This paper has passed peer review by the IPENZ Publications Committee 26/06/99

Rakaia Catchment Water Resource System Engineering

D J Painter*, BE(Hons)(Mech), PhD(Eng), F.IPENZ

The water resources of the Rakaia River catchment, including Lake Coleridge, are very significant in Canterbury. A National Water Conservation Order and other resource use consents constrain their use. This paper illustrates the potential value of a water resource system engineering approach to planning development and conservation.

Keywords: *Water Resources - Hydrosystems - Engineering - Rakaia Catchment*

* *Consulting Engineer, Greenpark, Canterbury.* David.Painter@clear.net.nz

1. Introduction

The Rakaia River in Canterbury, South Island, New Zealand, drains a 2810 km^2 catchment which extends from the South Pacific Ocean in the East to the Southern Alps mountain range in the West, at about 44 degrees South latitude (Figure 1). Mean annual rainfall increases from about 650 mm near the coast, to 1200 mm near the gorge, 60 km inland, and to about 7000 mm near the Southern Alps main divide. The river has a wide, braided channel over much of its length and transports a lot of gravel to the sea. The largest of several lakes in the catchment above the gorge is Lake Coleridge, of about 35 km^2 surface area. It has tunnels leading water to an historic (1914) 35 MW hydro-electric power station and thence to the Rakaia River. The water from three rivers tributary to the Rakaia can be diverted into the lake. An excellent resource survey of the Rakaia River and its catchment was published in 1983[1].

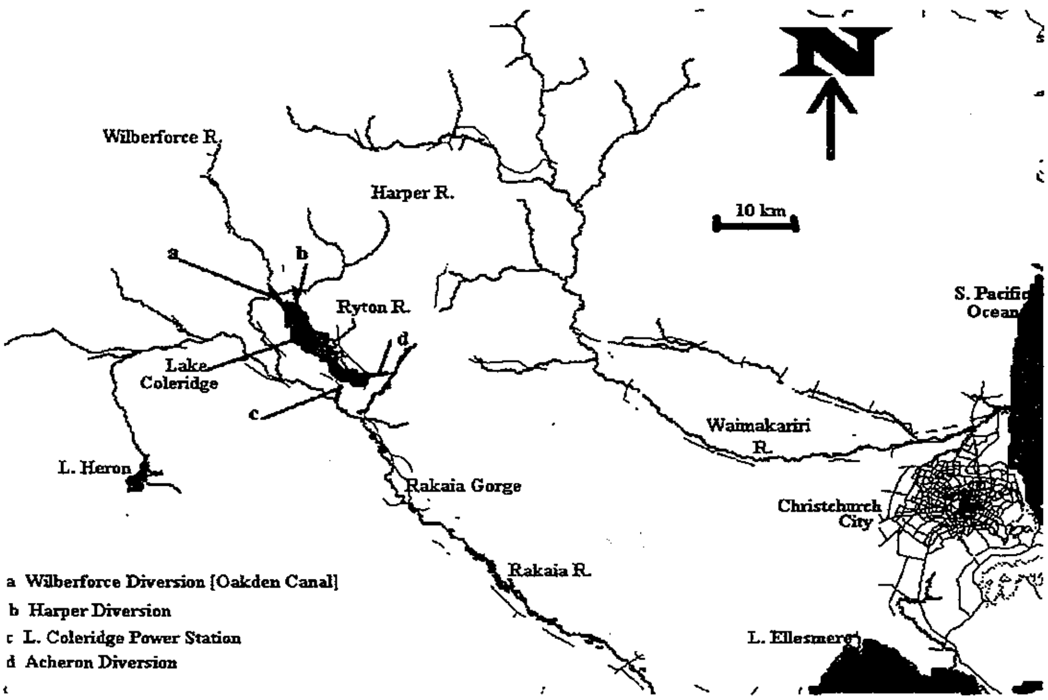


Figure 1. Lake Coleridge and Rakaia River location in Canterbury, New Zealand.

The Rakaia River is a fine example of a braided, gravel-bed river and is valued as such, aesthetically, scientifically and for human recreation on foot, in the water or in boats (especially jet boats). It is also an important home for a unique, bent-billed bird, the wrybill plover (*Anarhynchus frontalis*), occurring only in New Zealand and fewer than about 7000 in number, all living on braided

South Island rivers, mainly the Rakaia. Another rare bird (250 birds in New Zealand in 1999, 3000 worldwide) is the crested grebe (*Podiceps cristatus australis*); it nests among reeds and other water surface level vegetation on Lake Coleridge and nearby Lake Heron (in Rakaia catchment), its breeding and chick-rearing success thus being affected by lake level fluctuations. Recreational fishers value the Rakaia highly; sea-running quinnat salmon (*Onchorhyncus tshawytscha*) have become successfully established and breed in specific headwater areas. There are two commercial salmon-rearing ventures and a hatchery located in the catchment. The two other major commercial activities are hydro-electric power generation and irrigation. With so many different purposes, and many different human expectations of the river and catchment, it is hardly surprising that there has been debate, disagreement and litigation over objectives seen to be in conflict. A National Water Conservation Order[2] was applied to the Rakaia River and catchment in 1988 in recognition of its outstanding features. A twenty-year planning case study (1969-1988) on the river and catchment is available, which expands on these paragraphs[3].

Water resource system analysis has been developed since the late 1950s specifically to deal with planning and management of complex water resource systems. New Zealand is not the only country where the methods have seldom been applied. Rather, it is apparent worldwide that application of the methods has lagged well behind their availability. The methods are powerful, useful and practical. There are excellent textbooks describing them[4,5,6] and excellent reviews of their use have been published[7]. A major reason for their non-use seems to be their sophistication, esoteric terminology and frequent use of operations research techniques (themselves frequently mistrusted by non-specialists). Operations research and system analysis techniques have been applied successfully in New Zealand to hydro-electric generation scheduling and costing[8,9,10]. In water resources management, important gaps in understanding have been identified between decision-makers (resource managers) and decision-aiders (system analysts)[11].

This paper chooses the Rakaia River/Lake Coleridge system as an example of a water resource system to which system analysis followed by conceptual experimentation (optimisation and simulation) could be beneficially applied.

2. The Present System

In a short paper concerned with systems engineering for planning and management it will suffice to discuss just a few aspects of the present system relevant to significant management opportunities. The Rakaia/Coleridge system has been chosen to illustrate methods which are more widely applicable, and many aspects could be included in the approach. Aspects of hydrology, ecology and commercial activity are briefly considered.

Volumes are used in the following to provide a common unit (million cubic metres, MCM) for river and power station flows (in a time period e.g. month) and lake storage. Mean annual discharge volume at the gorge is about 6400 MCM; it varied between 4900 MCM (1971) and 8800 MCM (1967) between 1958 and 1989. Mean monthly volumes are highest in Summer (due in part to snowmelt) and lowest in Winter; they varied from 185 MCM (September 1977) to 1530 MCM (December 1979) during the same period. Daily flow volumes varied from 4.7 MCM (21 July 1990) to 247 MCM (27 December 1957) over the slightly longer period from December 1957 to July 1990. The increasing variability as shorter time periods are considered is obvious. Also noteworthy is that it is possible to have a much greater volume of water pass down the river in a day of flooding than in a month of low flow.

Hydro-electric generation capability was progressively developed between 1911 and 1977, focussed on a 35 MW power station making use of a 150 metre drop between Lake Coleridge and the Rakaia River above the Acheron confluence (Figure 1). The power station was built between 1911 and 1914; provision has since been made to divert water from the Harper River (1921), the Acheron River (1930) and the Wilberforce River (1977) into the lake. With all turbines operating at full capacity for a day, the power station would pass 3.5 MCM to the Rakaia River (of the same order as the observed minimum daily flow volume at the gorge). Water right conditions stipulate that Lake Coleridge surface water level must be kept between 505.35 and 509.5 metres above the power station datum (equivalent to mean sea level). As the lake surface area is 35.4 km^2 at 507.4 metres AMSL, the water volume stored in the lake between these levels is about 150 MCM (6 weeks supply to the power station at maximum flow with no inflows). The effective catchment area of the lake has been increased from 210 km^2 to 980 km^2 by the river diversions and the mean annual flow volume entering the lake has been increased from 125 MCM to about 915 MCM. About 205 GWh of electricity is generated in a typical year (less than 1% of national electricity generation, but important regionally). There is at present more water available than the installed plant in the existing power station can use. Ownership of the power station passed from ECNZ (a state-owned enterprise, now split into three entities) to Trustpower Ltd (a private company based in Tauranga) in October 1998. At the time of writing (June 1999), Trustpower are upgrading plant to 52 MW and building a gate structure for the Wilberforce Diversion (Oakden Canal)[12].

Water rights for irrigation current in 1997[13] indicated about 280 MCM could be extracted from the river in the six months from September to February. As 1 MCM will irrigate 50 to 100 hectares (depending on volumetric efficiency of use) with 75 mm each 2 weeks for six months, this would be sufficient for 14 000 to 28 000 hectares. This is less than 20% of the land potentially irrigable with Rakaia River water.

Lake Coleridge is an important sport fishery. Anglers catch quinnat salmon mostly, followed by rainbow trout (*Salmo gairdnerii*)and brown trout (*Salmo trutta*). Native fish species are small; they are important as food for the salmon and trout. Major inflows to the lake, such as at the diversion entries and the Ryton River (Figure 1), are important feeding grounds. Undesirable sediment entry to the lake and turbidity of the diversion water is subject to water right conditions, as sediment and turbidity have unwanted effects on the composition of bottom-dwelling fauna as well as on the ease with which fish are caught and the lake's appearance.

The Rakaia River is a very important sport and commercial fishery. Only the lower Waimakariri River (just North of Christchurch, Figure 1) attracts more anglers in Canterbury, and it is possible that fewer fish are caught there[14]. Although some brown trout are taken, and native eels, torrentfish and bullies are abundant, it is quinnat salmon which are the most prized and the most caught. A flow rate of 160 m^3/s (at Rakaia Gorge) is 'optimal' for salmon fishing[15], the required range being 120 to 200 m^3/s. The peak of the adult salmon run up-river varies in occurrence from January to March.

3. Possibilities for Change

Some possibilities for different management of the Rakaia River/Lake Coleridge system, or for changing the system, are obvious. As there is more water available to pass through Lake Coleridge than can be passed through the existing power station generating plant, more electricity could be generated by adding plant and increasing diversion maximum flows. More storage in Lake Coleridge (or elsewhere), as well as allowing more electricity generation of desirable timing, would allow more modification of Rakaia River flows. This could allow greater flood peak reduction to reduce damage downstream or more prolonged low flow enhancement to maintain fishing and boating conditions or irrigation supplies.

Recognizing different objectives could result in river flow and lake level manipulation to improve fishing conditions, enhance or protect bird habitat, enhance irrigation water supplies or provide specific recreational conditions (such as for jet boat racing). In the past, such possibilities have been discussed without the benefit of adequate understanding of the existing system. This has led to over-simplified arguments and dualistic thinking. It was water right applications for irrigation in the late 1970s which led acclimatisation societies to apply in 1983 for a National Water Conservation Order. The protracted legal arguments over the next five years tended to intensify the dualisms: fishers against farmers, conservers against developers and scientists against engineers. There are possibilities for changes of widespread benefit and minor potential for disadvantage.

Two important qualifications must temper consideration of possibilities for change using system analysis and conceptual experimentation. The first is the existing sensitivity of people concerned about the Rakaia River and its catchment. The National Water Conservation Order in force is intended to preserve outstanding characteristics and features of the Rakaia River and its tributaries. The Order was more the result of the protracted litigation than of community agreement[3], but it is the expression of societal wishes made at the time. Among other provisions, it specifies 'minimum gorge flows' for each month; an annual flow volume made up of a sequence of these minimum gorge flows is 3065 MCM (48% of mean annual discharge volume). Actual annual discharge volumes range from 65% to nearly 200% more than this, showing the abundant supply of water for all purposes if it could be suitably timed. But there exist entrenched positions into which various interest groups have 'dug in'. Possibilities for change will need to be clearly and fairly exposed in ways which allow such groups to discuss and evaluate advantages, disadvantages and trade-offs.

The second qualification is the need for an awareness of a history of human arrogance when modifying natural systems. Changing the magnitude of water flows might change the magnitude of sediment flows. Changing the timing of water flows to suit one or more human objectives might not suit another human objective or some wildlife feature. Varying the pattern of lake level changes might change shoreline processes and flora, and sediment deposition. While this water resource system is not of great size and significance on an international scale (compare, for example, the current "Three Gorges" project in China), unforeseen consequences of well-intentioned modification of natural systems have been all too apparent in hindsight, in New Zealand, and throughout the world.

4. System Analysis

Successive simplification is necessary to reduce a real-world system to an entity which can be analysed. Such analysis allows modifications to the simplified system to be synthesised in an attempt to predict behaviour of the real-world system if it were to be modified in an analogous way. The Rakaia/Coleridge system can be analysed for present purposes in six steps:

1. There is a **real-world Rakaia/Coleridge system.**

   The system can only be completely described by itself. It is embedded in a larger system and its 'boundaries' are human constructs.
2. I have my **perception** of this system.

   It is more or less sharply focussed on different aspects and varies in time. I use photographs, maps, diagrams and written words or symbols to aid my memory of the system. At this level, I can be motivated to alter the system, according to values I hold.
3. I can encapsulate a **conceptual model** of the system.

   Typically, this could take the form of diagrams and written description (e.g. Figure 1 and 'The Present System', above). It aids my perception, and allows communication with others.
4. From this, I can define a **mathematical model** of the system.

   This follows [see Figure 2]. I use variables, parameters and structure suited to known techniques of analysis and the available data.
5. Further simplification leads to **simplified mathematical models.**

   These are chosen to allow solution by specific analytical techniques. Conceptual experiments can then be carried out which might relate more or less well to the real-world system. In particular, this paper will mention optimising techniques (to define 'better' policies for managing controllable aspects of the system); and simulation techniques (to allow 'what if ...?' experiments to aid managers and planners). It is often found that optimising techniques guide experiments in 'better' directions, but necessitate over-simplified models, while simulation can cope with more realistic models but offers little other than repeated experiments to define 'better'.
6. A further step which can be helpful is to **prototypical mathematical models.**

   These might aid in synthesising the simplified mathematical models by being familiar from repeated use in other studies. The analysis outlined here contains three prototypical mathematical models: a flow supplementation model, a flood detention model and a reservoir yield model. The last becomes a single hydro-electric reservoir model if surface level as well as stored volume is considered.

The following analysis uses language which is a compromise between plain English and that common in system analysis, thus risking offending users of each in the hope of being intelligible to both. The meaning of symbols should be clear from Figures 1 and 2 and the appendix on terminology.

4.1 Variables

State Variables

I choose to describe the "state" the system is in at a certain "stage" (time period) by the volume of water in Lake Coleridge (x_l, relative to some datum) and the volume of water which has flowed past the Rakaia Gorge gauging site (Figure 1) in that time period (x_r). In the mathematical model:

State variables: x_l x_r

Decision variables

These represent the controllable variable aspects of the system, decisions about which influence the future states of the system. They are the volumes of water diverted from the Harper and Wilberforce Rivers (x_d), the volume passed through the power station (x_p) and the volume of water spilled (x_s), at a certain stage. In the model:

Decision variables: x_d x_p x_s

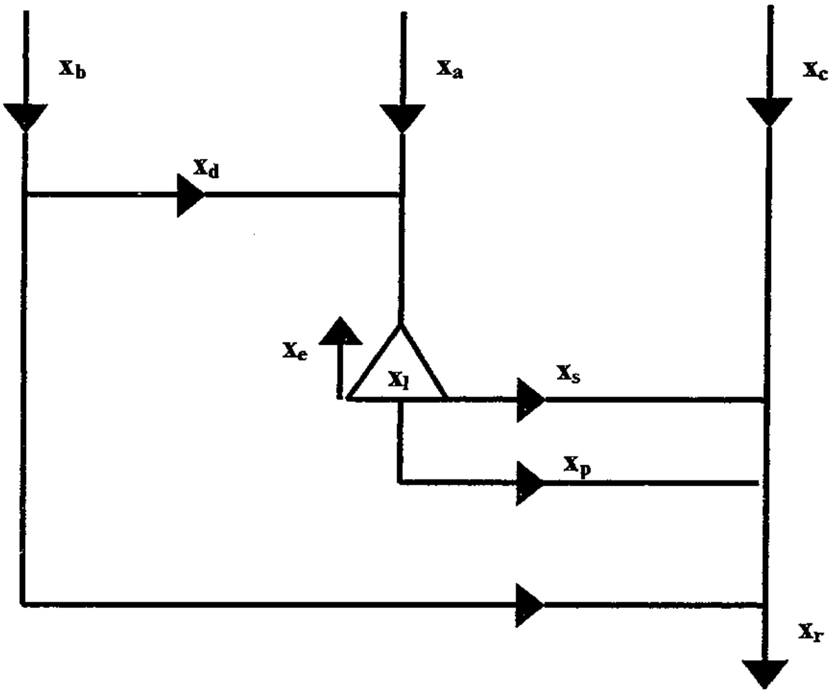


Figure 2. **The Mathematical Model**

Exogenous variables

These represent the uncontrollable variable aspects of the system. They are direct inflows to the lake from tributary streams on the north-east shore and the Acheron diversion (together equivalent to x_a in the model), the volume of water flowing out of the Harper and Wilberforce catchments (x_b), the volume of water flowing from all other parts of the Rakaia catchment (x_c, including the un-diverted part of the Acheron River), and the evaporation net of rainfall from the lake (x_e):

Exogenous variables: x_a x_b x_c x_e

4.2 Constraints

Hard constraints

The necessity to satisfy continuity (the 'law' of conservation of matter) can be called a hard constraint, as it is unavoidable. Non-negativity of variables is also unavoidable for some of the mathematical techniques to be employed.

$$x_i \geq 0 \qquad i = a,b,c,d,e,l,p,r,s$$

$$x_r = x_b - x_d + x_c + x_p + x_s$$

$$x_l^{t+1} = x_l^t + x_a + x_d - x_e - x_p - x_s$$

$$x_s = F(x_l \text{ or } z_l) \qquad x_l > x_{lsn}$$
$$x_s = 0 \qquad x_l \leq x_{lsn}$$

$$x_d \leq x_b$$

$$x_d \leq x_{dx}$$

$$x_p \leq x_{px}$$

x_{lsn} is the lake level above which the spillway operates in the model. In reality, the Oakden canal at the upper end of Lake Coleridge acts both as a diversion from the Wilberforce River, and as an overflow back to the Rakaia River from the lake. There is also another overflow route to a small tributary to the Rakaia River. x_{dx} and x_{px} are physical upper limits due to diversion and power station capacities.

Soft constraints

Some constraints are more like objectives; the model tries to satisfy them, and there might be penalties incurred by not doing so, but if necessary they can be violated to allow a solution to proceed. These can be called soft constraints. For the Rakaia/Coleridge system there are several: the minimum flows in the Rakaia River are specified by the National Water Conservation Order; the maximum and minimum lake levels and the minimum diversion flows are Water Right conditions; and there are environmental or wildlife habitat requirements which are of this kind.

$$x_d \geq x_{dn}$$

$$x_r \geq x_{rn}$$

$$x_{ln} \leq x_l \leq x_{lx}$$

The hard and soft constraints and terminology define the mathematical model in symbols.

4.3 Policy

A policy lays down a management rule or guideline for how decision variable values should be chosen. Policy can be derived from a mathematical model such as we are considering by using optimising techniques to specify 'best' policy, or by using simulation techniques to explore a variety of policies, observing their outcomes and choosing a policy that was shown to be better than some others. For the mathematical model:

Given: $[x_a, x_b, x_c, x_e, x_l]$ $t = 1,2,3,...,T$

What rules for choosing x_d, x_p, x_s during T best satisfy the objectives? t measures months, and T is 48 in the experimentation to be described.

4.4 Objectives

It is not unusual to begin discussing water resource planning objectives by referring to lofty goals such as: sustainability; national economic development; environmental quality; regional autonomy and development; Treaty of Waitangi values. I favour all those things, but it is necessary to be much more limited and precise to formulate suitable objectives for the techniques relevant here.

As for most multi-purpose systems, there could be many worthwhile objectives for the Rakaia/Coleridge system. There are already many expectations, as pointed out in the introduction. Optimisation of more than one objective simultaneously can only be achieved if the objectives can be valued relative to one another. Even when methods are available, the computational effort involved usually restricts consideration to two or three objectives.

I have chosen five objectives, but they can be reduced to two by introducing a further simplification and modifying the constraints. The objectives are:

- * to minimise flood flow volumes in the Rakaia River
- * to maximise electricity generation from Lake Coleridge Power Station
- * to maximise the volume of water available in the Rakaia River for irrigation or other out-of-stream uses at certain times
- * to keep Lake Coleridge surface level within a desired range (for grebes and humans) at certain times
- * to provide desirable flows for fishing and boating in the Rakaia River at certain times.

It can be seen intuitively that these will sometimes work together, and sometimes be in conflict. This accentuates the need for some mechanism of valuing the objectives relative to one another.

The further simplification facilitates use of known analytical techniques as well as reducing the number of objectives. Rather than treat flood volume minimisation, irrigation volume maximisation and desirable flows for fishing and boating separately, these optimisations are combined as minimising the departures from a 'desirable' flow volume, x_{rq}. This needs to be set below all flow volumes regarded as floods, and above most natural flows which could be augmented for irrigation. It could be set at a low value outside the irrigation season or at a value suited to salmon fishing or boating during certain months. In mathematical model terms:

Minimise $f[\,|x_r - x_{rq}|\,]$

Maximise $g[x_p]$

subject to the constraints, over total time period T.

This formulation of the system is typical of mathematical optimisation problems and several well-known techniques can be applied following further specification of the nature of the functions f, g and F (spillway operation) and specification of the constraints. The choice of technique is influenced by the kind and amount of data available and the kind of questions which will be asked.

5. Data and Techniques

Historical time series data are available for x_l, x_r, x_d, x_p and x_s. x_e can be estimated from climatological records at Lake Coleridge and a relationship between surface area and elevation of the lake surface. Estimates of Harper River flow are available from daily visual observations, but are not as reliable as the data derived from rated continuous measurements. Harper and Wilberforce flows together make up x_b; there is a short period of flow measurements for the latter from 1974 to 1980. The combination of direct inflows from tributary streams and the Acheron diversion, x_a, can only be estimated from back-calculation using a continuity equation and the other data. There are no data available for x_c. In summary, the data most necessary to examine how the system would have behaved given different policy, decisions or constraints are the very data which are weak or missing (x_a, x_b and x_c). Fortunately, it is possible to back-calculate combinations of x_a, x_b, x_c and x_e from the historic data for periods where the time series overlap, including the historic decision variables. These combinations can then be used in simplified mathematical models with the historic values of the exogenous variables, but with experimental values of the decision variables.

The simplified mathematical models appropriate for conceptual experimentation on this system include models suitable for the techniques of standard linear programming, non-linear programming, network linear programming, dynamic programming and simulation. Versions which are deterministic or stochastic and which use discrete or continuous variables could be applied. Present purposes will be served by describing only the simplest - deterministic standard linear programming with continuous variables (abbreviated LP henceforth).

The main additional requirements to be met in order to use LP are that all objective functions and constraints be linear and all variables non-negative. The major advantage of LP is that computer packages are widely available, avoiding the need for extensive programming. A disadvantage is that this kind of problem, involving time series of several variables, results in inefficient computation and therefore possibly expensive computing. The standard LP formulation is:

$$\text{MINIMISE } \{\mathbf{C}^T \mathbf{x}\} \qquad \text{subject to} \qquad \mathbf{A}\,\mathbf{x} = \mathbf{B} \text{ and } \mathbf{x}_n \leq \mathbf{x} \leq \mathbf{x}_x$$

where $\mathbf{C}^T$ is a matrix of objective function coefficients (transposed to operate on $\mathbf{x}$),
$\mathbf{x}$ is a vector of decision variables
$\mathbf{A}$ is a matrix of constraint coefficients
$\mathbf{B}$ is a matrix of constraint constants

Maximisation is achieved by minimising the appropriate negative quantity (see $-w_p x_p$ below). Relative valuing of different objectives can be achieved by applying 'weights', w, as objective function coefficients. Minimising departures from a reference value without using negative variable values can be done by introducing two non-negative variables (x_r^+ and x_r^-) whose sum with x_r is the reference value (x_{rq}). These are standard moves explained in operations research texts[16,17]. Time series are handled by having a new variable for each original variable at each stage (thus having very large numbers of variables for short time intervals or long total time periods). The result in this case is a simplified mathematical model based on the system analysis above:

$$\text{MINIMISE } \{ w_r^+ x_r^+ + w_r^- x_r^- - w_p x_p \}^t \qquad t = 1 \text{ to } T$$

SUBJECT TO THE CONSTRAINTS:

$$\{ - x_l - x_d + x_p + x_s \}^t + \{ x_l \}^{t+1} = \{ x_a - x_e \}^t \qquad \text{all } t \quad \text{(storage equation)}$$

$$x_r - x_r^+ + x_r^- = x_{rq} \qquad \text{all } t \quad (\text{desired } x_r)$$

$$x_r + x_d - x_p - x_s = x_b + x_c \qquad \text{all } t \quad \text{(continuity)}$$

WITH VARIABLE BOUNDS:

$$x_i \geq 0 \qquad \text{all } i \text{ and } t$$

$$x_{in} \leq x_i \leq x_{ix} \qquad \text{all } i \text{ and } t$$

Special arrangements are made to use starting and ending lake levels as given. x_r^+, x_r^-, and x_r have no upper bounds; x_r^+, x_r^-, x_p and x_s have zero lower bounds; all other bounds are positive. There are 7T variables and 3T constraints; if monthly time intervals are considered and the record length is 10 years, for example, there are 840 variables and 360 constraint equations. LP packages commonly cope with much greater numbers.

The simplified mathematical model has considerable versatility. Emphasis on the power generation objective compared to the river flow objectives can be varied from none (w_p zero) to total (w_r^+ and w_r^- zero; w_p unity). The desired river flow (x_{rq}) can be varied month by month. Upper and lower bounds on lake level or diversion volumes can be altered in whatever time pattern is desired. x_p can be increased to simulate the effect of having more hydro generation plant. It is a feature of LP solutions that information on what constraints are controlling the 'optimal' decisions, and the sensitivity of the solutions to changes in constraints, is automatically provided.

However, there are also limitations in addition to computational inefficiency. The spillway flows are chosen without taking account of the physical means in place to provide them. The objective function, being linear, treats flow volumes far from the desired value just the same as flow volumes quite close to it. The model is most suited to exploring planning alternatives at (say) monthly time intervals, but identified policies are dependent on being able to implement diversion decisions at (say) daily time intervals. Both its strengths and weaknesses can be illustrated by using it for experimentation.

6. EXPERIMENTATION

The simplified mathematical model was used with a standard LP package (IMSL DDLPRS subroutine - revised simplex method) using monthly water volumes (MCM), actual water right conditions, and historical time series data for the four years January 1978 to December 1981. Tributary inflows were back-calculated from actual power station and diversion monthly volumes, and measured lake levels. In the absence of better information, for purposes of illustration, the "desirable" river flow volumes were set at 50% greater than the monthly mean (1958-1989) volumes.

Verification of the model (that it was programmed correctly) was achieved informally by observing that all constraints were met and maximisation or minimisation was occurring as expected. Validation of the model (that it was reproducing real-world behaviour satisfactorily) was not strictly possible, both because the model had known differences from the real situation (e.g. spillway operation), and because the real operators of the system were working with an uncertain future, whereas the model was working with known historic data. However, some confidence in the model results is provided by results which reflect policies that would be expected from the real system, given similar inflows, constraints and policies. This paper aims to demonstrate techniques in a realistic setting. Further validation would be required for the model to be used for planning and management.

Optimisations were carried out for:

- existing power station (35 MW ≡ 97 MCM/month at full generation capacity)
- hypothetical power station upgrade (120 MW ≡ 333 MCM/month)

and for three objective sets:

- maximise x_p
- minimise $|x_r - x_{rq}|$
- maximise x_p and minimise $|x_r - x_{rq}|$ ($w_p = w_{r+} = w_{r-} =$ 🗎)

The LP procedure works out how the decision variables must be chosen to best meet the objectives, while satisfying the constraints.

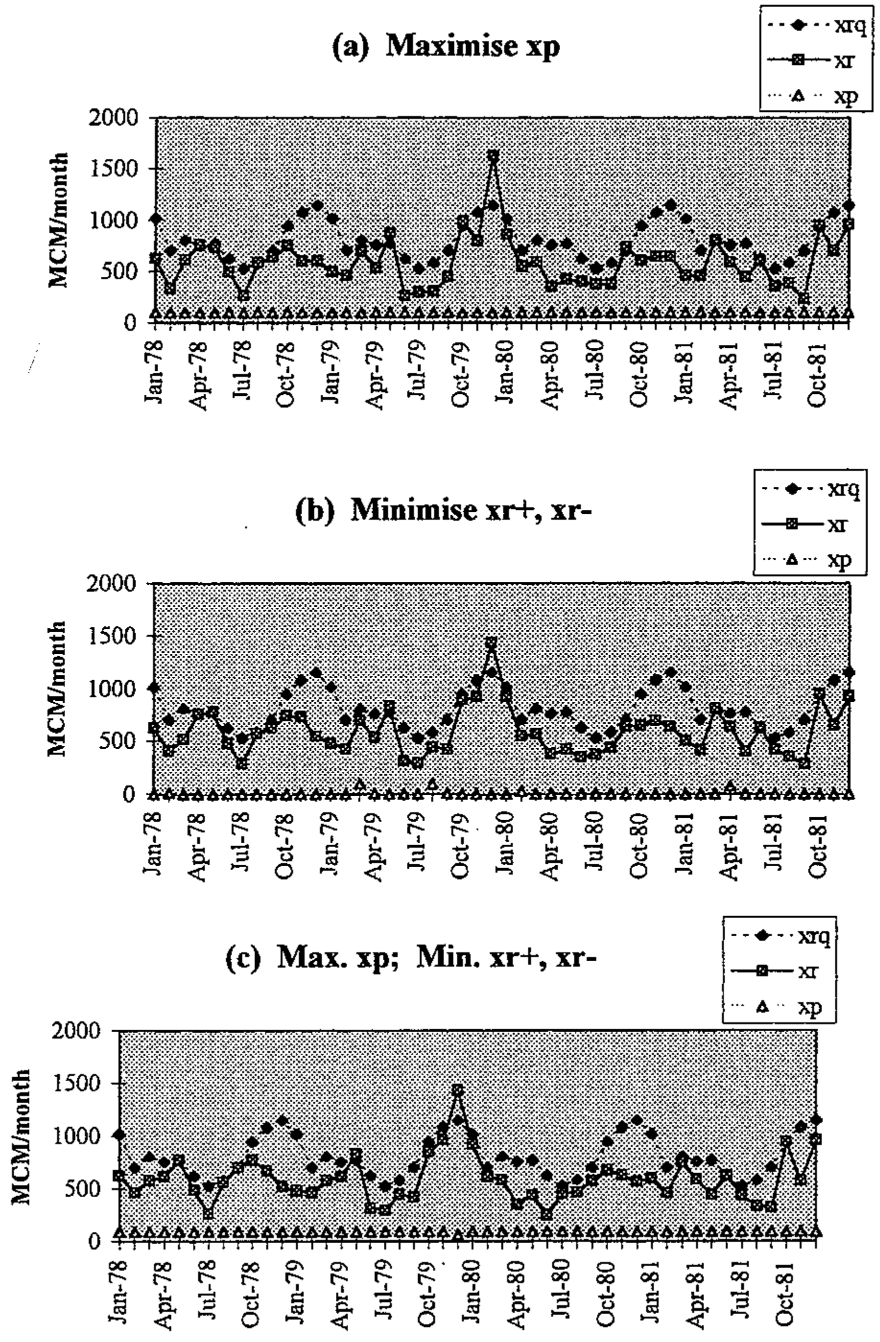


Figure 3. Optimisation results for 35 MW (97 MCM/month) and 3 objective sets.

6.1 The Existing System

Figure 3 shows the results of the three objective sets for the "existing system" model configuration. Not surprisingly, given the small flow the power station can take (97 MCM/month using all plant continuously) compared to the available water supply (up to 250 MCM/month, see Figure 6), there is very little "regulation" of downstream river flow available. Greater regulation would have been possible if daily time intervals had been used. To maximise power, the flow through the power station simply remains constant at its maximum physical limit (Figure 3(a)). This is in fact how the real power station has operated, subject to plant availability, for many years. Even if departures from the desirable river flows are minimised with no requirement to maximise power generation (Figure 3 (b)), there is little change in the river flows, in spite of zero generation in all but 7 of the 48 months. Requiring both to be optimised, with one-third weightings applied to each of x_p, x_r^+, and x_r^-, there was very little lost power generation (63 MCM instead of 97 in December 1979). Lake level was at its maximum allowable level (248 MCM) for 10 of the 48 months, at its minimum (110 MCM) for 18 months, and at intermediate levels for the remaining 20 months (Figure 5).

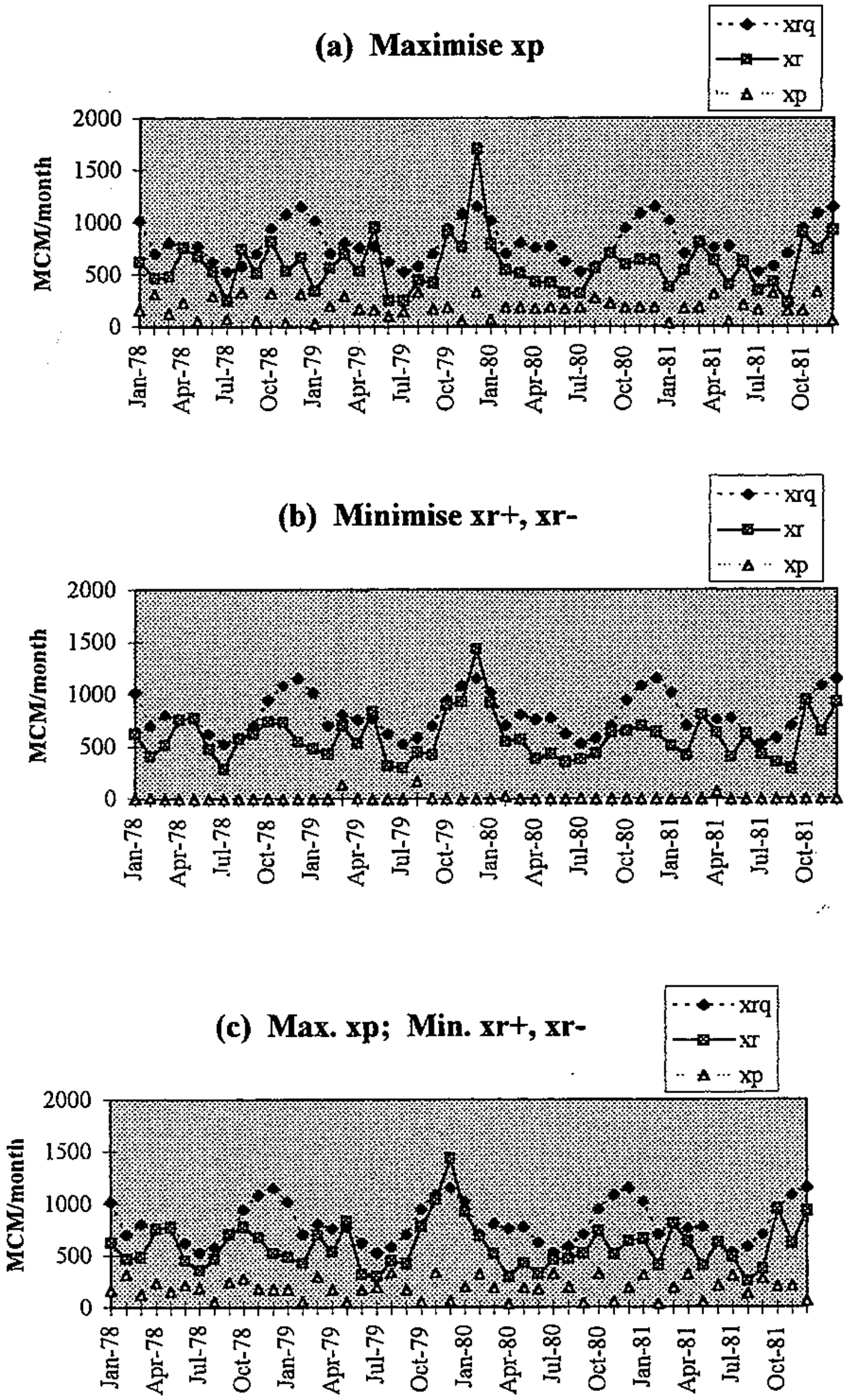


Figure 4. Optimisation results for 120 MW (333 MCM/month) and 3 objective sets.

Figure 4 shows the results of the three objective sets for the "revised system" configuration of the model. Plant capacity of the power station is increased to 120 MW (333 MCM/month), while all constraints and inputs stay the same. In particular, diversion upper limits were not increased for these runs of the model.

Compared to the present system, there was a considerable variation in monthly generation when maximising power produced (Figure 4(a)). Only 3 of the 48 months generated the plant maximum (using 333 MCM) and altogether 9 months used over 300 MCM. But there were also 10 months in which less than 100 MCM were used. This reflects the much closer balance between net inflows and plant capacity (Figure 5). Plant maximum was not reached in any months when one-third weightings were used to optimise both power and departures from required river flows, but monthly flows over 300 MCM were still recorded in 8 months, and there was only one more month (11) in which less than 100 MCM were used (Figure 4(c)). In spite of the tripling of power station flows the overall effect on river flows was small, reflecting the relatively small effect of changed timing of flows between passing directly down the rivers compared to being diverted through the lake and power station. As noted in §6.1, more regulation would have been possible using daily flows.

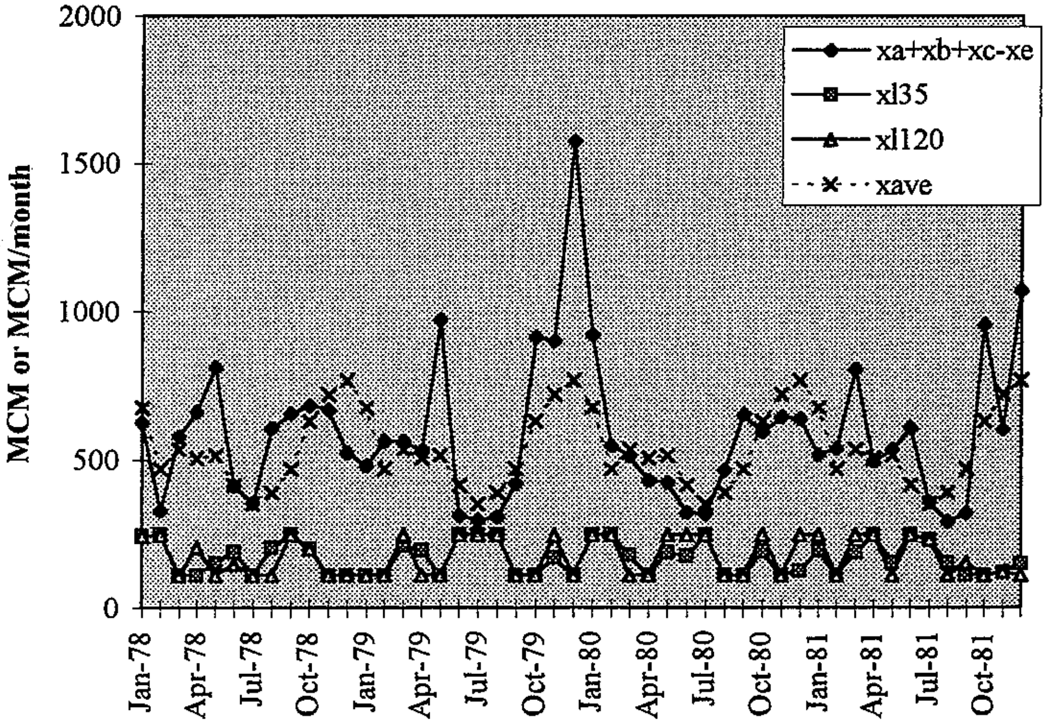
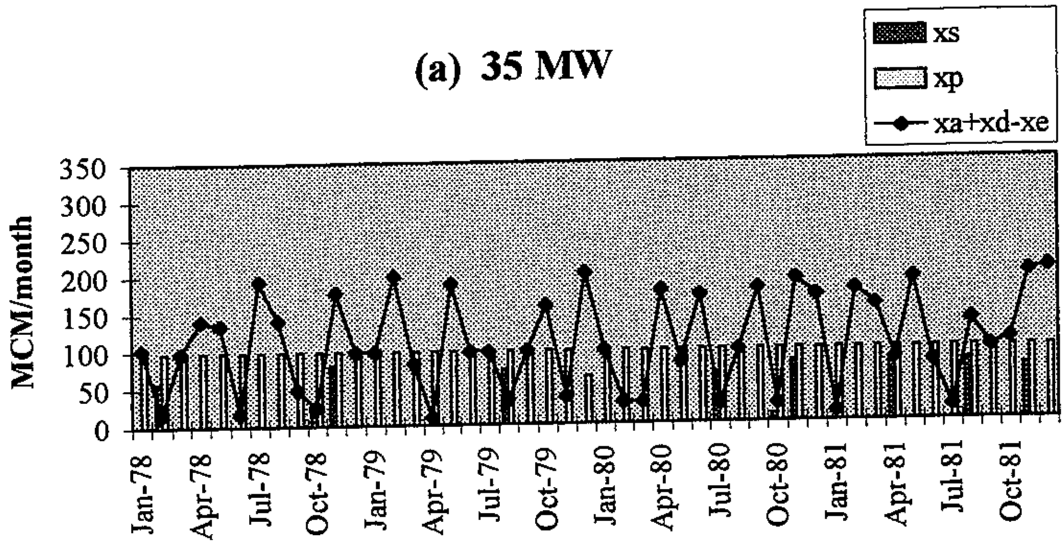


Figure 5. Monthly tributary river flows 1979-81 c.f. 1959-89 (ave); lake levels for existing and revised power station flows.

Figure 5 shows two comparisons: of river flows tributary to the Rakaia River 1978-1981 compared to the monthly means 1958-1989; and of lake levels for the existing capacity and revised capacity power station flows. The former shows that there was little unusual about flows in the period of modelling, although December 1979 was high. The latter shows a tendency for the lake to be either at its lower or upper water right limit with the revised capacity power station, whereas the level is intermediate more often with the existing lower plant capacity. It should be noted that the model has not been required in these example runs to observe any "rule curves", e.g. for flood detention, other than the two time-invariant water right maximum and minimum levels.

The electricity market which since 1998 has set wholesale prices in New Zealand has markedly changed the value of stored water at various times and places compared to values it might have had with the previous more unified electrical energy wholesale supply system. Figure 6 illustrates the kind of comparison which can be made of net inflows to the lake, generation, and spilled water, with the existing and revised power station plant capacity. The annual spill in the revised case (Figure 6(b)) is zero! The 4-year average annual spill from the model using the existing capacity (Figure 6(a)) is 152 MCM. This represents about 20% of what has recently been annual production from the real system.

Although it is not immediately obvious from Figure 6(b), the revised system is "choked" by the upper limits on diversion capacity. Further experimentation could be carried out optimising as already reported, but varying diversion capacity as well as power station plant capacity. Varying constraints in this way is a kind of simulation modelling. A fruitful combined approach is to use optimisation modelling to guide simulation modelling. Then the realism of simulation can be combined with the direction-finding of optimisation to lead to an overall "better" result.


(a) 35 MW

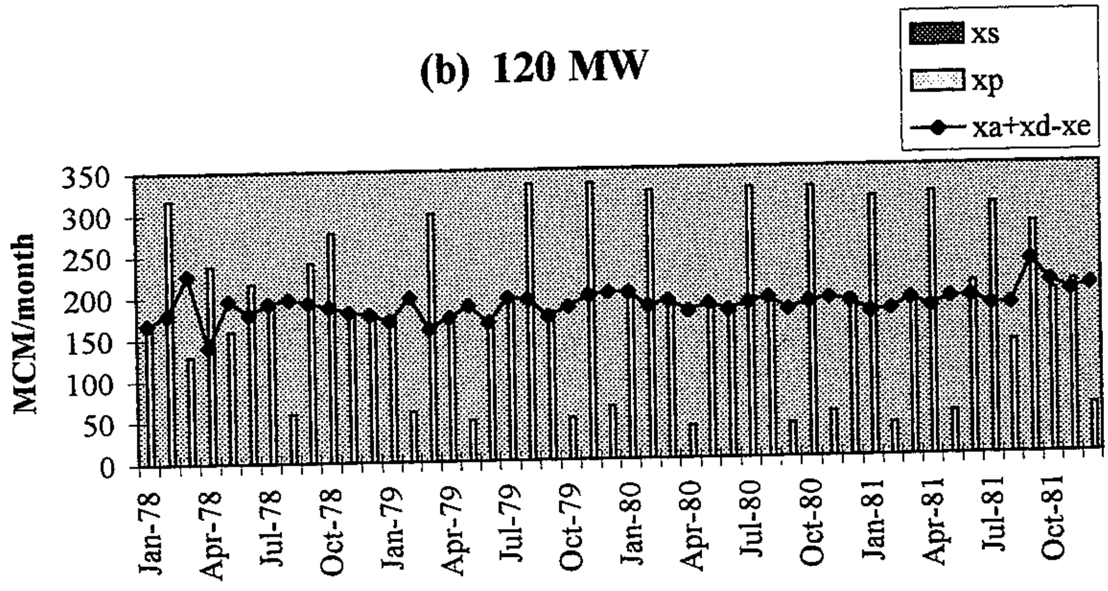

(b) 120 MW

Figure 6. **Net lake inflows, power station flows, and spill flows for existing and revised power station plant capacity.**

7. CONCLUSION

The water resources of the Rakaia River catchment, including Lake Coleridge, are very significant in Canterbury. There are multiple human expectations of these resources, and important environmental and sustainability issues involved in their use. The three main existing industrial uses of the water resources are for: irrigation, hydro-electric energy generation, and fish production. A National Water Conservation Order, and existing resource use consents, provide legal constraints on their use. Viewed in an integrated way as a water resource system, the Rakaia River catchment is multi-faceted and complex. Both conserving catchment natural values, and developing industrial and other human opportunities, could benefit from the systematic, integrating, approach provided by water resource systems engineering.

Many techniques are available in a systems approach, complementary to the kind of thinking involved. Although the techniques are often computer-based, that is more because of the high computation loads they engender, than because of any inherent complexity of their bases. Unfortunately, both the thinking and the techniques have often been obscured in the past by complex jargon and terminology used to describe them.

This paper has set out a systems approach to experimenting with some possible changes to the system structure (power station plant capacity), and operation (timing of power station flows). Other possible changes (e.g. to diversion capacities, lake level constraints) are mentioned, but experimentation concerning them is not reported here. As an example of optimisation techniques, a linear programming model of the system is described, and used with two objectives, for two representations of the system: one which mimics the real power generation water system, and one which revises upwards the installed plant capacity in the power station. The two objectives are formulated in a way which allows five related objectives to be optimised.

The existing system model shows that power station flows (and hence energy generation) are limited by installed plant capacity, as are opportunities to enhance river flows. The revised system model (with a 240% increase in installed plant capacity!) shows that the system then becomes limited by diversion capacity, yet still has a limited ability to "regulate" downstream river flows. There are a number of unrealistic aspects of the models, including the way spill flows are decided. Complementary simulation modelling could be used to provide more realistic imitation of the real-world system, guided in choice of decision variable values (policy) by the optimisation modelling.

The objective of the paper — as distinct from the modelling — is to illustrate the potential value of a water resource system engineering approach to planning development and conservation. The Rakaia River catchment is a very suitable context to use for such an illustration and 1999 is a very appropriate time to do so. This year, many of the irrigation water resource consents are being reviewed and some large new ones are being considered, the historic power station is being upgraded, and the Canterbury Regional Council is working towards a Draft Regional Water Resource Plan. A water resource system engineering approach could be a very useful complement to other planning tools.

8. ACKNOWLEDGEMENTS

The LP computation used as illustration in this paper was carried out while I was a Research Fellow hosted at Melbourne University by Tom McMahon, on leave from employment at Lincoln University. Graeme Horrell, Trish Lockington, Craig Mason, Jason O'Brien and John Talbot (Canterbury Regional Council); Roger Fairclough and Lennie Palmer (ECNZ); John Bright (Lincoln Ventures Ltd); Alistair McKerchar and Graeme Davenport (NIWA) and Roger Burchett (Trustpower Ltd); provided data, information and comment.

9. REFERENCES

1. Bowden, MJ; Ayrey, RB; Lineham, IW; Duffield, DN; Saville-Smith, K; Mason, CR; Talbot, JD; Weeber, JH; Glennie, JM; Moore, K. 1983. *The Rakaia River and Catchment - A Resource Survey.* (4 volumes), North Canterbury Catchment Board and Regional Water Board, Christchurch, New Zealand.
2. New Zealand Government 1988. *National Water Conservation (Rakaia River) Order 1988.*
3. Painter, DJ. 1990. *Rakaia River and Catchment New Zealand: Twenty-year Planning Case Study.* in *Water Resource Systems Application*, Simonovic, SP; Goulter, IC; Burn, DH; Lence, BJ (Eds), pages 16-25, University of Manitoba, Winnipeg, Canada.
4. Loucks, DP; Stedinger, JR; Haith, DA. 1981. *Water Resource Systems Planning and Analysis.* Prentice-Hall.
5. Haimes, YY; Hall, WA; Freedman, HT. 1975. *Multiobjective Optimization in Water Resources Systems.* Elsevier.
6. Mays, LW; Yeou-Koung Tung. 1992. *Hydrosystems Engineering and Management.* McGraw-Hill.
7. Yeh, WW-G. 1985. *Reservoir Management and Operation Models: a State-of-the-art Review.* Water Resources Research 21(12):1797-1818.
8. Boshier, JF; Manning, GB; Read, EG. 1983. *Scheduling Releases from New Zealand's Hydro Reservoirs.* IPENZ Transactions 10:33-41.
9. Read, EG; Culy, J; Halliburton, TS; Winter, NL. 1987. *A Simulation Model for Electricity Planning in New Zealand.* Proceedings of the IFORS Conference, Operational Research 1987, Argentina.
10. Westergaard, E; Mullon, G; Sise, G; McCord, A. 1996. *Development of Transpower's Wholesale Pool Simulation Model.* IPENZ Annual Conference Proceedings 2(1):78-83.
11. Schultz, GA. 1989. *Ivory Tower Versus Ghosts? or - the Interdependency Between Systems Analysts and Real-world Decision Makers in Water Management.* Proceedings of the Symposium on Closing the Gap Between Theory and Practice, Baltimore, IAHS Publication 180:23-32.
12. Burchett, R. 1999. (Trustpower Ltd). Personal Communication, June.
13. O'Brien, J. 1997. (Canterbury Regional Council). Personal Communication, December.
14. Davis, SF. 1979. *Fish and Fishery Values of the Rakaia River: a Preliminary Report.* Fisheries Environmental Report No. 2, Ministry of Agriculture and Fisheries, Christchurch, New Zealand.

15. Glova, GJ. 1990. (Ministry of Agriculture and Fisheries, Christchurch). Personal Communication, December.
16. Daellenbach, HG; George, JA; McNickle, DC. 1983. *Introduction to Operations Research Techniques.* Second Edition, Allyn and Bacon.
17. Taha, HA. 1987. *Operations Research: An Introduction.* Fourth Edition, Macmillan.

10. APPENDIX - TERMINOLOGY

Symbols

A	lake surface area (function of x_l or z_l)
f,g,F	functions
w	weighting coefficient
x	volume of water [usually per month]
z	elevation of water surface AMSL

First subscripts

a,b,c	upper catchments	p	power, electric
d	diversion	r	river
e	evaporation	s	spill
l	lake		

Second subscripts

n	minimum
q	reference value
x	maximum

Superscripts

t (T)	time period (total)