursion is an extension of the logistic population model to incorporate n age cohorts

$$(2) \quad \begin{aligned} Cohort_j^0 &= \omega_0 \sum_{i=m+1}^n (1 - \rho_n) \psi_i Cohort_i^t - \omega_1 \left[\sum_{i=m+1}^n (1 - \rho_n) \psi_i Cohort_i^t \right]^2 \\ Cohort_i^t &= (1 - \rho_i) Cohort_i^{t-1} \quad i = 1, \dots, m \\ Cohort_i^t &= (1 - \rho_i) (1 - \psi_i) Cohort_i^{t-1} \quad i = m+1, \dots, n \end{aligned}$$

where:

- j denotes an individual spawning ground,
- ω_i are the logistic population model coefficients,
- m is the last juvenile cohort,
- ρ_i is the death rate for the i th cohort,
- ρ_n is the death rate for returning adults from cohort i ,
- ψ_i is the proportion of returning adults from cohort i .

The juvenile salmon or smolts migrate down river after spawning in spring or early summer. The populations are subject to natural losses through predation and losses in dam passage. The equation structure for these components of the model have been adapted from the CRiSP1 model (Columbia River Salmon Passage model) developed at the University of Washington (1995). The CRiSP1 model has detailed specifications of migration, predation and dam passage. These relationships have been simplified considerably, while attempting to maintain the basic relationship between flow rates and fish survival.

The migration of smolt populations down river follows the propagation of water flows in accordance with equation (1). Fish migration rates in the i th reach of the river are deterministic and are assumed to be proportional ($drift_i$) to river flow

$$migration_i = flow_i drift_i$$

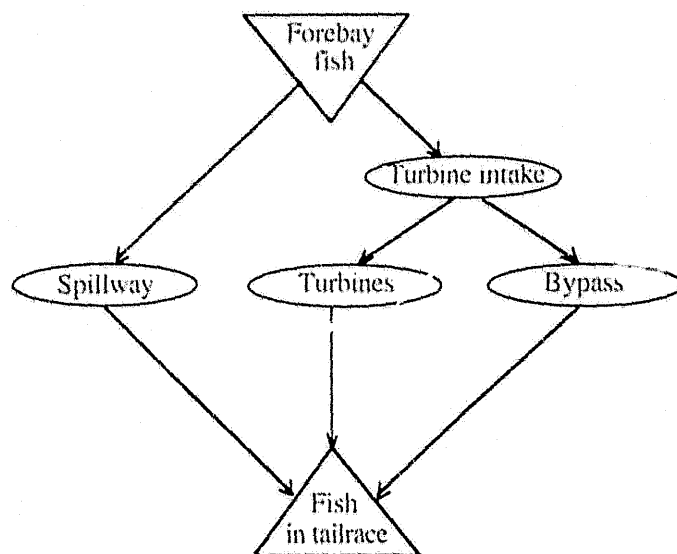
Instream mortality rates depend on river flows, according to the formula:

$$mortality_i = \frac{1}{1 + \exp\left(\frac{\beta_{0i}}{reach_distance_i} + \beta_{1i} flow_i\right)}$$

where *mortality_i* is the percentage of fish dying in the *i*th reach, and β_i are coefficients derived from the CRISP1 model by holding other covariates at their mean values.

Upon entering the forebay of the dam, the smolts must either pass over the spillway, through the hydroelectric turbines or through a turbine bypass channel, as illustrated in figure 1.

Figure 1: Passage of fish past a hydro dam



The basic equation structure for the passage of fish past the dam is taken directly from CRISP1. The proportion of fish migrating from the forebay of the *i*th dam is a function of total flow rates from the dam:

$$forebay\ passage_i = k_i \frac{flow_i}{max\ flow_i}$$

where *k* is a constant, and *max flow_i* is the maximum hydraulic capacity of the turbines at the dam. The proportion of fish passing over the spillway is a function of the relative flows through the turbine intakes and the spillway:

$$fish\ spilled_i = \frac{spill\ flow_i}{flow_i}$$

The fish which pass through the turbine intake may either go through the turbines or enter a bypass channel. The proportion of fish which enter the bypass is a constant, and depends on the design of the bypass at each dam.

Hydroelectric power generation

Overlaying the physical and biological components of the river is an economic framework which can be generated by attempting to constrain the physical and biological components. The most significant example is the use of a river system for hydroelectric power generation, and this example, is developed in this model. Hydroelectric power generation results in an adjustment of a river's natural flow patterns to conform more closely to water use requirements through the construction of dams.

A hydro dam can serve two purposes: to raise the water level, thus creating hydraulic head (the vertical distance between the surface of the reservoir and the surface of the river immediately downstream from the dam), and to create a water reserve for use in periods of low river flow or high power demand.

In the model developed, a hydroelectric authority is assumed to release water from those dams on the river which it operates to maximise profits subject to constraints arising from its generation capacity, and the physical characteristics of the river and reservoirs. The amount of electricity generated (E kilowatts) is a function of the quantity of water falling through the turbines (v metres per second), the hydraulic head (h metres), and the efficiency (y) of the operating equipment (generally in the range of 85–95 per cent). One kilogram of water falling one metre will generate 9.8 watts of electricity, where the velocity of water is that obtained from the acceleration resulting from gravity. Hence, the number of kilowatts of electricity generated per unit of time through one turbine is given by

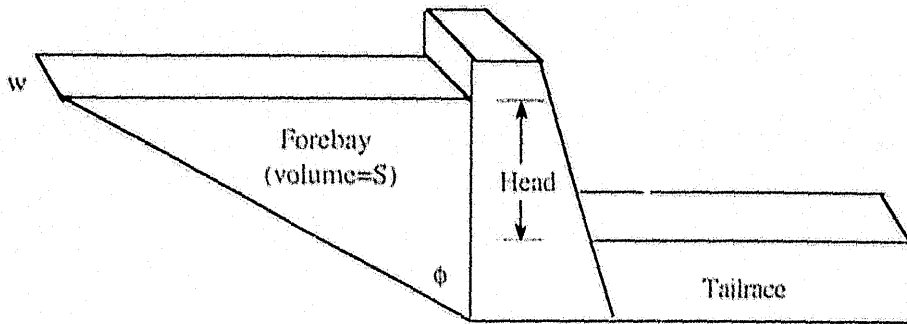
$$(3) \quad E = 9.8vhy.$$

The relationship between the storage volume (S) and the hydraulic head for a idealised reservoir geometry, (figure 2), is given by:

$$\begin{aligned} \text{head} &= (\text{forebay elevation}) - (\text{tailrace elevation}) \\ &= (\text{dam height}) \sqrt{\frac{\text{storage volume}}{\text{reservoir capacity}}} - (\text{tailrace elevation}) \\ (4) \quad &= \sqrt{\frac{2S}{w \tan \phi}} - trH \end{aligned}$$

where w is the width of the river at the dam, ϕ is the angle subtended by the dam wall and the river floor, trH is the elevation of the tailrace.

Figure 2: Geometry of reservoir



Combining equations 3 and 4 for power generated and hydraulic head gives

$$(5) \quad E = v (\alpha \sqrt{S} - \delta)$$

where:

$$\alpha = 9.8y \sqrt{\frac{2}{w \tan \phi}}$$

$$\delta = 9.8y(trH)$$

Consider a utility facing a linear demand function for electricity on a river system with unregulated inflows. Over its planning horizon, the utility is assumed to choose the outflow from each dam (v_i) that maximises the present value of its profits subject to the constraints of each dam and the sequential relationship between dams. The change in the volume of water stored at dam i over an interval of time (\dot{S}) is a function of flows into that dam — both unregulated inflows and spills from higher dams (x_i) and flows which are the result of electricity generation at the dam immediately above (v_{i-1}), and flows out of the dam (v_i). Flows must be non-negative and less than the hydraulic capacity of the turbines (v_{max_i}). Storage volumes must be within operating limits ($S_{maximum}$ and $S_{minimum}$). As a result of evaporation and percolation, only a proportion (τ), of flows reaches downstream dams.

For a linear sequence of dams, the problem can be formulated as an optimal control problem (for a general reference, see Intrilligator 1971):

$$\max \int_{t=0}^T e^{-\rho t} \left[\rho \sum_{i=1}^n v_i (\alpha_i \sqrt{S_i} - \delta_i) \right] dt$$

Subject to

$$\frac{dS_1}{dt} = \dot{S}_1 = (-v_1 + x_1)\tau,$$

$$\frac{dS_i}{dt} = \dot{S}_i = (v_{i-1} - v_i + x_i)\tau, \quad \text{for } i > 1$$

$$0 \leq v_i \leq v_{max}$$

$$S_i(t=0) = S_i^0$$

$$S_{i_{min}} \leq S_i \leq S_{i_{max}}$$

For a utility producing output E and facing a linear demand curve for electricity with price intercept a and slope b , then:

$$(6) \quad \begin{aligned} P &= a - bE \\ &= a - bv_i (\alpha_i \sqrt{S_i} - \delta_i) \end{aligned}$$

To generalise the sequence of dams, the Hamiltonian may be expressed in matrix notation as:

$$H = e^{-\rho t} \{ a - bv^T (\alpha S^{1/2} \mathbf{1} - \delta) \} v^T (\alpha S^{1/2} \mathbf{1} - \delta) + v^T \Lambda^T \lambda + x^T \lambda$$

where

$$\alpha = \text{diag}(\alpha_1, \dots, \alpha_n)$$

$$s = \text{diag}(s_1, \dots, s_n)$$

$$v^T = (v_1, \dots, v_n)$$

$$x^T = (x_1, \dots, x_n)$$

$$\lambda^T = (\lambda_1, \dots, \lambda_n)$$

$$\mathbf{1}^T = (1, \dots, 1)$$

$$\delta^T = (\delta_1, \dots, \delta_n)$$

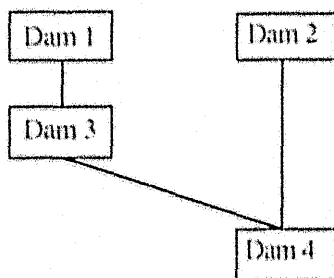
Λ is an $(n \times n)$ matrix

The organisation of dams along the river system is specified in the Λ matrix of the Hamiltonian, which describes the sequence of flows between dams in the river system. Each row is associated with a λ_i coefficient or the value of an additional unit of water at dam i . The value of an additional unit of water

released from dam i is equal to the value of the power generated at dam i plus the value of any power generated at the next dam downstream which receives the water released from dam i .

There are a number of different ways in which dams may be arranged along a river system. The model developed allows for a dam below an unregulated headwater, a dam with a single dam directly above it and a dam with a confluence from two dams above it (figure 3).

Figure 3: Sequence of dams



The corresponding Λ matrix for the sequence of dams in figure 3 would be a matrix with four rows and four columns:

$$\begin{pmatrix} -1 & 0 & 0 & 0 \\ 0 & -1 & 0 & 0 \\ \tau_3 & 0 & -1 & 0 \\ 0 & \tau_3 & \tau_4 & -1 \end{pmatrix}$$

The first order conditions to maximise the time discounted flow of power through the system are:

$$(7) \quad \frac{\partial H}{\partial v} = \frac{\partial F}{\partial v} + \Lambda' \lambda = 0$$

$$(8) \quad \frac{\partial H}{\partial s} = \frac{\partial F}{\partial s} = -\dot{\lambda}$$

where

$$(9) \quad F = e^{-n} [a - b v^T (\alpha s^{1/2} \mathbf{1} - \delta)] v^T (\alpha s^{1/2} \mathbf{1} - \delta)$$

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solution is computed. This step is repeated until all dams are at or below maximum levels. Third, with those dams which have forced spills not fully used, flows are exogenised to fully use the spill, all other dams flows are endogenised, and a new interior solution is computed. Then, the algorithm returns to the second step.

A hydroelectric authority operating on a river system may not operate in isolation because flows from a hydro dam are likely to influence future downstream conditions and other water uses. As a result, dams may include fish ladders to aid in upstream migration of fish, spillways to allow fish to pass over the dam in downstream migration, and bypass facilities to redirect fish away from turbines. The water flow available for electricity generation will be reduced by the allocation of water to other river uses, such as required spillage at each dam for fish passage, diversions from the river for urban or agricultural use, maintenance of a minimum storage level for recreational uses of the river, and losses from river flows as a result of seepage and evaporation. Water spilled from a reservoir is unavailable for hydro power generation at that particular dam, but may be available for future power generation at lower dams or for diversion to other river uses downstream.

The reduction in water flow available for electricity generation as a result of spillage or diversions to other river uses may mean that insufficient flows are available for generation of hydro power in times of peak power demand. This would depend on the timing and location in the sequence of hydro dams of any required spillage or diversions from the river system. The opportunity cost in terms of lost potential power generation is greater from dams which are lower in the river system. Nevertheless, the potential reduction in hydro power generation capacity raises the possibility that alternative forms of energy generation may viably meet peak power demand in the region. Two forms of electricity generation specifically modelled are a gas generated power facility and a wind generator farm.

Gas generated electricity

Gas fired power generation plants are ideally suited to meeting peak power demand because, unlike a coal fired power station, they can be quickly started up to meet increases in power demand and shut down when power loads drop. In contrast to the physical constraints faced by a hydroelectric utility in maximising its profits, the profit maximising decision of the gas utility is unconstrained in the model developed. The gas utility is assumed to face a linear demand curve for electricity, as represented by equation 6, and to produce that quantity which equates the marginal revenue of an additional unit with the marginal cost of producing that additional unit.

Marginal revenue is derived from the current demand for electricity in the market. Marginal cost is a function of the per unit gas price and maintenance costs. The major running cost of a gas fired plant is the cost of fuel. Maintenance costs for gas turbines are heavily influenced by their operational pattern and the number of startups. The startup of a gas fired power plant reduces the time between major overhauls of

the plant equipment by around thirteen hours over a typical life of 30 years (Intelligent Energy Systems Pty Limited 1991). Hence, maintenance costs are higher for a plant used for peak power generation than for base load power generation, given the increased number of startups required. The decision to shut down a gas turbine takes account of the fact that the subsequent startup brings forward the costs which would be incurred in overhaul or replacement of the turbine.

The algorithm employed to optimise returns from gas fired production constructs a piecewise continuous marginal cost curve, then determines the point at which marginal costs equals marginal revenue. The number of segments of the marginal cost curve is determined by the number of turbines. Gas turbines may be operated separately or jointly with a stream turbine in a combined cycle. The marginal cost along each segment depends on whether turbines are operating on an open or a combined cycle, given the higher efficiency of combined cycle operation. Marginal costs on complete segments of the curve which are below current output include an additional shutdown cost. For a given segment:

$$(13) \quad \text{marginal cost} = \begin{cases} \text{gcost} / \text{effic}_{open} + \text{maint} & \text{if power} \geq \text{current output} \\ \text{gcost} / \text{effic}_{combined} + \text{maint} + \text{shutdown} & \text{if power} < \text{current output} \end{cases}$$

where 'gcost' is per unit cost of a million watts equivalent of gas energy, 'effic' is the turbine efficiency, and 'maint' and 'shutdown' are maintenance and shutdown costs expressed on a per million watts basis.

A key disadvantage arising from the use of non-renewable fuels such as gas for electricity generation is the emission of greenhouse gases. Per unit of power generated, exhaust gases such as carbon dioxide are lower from a combined cycle plant than from a plant which consists only of open cycle gas turbines. A combined cycle plant can operate at around 45 per cent efficiency in the conversion of fuel energy to electricity, compared with around 31 per cent efficiency from an open cycle turbine (Electricity Supply Association of Australia 1991). The amount of greenhouse gases emitted (carbon dioxide in the case of a gas utility) with the production of a kilowatt of electricity is given by the following relationship between kilograms of carbon (carb) per kilowatt hour of electricity (E) and a conversion factor of (44/12) to convert carbon to carbon dioxide (CO_2):

$$(14) \quad \text{CO}_2 = E(\text{carb}) * 44/12$$

Carbon dioxide per kilowatt hour of electricity generated is typically in the range of 0.3–0.8 kilograms, depending on the efficiency of the plant and the carbon content of the gas used (Electricity Supply Association of Australia 1991).

Wind powered generators

Wind powered generators provide an alternative renewable energy source of electricity generation. As with hydro power, in the generation of electricity they do not impose externalities such as air pollution on the surrounding region. However, wind power generators may present alternative externalities such as a hazard to bird life in the region. The ability of a wind powered electricity generation plant to meet power demand is limited to those times when wind velocity is reliable and sufficient to drive a turbine.

In the model developed, wind speed over an interval of time is assumed to follow a Weibull distribution, as used in Carlin and Diesendorf (1983). The Weibull distribution is right skewed, non-negative and can take on a variety of shapes. The fit of the Weibull is generally very good in the tail of the distribution, particularly important in wind energy applications. The distribution can be described by two non-negative parameters, a shape argument and a scale argument. The smaller the shape argument (a real number close to 1), the closer the distribution to an exponential distribution. The larger the shape argument, the more the distribution approximates a Gaussian.

As in the case of a gas utility, the profit maximising decision of the wind farm utility is assumed to be unconstrained. However, the utility can only operate its wind generators to produce electricity when the wind speed exceeds a minimum cut-in speed but is less than the rated shut down wind speed. The cut-in and shut down wind speeds are specific to each wind farm (Warne 1983). The amount of electricity generated by a wind driven turbine is determined as a function of the rated capacity of the wind turbine and the wind speed:

$$(15) \quad E = \begin{cases} 0 & \text{if } \text{shutdown speed} \leq \text{wind speed} \leq \text{cut in speed} \\ \left(\frac{\text{wind speed}}{\text{rated speed}} \right)^3 \text{ capacity} & \text{if } \text{cut in speed} < \text{wind speed} \leq \text{rated speed} \\ \text{capacity} & \text{if } \text{rated speed} < \text{wind speed} < \text{shutdown speed} \end{cases}$$

The wind farm utility is assumed to face a linear demand curve for electricity, as represented by equation 4, and to produce that quantity which equates the marginal revenue of an additional unit with the marginal cost of producing that additional unit. Marginal revenue is derived from the current demand for electricity in the market. Marginal cost is a function of maintenance costs incurred in the operation of the wind farm (Intelligent Energy Systems Pty Limited 1991). The algorithm implemented in the model simply turns on turbines up to the maximum number of turbines installed if, given the current estimate of demand, revenue is increasing.

Economic links between optimising utilities

In the provision of electricity, it is common for there to be few utilities supplying electricity in a region, so the electricity market is often far from perfectly competitive in operation. An imperfectly competitive utility must take account of its rivals' actions in making its own pricing and output decisions. One

approach to modelling such a market is to incorporate in the profit maximising framework for each utility, how that utility expects its rivals' output to change in response to its own output decisions. Each utility will react to changes in the level of output from the other utility and have a reaction function describing how much each utility will produce as a function of given output of the rival utilities. There are a number of models of imperfect competition (see Binger and Hoffman 1988), including both price and output conjectural variations. The approach adopted here derives residual demand functions from conjectural output variations.

Consider a market for electricity in which there is one utility facing a linear demand curve with price intercept a and slope b :

$$(16) \quad P = a - b \sum_{i=1}^n Q_i$$

where P is the price received per unit of electricity produced, and Q_i is the quantity of the electricity produced. The profit function for the i th utility is given by:

$$(17) \quad \pi_i = \left(a - b \sum_{i=1}^n Q_i \right) Q_i - C(Q_i)$$

where $C(Q_i)$ is a variable cost function. The i th utility's reaction function can be derived by differentiating the profit function with respect to Q_i and setting the derivative equal to zero:

$$Q_i = \frac{1}{\gamma b} \left(a - b \sum_{j \neq i}^n Q_j - \frac{dC}{dQ_i} \right)$$

where:

$$\gamma = 2 + \sum_{j \neq i}^n \frac{\partial Q_j}{\partial Q_i}$$

The parameter γ describes how each utility expects its rivals' output to change in response to its own output decisions. A exists γ for each utility, and is taken to be constant across all utilities in the market. That is, $dQ_j/dQ_i = dQ_i/dQ_j$ for any utilities i and j in the market. If each utility makes its output decision assuming each other utility's output to be independent of its own output, then $\gamma = 2$ and a Cournot solution is achieved. On the other hand, if the utilities collude, exactly matching each other's output decisions, then $\gamma = 3$ and a monopoly solution is achieved. At the other extreme, if an increase in the output of one utility is exactly offset by a decrease in the outputs of all other utilities such that the price of electricity remains unchanged, then $\gamma = 1$ and a competitive solution will be achieved at a price equal to the average marginal cost of the n utilities.

The reaction function is equivalent to the utility facing an individual residual demand:

$$(18) \quad P_i^* = a - \frac{b_i}{2} Q_i - b \sum_{j \neq i}^n Q_j$$

where P_i^* is the conjectural price for the i th utility. This can be confirmed by simply comparing marginal revenue derived from equations 17 and 18. The economic links in the utility market were implemented recursively, by specifying the demand curve that each individual utility faces using quantities produced in the previous period.

Simulation design

The modelling environment was developed as a generic platform using the programming and user interface development tools in EXTEND (Imagine That Inc. 1995) and code for an optimisation problem with constraints from Press, Teukolsky, Vetterling and Flannery 1992. The objective was to implement a series of library modules which could be used to model any number of river systems in a graphical environment.

River reach modules

A river is divided into a series of reaches, for which a number of common characteristics are specified. These are the length of the reach, water velocity and system losses resulting from evaporation and percolation. The reaches are linked through flow lines in the graphical interface of EXTEND, which pass a reference or pointer to a data structure. The data structure can contain any number of river characteristics, including water flows, water quality characteristics and fish populations sourced to their point of origin. By convention, the data structure is created or received and modified at the head of the reach, then passed through a queue. The length of the queue is determined by the length of the reach, water velocity or migration rates, and by the time step of the simulation.

In addition to the physical flows, information can be transmitted in both a downstream and upstream direction. This information is used to determine the structure of the river as it has been specified in the graphical interface. Initially, this information is used to identify points of origin of fish populations and to allocate memory for the data structures. However, information is also made available to the optimisation modules which represent economic behaviour, including the sequence of links between dams and water losses throughout the system.

The headwater module can be used to represent either a regulated or unregulated headwater because flows are generated from a lookup table containing both mean flow rates and standard deviations. Stochastic flows can be generated using either a normal or log normal distribution function. Fish spawn in the headwater block over a specified range of dates, according to the equation specified for Cohort⁰ (equation 2). The spawning equations can also be subject to stochastic disturbances drawn from a normal

distribution. The headwater is the unique source of fish populations within the model, and each headwater propagates only one species.

The confluence module serves to combine river flows. However, the identity of the headwater from which any fish originate is maintained. Water flows resulting from the release of water for hydroelectric power generation are also uniquely identified, as required by the optimisation problem for the hydroelectric authority. The ability to source and distinguish flows throughout the system has potential uses in considering water property rights.

The diversion module allows the diversion of water from the stream for agricultural, industrial and urban use. The diversion can be generated through a lookup table within the module, or by an external module which is linked to the diversion. A linear programming module has been developed to represent either agricultural or industrial water demands at points along the river system. However, this has not been included in the Columbia River simulation.

The dam module incorporates the physical operating characteristics of the dam, including the dam height, storage capacity, the hydroelectric capacity of the dam, operational constraints such as minimum flow and spill requirements, and death rates for fish during dam passage.

Model calibration

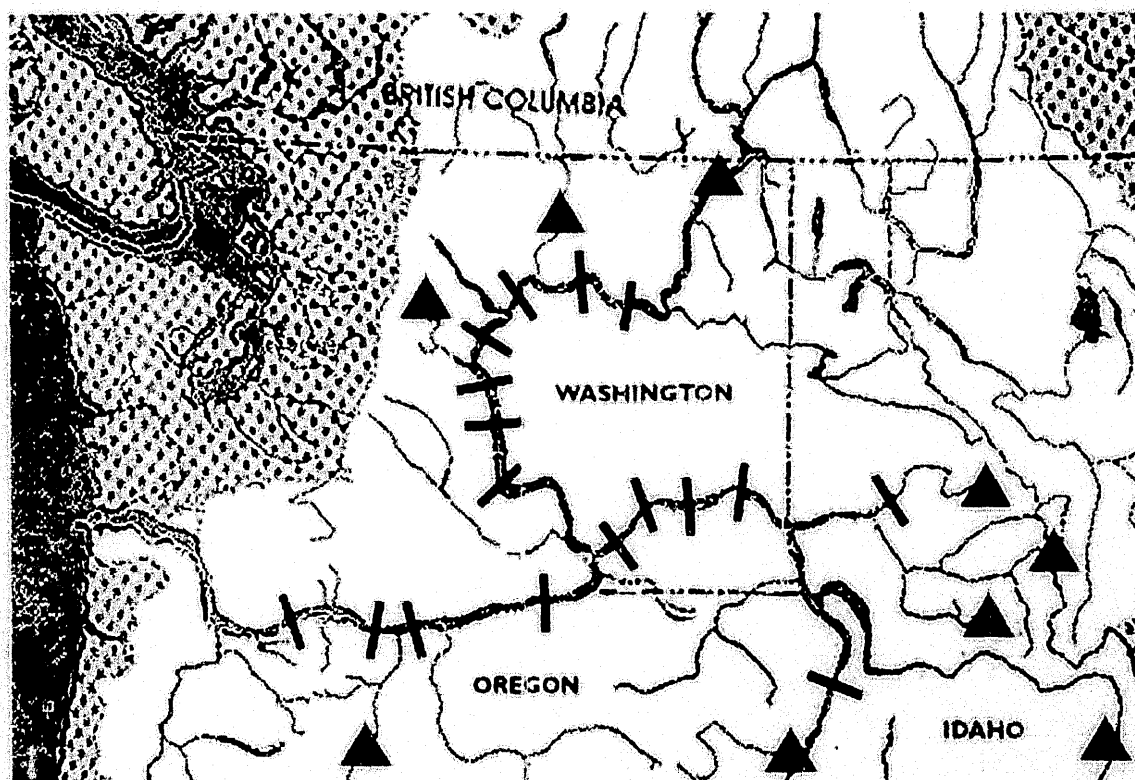
Data requirements for the model are extensive. The initial effort to calibrate the model is reported here using readily available data on river flows, dam structures and fish releases from the CRISPI database, along with generating capacity and load data (Bonneville Power Administration, US Army Corps of Engineers and US Bureau of Reclamation 1991, 1994; University of Washington 1995). The initial specification of the model includes seventeen hydroelectric dams and the major spawning headwaters for both salmon and steelhead trout (figure 4). The design of the simulation is intended to capture the essential tradeoffs between migration survival rates and power generation.

The seventeen dams in the model include twelve federal facilities and five state owned utilities, but, they are assumed to be operated as one system by the utilities. Three dams are storage facilities and are located at the top of the river system. The remaining dams are river run facilities. Technical specifications for the hydro dams are detailed in table A1. A number of operational constraints on dam operations, such as flood control and maximum changes in stream elevation were not explicitly considered. However, minimum flow requirements, storage and generating limits were imposed at each dam. There are a number of large storage facilities with generation capacity on the upper reaches of the Columbia. These facilities, along with Grand Coulee Dam, provide the overwhelming majority of available storage capacity. Grand Coulee is the highest dam on the Columbia River represented in the model, so additional storage from three dams up river was incorporated, without the associated power generation capacity, at

Grand Coulee dam. From an operational perspective, the hydroelectric power generating system is at full capacity if storage at Grand Coulee is fully used at some point in time. Excess flows which cannot be stored at, or generate power from, Grand Coulee may be used to generate power from down stream river run facilities, or are in excess of system requirements.

Monthly water flow data for the nine headwaters included in the model are reported in table A2. Salmon populations were introduced at only three headwaters, most notably the Salmon River which is associated with the endangered species. Initial populations of migrating juvenile salmon were taken from the CRISP1 database. Dam passage parameters were taken directly from the CRISP1 model (reported in table A3), while instream mortality factors were estimated for the simulation. Data on ocean mortality and adults fish returning to specific headwaters were not readily available, so the logistic population equations and ocean mortality parameters were calibrated to yield stable or gradually declining fish populations.

Figure 4: Columbia River region



Note: Modelled headwaters are represented by a solid triangle; dams included in the model are represented by an extended line.

Gas and wind generation facilities are assumed to operate independently, and competition was assumed to be intermediate between perfect competition and collusion, a conjectural variation leading to a Cournot type equilibrium ($\gamma = 1.9$). Technical specifications and cost data are detailed in tables A4 and A5.

The demand for power was calibrated to an average price of approximately US2.2c per kilowatt hour and a total load which fully used storage capacity. The seasonal pattern in power demand was calculated using 1994 Bonneville Power Administration load data (see appendix B). The seasonal load factors were used to scale the intercept of the demand curve. The simulations were run on a daily time increment with an annualised discount rate of 5 per cent.

Simulation results

A total of seven simulations were run over a ten year period using a deterministic specification of the model. The results are summarised in table 1. In the baseline simulation, generation of electricity is given priority in the operation of hydro dams, storage is fully used and gas generated electricity is used to meet peak loads in the winter. Despite operating well below full capacity throughout much of the year, gas generated electricity yields a high rate of return (figure 5). Fish survival during passage from both the Methow and Salmon headwaters is relatively low, at about 23 per cent, as a result of the number of dams which need to be passed and the distance travelled.

In the second and third scenarios, 300 million watts of additional gas and wind generation were added, respectively. The additional gas plant was economic, with a projected rate of return on capital of 11 per cent. Further investment in gas generation appears to be marginal. Wind power generation yielded a negative rate of return, largely as a result of the high capital costs and low returns when power was generated during a period of reduced demand. Neither of these options changed the basic shaping of river flows, so, fish survival rates were unchanged.

To increase fish survival, minimum flow requirements for each dam were converted to minimum spill requirements when fish entered the forebay of a dam (simulations 4-7). This increased fish migration survival rates by 6-16 percentage points from migration survival rates in simulation 1. The largest increases were from the Methow headwater, where flow rates drawn from Grand Coulee were considerably larger. With limited storage capacity feeding the Snake River, the increase in the survival rate from the Salmon River was substantially smaller. The spills resulted in an average reduction in power supply of about 500 million watts, nearly all in winter, and a 10 per cent increase in the average price (simulation 4). Higher prices in winter increased the rate of return of gas generation, but, the increase in gas power generated was limited because power requirements throughout the remainder of the year were met by hydroelectric power.

Table 1: Simulation results

Scenario*	Electricity grid	Hydro utility			Gas utility				Wind utility			Surviving salmon population		
	Price	Average load	Average load	NPV Revenue	Average load	Revenue	Rate of return	CO ₂	Average load	Revenue	Rate of return	Salmon	Methow	Desci
	USc	MW	MW	US\$ million	MW	US\$ million	%	'000 t/y	MW	US\$ million	%	%	%	
1	2.1	8232	7081	8523	1154	632	29	5.7				24	23	
2	2.1	8315	7096	8440	1221	651	11	6.0				24	23	
3	2.1	8352	7120	8430	1110	584	19	5.5	125	113	-46	23	23	
4	2.3	7746	6567	8368	1180	770	58	5.8				30	39	
5	2.2	7918	6566	8187	1353	866	27	6.7				30	39	
6	2.2	7988	6567	8116	1424	895	15	7.0				29	39	
7	2.2	8011	6581	8108	1307	816	19	6.7	125	121	-42	30	39	

- *1 Baseline simulation — generation of electricity given priority in operation of hydro dams; gas utility with capacity of 1.5 billion watts.
2 Generation of electricity given priority in operation of hydro dams; gas utility with capacity of 1.8 billion watts.
3 Generation of electricity given priority in operation of hydro dams; gas utility with capacity of 1.5 billion watts; wind utility with capacity of 300 million watts.
4 Spills for fish given priority in operation of hydro dams; gas utility with capacity of 1.5 billion watts.
5 Spills for fish given priority in operation of hydro dams; gas utility with capacity of 2.1 billion watts.
6 Spills for fish given priority in operation of hydro dams; gas utility with capacity of 2.4 billion watts.
7 Spills for fish given priority in operation of hydro dams; gas utility with capacity of 2.1 billion watts; wind utility with capacity 300 million watts.

Figure 5: Power output and price – scenario 1

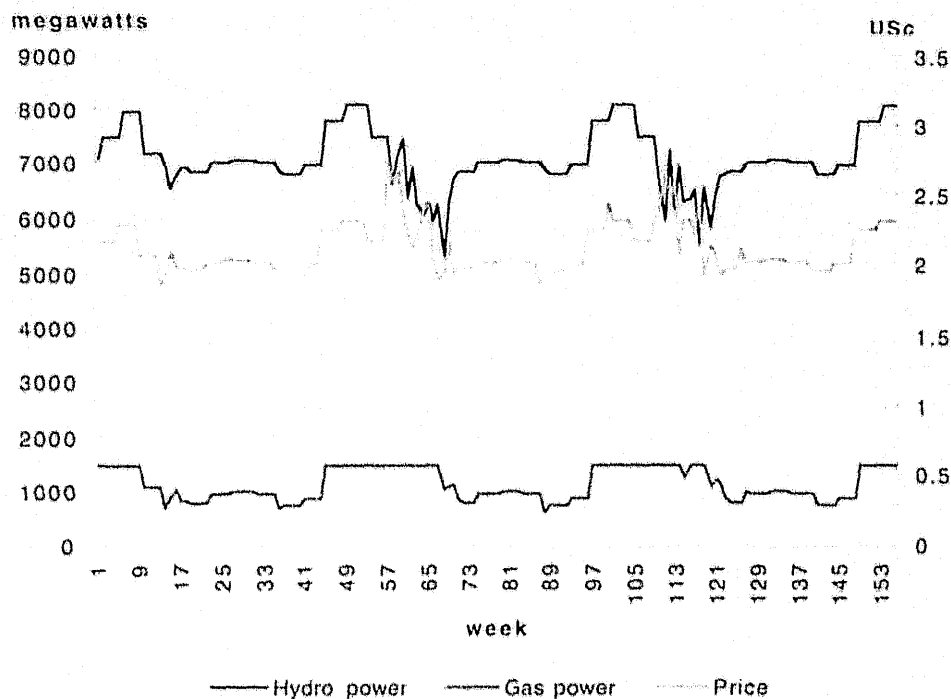
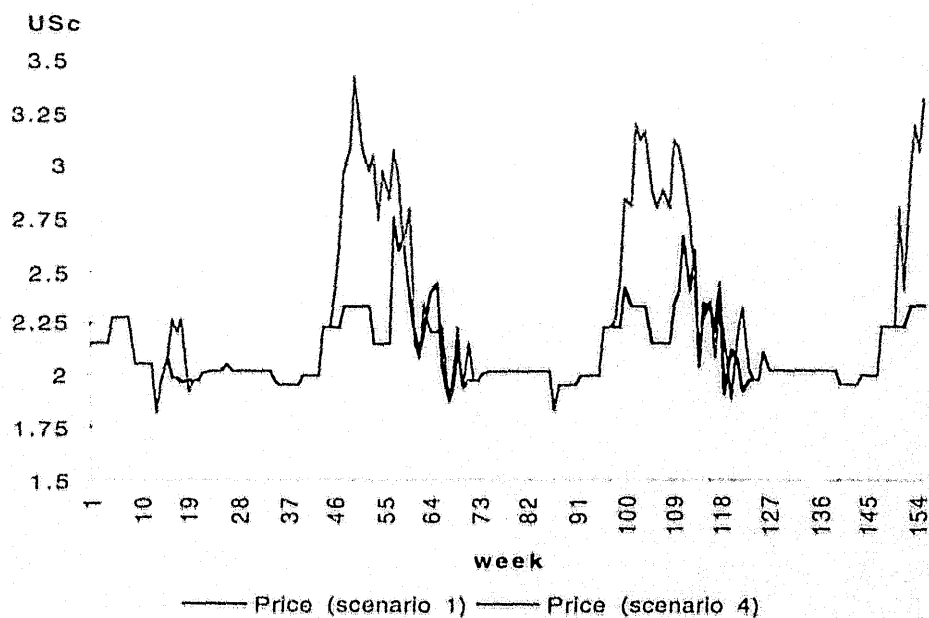


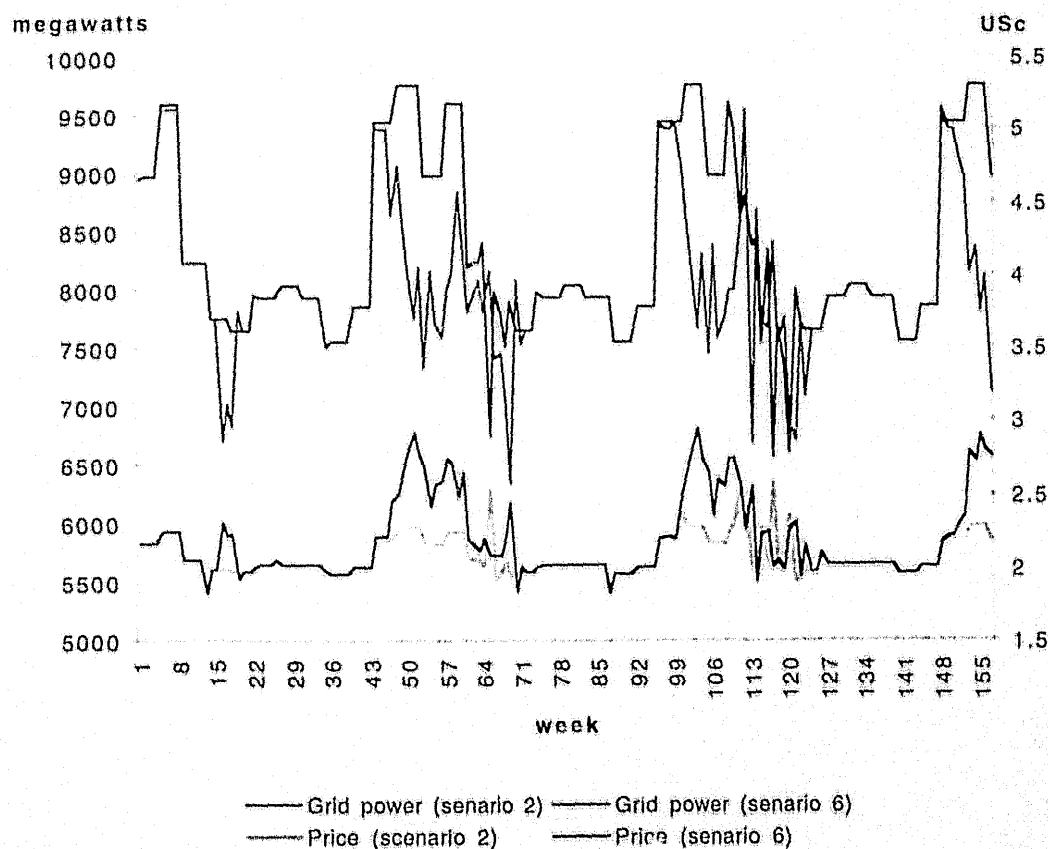
Figure 6: Seasonality of electricity prices



The fifth and sixth scenarios represent the addition of a further 300 and 600 million watts of gas powered capacity to meet peak demand in winter, bringing the total capacity of the gas power generation utility to 2100 and 2400 million watts respectively. While the increase in capacity to 2100 million watts is economically viable, the rate of return on capital declined from 27 per cent in the fifth scenario to 15 per cent in the sixth scenario, indicating that further investment in gas utility would be limited.

The increased seasonality of flows results in greater seasonal variation in prices (figure 6). However, the peak prices in winter are not sufficiently high to bring on enough additional investment in gas or wind power capacity to fully offset the loss in power supply resulting from the spills (figure 7). The introduction of more seasonal flows creates a net loss in overall generation, which cannot be fully offset by alternative investments.

Figure 7: Impact of increased seasonality of flows on power prices and production



With the additional power produced by the gas utility in scenarios five and six, emissions of greenhouse gases increased by up to 1.3 million tonnes. In the seventh scenario, gas utility capacity was set at 2100 million watts, and wind capacity of 300 million watts was introduced. However, as in scenario three, wind powered electricity generation yielded a negative rate of return, and a reduction in the average power supply of around 100 megawatts remained.

Conclusions

The research presented here develops a modelling framework in which to examine tradeoffs associated with environmental flow regulations in multiple use river systems. The framework is quite general in that it can be used to integrate physical water flows, biological populations and competing economic uses of rivers and other resources. Water use policy options are likely to involve tradeoffs between externalities. The approach allows externalities to be modelled explicitly as a consequence of changing resource access.

In the example considered, the impact of environmental flow requirements for the Columbia River on future investment in power generation was examined. An increase in spills from hydro dams in order to promote fish survival results in a reduction in power supply and higher prices, principally in winter. Higher prices in winter increase the rate of return for gas power generation at that time of the year. Nevertheless, power supply remains lower as a result of the spills, even with additional investment in gas power generation and/or investment in wind power generation. Wind power generation proves economically unviable, largely as a result of the high capital costs and low returns when power is generated during periods of reduced demand. The increase minimum spill requirements from hydro dams effectively increases the inpassage survival rates of the salmon populations by 6–16 percentage points. However, greenhouse gas emissions rise by around 1.3 million tonnes if the power supply is increased through additional investment in gas power generation.

Principal areas for further extension of the model developed lie in investment in power generation capacity and in alternative specifications for conjectural variations of a utility. The model developed evaluates the returns from capital investment for each utility. An extension of this would be to explore the optimal capital investment for utilities in generation capacity, given characteristics of the electricity market, constraints presented by physical water flows, biological populations and other resources. Conjectural variations of the utilities in the model are based on output decisions of each utility in the market. An extension of this would be to include price based conjectural variations in the determination of reaction functions for each utility.

Table A1: Dam and reservoir specifications

	Full capacity ML	Minimum volume ML	Dam width m	Dam elevation m	Tailrace elevation m	Initial outflow m ³ /s	Max outflow m ³ /s	Turbines no.	Turbine rating average MW	Plant efficiency %	Fish in bypass %
<i>Columbia River dams</i>											
Bonneville	697	596	1111	28	9	2.5	8.1	18	58	0.9	0.300
The Dalles	409	371	1105	32	8	2.5	10.5	22	81	0.9	0.344
John Day	2922	2520	1646	47	15	2.2	15.0	16	135	0.9	0.567
McNary	1665	1519	1571	34	13	2.3	6.5	14	70	0.9	0.525
Priest Rapids	245	146	978	31	9	2.3	5.2	10	79	0.9	0.000
Wanapum	724	384	913	35	13	2.3	5.0	10	83	0.9	0.000
Rock Island	139	126	299	25	15	2.3	6.2	19	33	0.9	0.000
Rocky Reach	530	492	553	33	7	2.5	6.2	11	110	0.9	0.000
Wells	370	283	922	34	15	2.0	6.2	10	77	0.9	0.960
Chief Joseph	636	490	922	65	13	1.8	6.1	27	77	0.9	0.000
Grand Coulee ^a	17862	3987	1067	119	18	1.8	7.8	24	271	0.9	0.000
<i>Snake and Clearwater river dams</i>											
Ice Harbor	502	480	657	42	12	0.4	3.0	6	100	0.9	0.568
Lower Monumental	465	434	591	46	15	0.5	3.6	6	135	0.9	0.520
Little Goose	450	424	671	52	22	0.5	3.6	6	135	0.9	0.494
Lower Granite	597	560	610	48	18	0.5	3.6	6	135	0.9	0.499
Hells Canyon	210	48	92	63	15	0.2	0.8	3	150	0.9	0.000
Dworshak	2486	1507	418	213	24	0.0	0.3	3	400	0.9	0.000

^a Total storage reported at Grand Coulee Dam includes 11 468 million litres held at three other storage facilities above Grand Coulee Dam.

Table A2: Headwater flow data

	Columbia	Deschutes	SNAKE	Clearwater	North fork Clearwater	Middle fork Clearwater	Salmon	Wenatchee	Methow
Mean monthly flow ('000 m³/s)									
Jan	2.19	0.06	0.17	0.20	0.03	0.03	0.17	0.01	0.04
Feb	2.88	0.06	0.16	0.19	0.04	0.03	0.16	0.01	0.04
Mar	2.25	0.06	0.22	0.28	0.03	0.04	0.24	0.01	0.06
Apr	2.07	0.06	0.34	0.46	0.05	0.06	0.38	0.04	0.17
May	2.89	0.06	0.47	0.67	0.34	0.08	0.54	0.07	0.32
Jun	3.84	0.06	0.30	0.40	0.04	0.05	0.33	0.04	0.17
Jul	2.80	0.06	0.18	0.21	0.37	0.03	0.18	0.02	0.09
Aug	2.06	0.06	0.11	0.10	0.04	0.02	0.10	0.01	0.02
Sep	1.53	0.06	0.11	0.10	0.04	0.02	0.10	0.01	0.01
Oct	1.84	0.07	0.18	0.22	0.03	0.03	0.19	0.01	0.03
Nov	2.36	0.06	0.14	0.14	0.03	0.02	0.13	0.01	0.02
Dec	2.31	0.06	0.14	0.15	0.03	0.02	0.14	0.01	0.02
Standard deviation of flows									
Jan	0.55	0.00	0.03	0.05	0.00	0.01	0.04	0.00	0.02
Feb	0.56	0.00	0.03	0.05	0.02	0.01	0.04	0.00	0.01
Mar	0.38	0.00	0.03	0.05	0.00	0.01	0.04	0.00	0.01
Apr	0.35	0.00	0.11	0.18	0.04	0.02	0.14	0.05	0.10
May	0.50	0.01	0.07	0.11	0.19	0.01	0.09	0.06	0.06
Jun	0.37	0.00	0.07	0.11	0.02	0.01	0.08	0.01	0.02
Jul	0.52	0.00	0.03	0.04	0.25	0.00	0.03	0.01	0.03
Aug	0.33	0.00	0.01	0.01	0.03	0.00	0.01	0.00	0.01
Sep	0.60	0.00	0.03	0.05	0.00	0.01	0.04	0.00	0.01
Oct	0.36	0.02	0.04	0.06	0.00	0.01	0.04	0.00	0.02
Nov	0.41	0.01	0.02	0.03	0.00	0.00	0.02	0.00	0.03
Dec	0.41	0.00	0.02	0.03	0.00	0.00	0.03	0.00	0.01

Table A3: Salmon population parameters

<i>Population parameters in headwater blocks</i>			
Fish headwater source	Methow	Salmon	Deschutes
Adult population	27000	2000	25000
Hatching days	107-36	115-44	101-30
<i>Parameters in river reach blocks</i>			
Fish migration rate	0.45	0.45	0.45
(% of river flow rate)			
Death rate constant	25	25	25
Death rate			
per unit water flow (%)	1	1	1
<i>Death rates in dam blocks (% passing smolts)</i>			
Forebay	0.11	0.11	0.11
Spillway	0.02	0.02	0.02
Turbine	0.11	0.11	0.11
Turbine bypass	0.02	0.02	0.02

Source: University of Washington (1995)

Table A4: Gas plant specifications

Unit cost of gas	US\$1.7/gJ
Maintenance cost	US0.031c/kW
Capital cost per installed million watts	US\$500 000
Life of plant	30 years
Time between major overhauls	48 000 hours
Overhaul cost per installed megawatt (US\$)	US\$1000
Shut down loss	13 hours
Gas turbine parameters	
number	10
electricity rating	100 MW
open cycle efficiency	0.35%
Steam turbine parameters	
number	5
electricity rating	100 MW
combined cycle efficiency	0.50%
number gas turbines per steam turbine	2
Carbon emissions	0.154 kg/kWh

Source: Intelligent Energy Systems Pty Limited (1991)
Electricity Supply Association of Australia (1991)

Table A5: Wind farm specifications

Maintenance cost	US4.5c/kW
Capital cost per installed megawatt	US\$1 073 000
Life of plant	30 years
Wind turbines parameters	
number	1500
electricity rating	200 kW
Wind speed parameters	
rated wind speed	11.2 m/s
cut-in wind speed	2.2 m/s
shut-down wind speed	17.8 m/s

Source: Carlin and Diesendorf (1983)
Intelligent Energy Systems Pty Limited (1991)
Warne (1983)

Appendix B: Estimation of electricity load equation

Time series models used to generate the monthly and daily electricity load can be expressed as:

$$\begin{aligned} \ln(Q_t) = & 9.051754 - 0.074041 D_1 - 0.018127 D_2 - 0.140975 D_3 - 0.193932 D_4 - 0.202096 D_5 \\ & (66.24) \quad (7.21) \quad (1.73) \quad (13.83) \quad (18.87) \quad (19.83) \\ & - 0.171555 D_6 - 0.155641 D_7 - 0.171225 D_8 - 0.214098 D_9 - 0.181902 D_{10} \\ & (16.69) \quad (15.27) \quad (16.80) \quad (20.83) \quad (17.85) \\ & - 0.034955 D_{11} + e_t \\ & (3.42) \end{aligned}$$

and

$$\begin{aligned} e_t = & 0.00055 + 0.877156 e_{t-1} - 0.211818 e_{t-2} - 0.061021 e_{t-4} + 0.243962 e_{t-7} - 0.307719 e_{t-8} \\ & (0.68) \quad (17.83) \quad (4.18) \quad (1.58) \quad (4.77) \quad (5.92) \\ & + 0.104439 e_{t-10} - 0.101246 e_{t-11} - 0.084392 e_{t-12} + 0.323623 e_{t-14} \\ & (2.07) \quad (1.62) \quad (1.74) \quad (6.26) \\ & - 0.279039 e_{t-15} + U_t \\ & (5.47) \end{aligned}$$

where Q_t denotes daily electricity load. D_1, \dots, D_{11} are monthly dummies for January to November. t -statistics are in brackets. Standard error of U_t is 0.0243118. These loads were used to scale the intercept of the demand equation to give equivalent percentage changes in demand.

$$(1) \quad \mu_1 = \int_0^B \tau \cdot f(\tau) d\tau + \int_B^{\infty} B \cdot f(\tau) d\tau$$

where μ_1 is the mean of the constrained; τ is the tariff rate; and f is the density function of the tariff rate.

Differentiating (1) with respect to B provides an illuminating result:

$$(2) \quad \frac{\partial \mu_1}{\partial B} = \int_B^{\infty} f(\tau) d\tau = (1 - F(B))$$

This shows that the impact of a change in a tariff binding on the expected tariff rate is less than one-for-one. Rather, this impact depends upon the proportion of the probability distribution accumulated at the binding. If a sufficiently large proportion of the distribution is accumulated at this point, then the binding is almost always effective, and a change in the tariff binding has an impact approaching one-for-one on the mean rate of protection. This provides a potential rationale for the widely made assumption in empirical studies that reductions in tariff bindings have a one-for-one impact on average rates of protection, but only in situations where the binding is well below the mean of the unconstrained distribution.

Such an assumption seems appropriate in considering the liberalization of manufactures trade in the developed countries, for tariff bindings have progressively been reduced to much lower levels than prevailed in the absence of GATT disciplines, and have come to be virtually synonymous with applied rates. For the Uruguay Round agreement on agriculture, however, Ingeco's work makes clear that a high proportion of the bindings on raw agricultural products were set substantially above the previous average rates of protection, implying that only a relatively small proportion of the distribution of protection is likely to be accumulated at the binding. Assuming that the agreed reductions in protection have a one for one impact on the rate of protection will therefore exaggerate the liberalization brought about by the Round.

The variance of the bound tariff may be written: