

Urban Water Research Association of Australia

Stochastic Economic Approach to Headworks Augmentation Timing



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Headworks Augmentation Timing**

**George Kuczera and Wan Sing Ng
University of Newcastle**

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URBAN WATER RESEARCH ASSOCIATION OF AUSTRALIA

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FOREWORD

This report is based on UWRAA Research Project No EF-12: 'Stochastic economic analysis of headworks augmentation timing' which was undertaken during the period July 1991 - December 1993. Organisational responsibility for the project was as follows:

Sponsoring Authority	:	Hunter Water Corporation
Project Officer	:	Dr R J Wilson Hunter Water Corporation
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The project was funded by the Urban Water Research Association of Australia.

SUMMARY

The problem of deciding when a headworks augmentation should commence and of optimizing restriction rules is considered using an economic-based approach. The approach uses information about consumers' willingness-to-pay for water to evaluate the economic impact of restrictions on water consumption. Multi-replicate simulation, which accounts for uncertainty in future streamflows as well as future demand, is used to estimate future expected economic losses due to restrictions for a given drought management plan and operating policy. Computer software for implementing this methodology was developed around the WATHNET generalized headworks simulation model and can be run on IBM-compatible and Macintosh computers and on Unix workstations supporting X Windows.

A case study based on the Newcastle headworks system demonstrates the methodology. It is shown that economic losses can be very sensitive to the shape of the demand-price curve in the subsistence region, where prices, well beyond those currently set by water authorities, force the consumer to drastically reduce consumption. However, presently there is insufficient information to reliably define the shape of the domestic demand-price curve in this region. The need for a comprehensive drought management plan is argued. Finally it is shown how the estimation of economic losses can assist in the optimization of restriction rules and in the selection of the augmentation date which maximizes net expected economic benefits.

The viability of the economic loss methodology depends critically on having reliable demand-price information. Given such information the tools developed in this study are capable of giving planners an economic perspective on system performance, which, together with current risk-based measures, should assist in the search for good solutions to managing headworks systems.

The main research priority lies in better definition of the demand-price relationship in the subsistence region, not only for the outdoor domestic sector but for all other sectors. Willingness-to-pay surveys and cross-sectional studies may better define this subsistence region. A sufficient outcome of such work would be an objective description of the uncertainty about the demand-price curve in the subsistence region.

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1. INTRODUCTION

Although it is recognized within the urban water supply industry that demand management is an important tool for managing water resources, a balanced view of both supply and demand management is, nevertheless, required to optimize system performance. Moreover, for an urban system experiencing growth in water consumption, demand management through water pricing and regulation as well as fine tuning of headworks operation to maximize yield can, at best, only defer the inevitable need to augment the headworks system.

Two issues confront the water supply manager when planning a future system augmentation. The first involves identifying from a range of alternative options the preferred augmentation option. The second involves deciding when to commission the system augmentation. Linked with the timing problem is the related issue of system operation; for example, optimization of system operation may lead to deferral of the future augmentation. This study focuses on the second issue.

In deciding on the timing of a system augmentation the manager needs to trade-off the deterioration in system performance against the deferral of scarce resources required to commission and operate the augmentation. It will be argued that making this trade-off is made difficult by presently accepted perceptions of system performance objectives.

At the conclusion of the National Workshop on Planning and Management of Water Resource Systems: Risk and Reliability (Dandy and Simpson, 1989) the following recommendation was made:

"The **risk** to the security of supply in a water resource system at any point in time should be described in terms of probability, degree, and duration of restrictive measures where:

- **probability** is the probability restrictions of a specified degree **will be** imposed in any particular year;
- **degree of restriction** describes the nature of restrictive measures and the amount by which consumption is expected to fall below unrestricted demand;
- **duration** characterizes the expected range of durations of periods during which unrestricted demands cannot be met.

The **reliability** of supply is the probability that restrictions of any given degree **will not be** imposed in a particular year.

This basis should be used by Australian water authorities in developing definitions of supply risk and reliability in particular water systems. Other parameters, such as water quality or price will require clarification if significantly changed during drought periods."

From the above recommendation it follows that the manager should consider solving the following constrained optimization problem when deciding on the timing of a future augmentation:

Minimize the present value of the system augmentation cost subject to the following constraints:

- Future reliability must exceed a minimum value;
- The restriction severity measure must be less than a maximum value;
- The restriction duration measure must be less than a maximum value.

Of significance is the fact that the manager has to make subjective judgements about what are acceptable constraints. The National Workshop on Planning and Management of Water Resource Systems: Risk and Reliability anticipated this problem when it recommended that:

"Risk management decisions of water authorities should be made with a level of community input appropriate to the risk situation."

"Water authorities decide on risk by offering, to the extent practical, a range of alternatives in security of supply and associated water prices so that consumers are in a better position to advise/select the reliability they are prepared to pay for."

In effect these recommendations attempt to shift the burden of making trade-offs from the manager to the community itself. Though an admirably democratic idea, the problem remains that complex trade-offs have to be made. Moreover, there exists the nontrivial problem of communicating the problem to the public. Morgan (1993) stresses the importance of good risk communication if the public is to make an informed decision. According to Morgan good risk communications entails learning what people already believe, tailoring the communication to this knowledge and to the decisions people face, and subjecting the resulting message to careful empirical evaluation.

Is there an alternative way which avoids, or at least eases, the burden of making complex risk-based trade-offs? The answer is maybe. Dandy (1989, 1992), Rhodes (1993) and others have argued that information about consumers' willingness-to-pay for water can be used to evaluate the economic impact of restrictions on outdoor domestic water consumption. The main potential benefit of an economic-based approach is that it transforms the augmentation timing problem from a constrained optimization problem to an unconstrained optimization problem in which the economic cost of restrictions is directly compared with the economic cost of a system augmentation.

The main objective of this study is to develop and demonstrate a stochastic economic approach for deciding when a headworks augmentation should commence. Chapter 2 describes the methodology for evaluating economic losses due to restrictions. The methodology uses information about consumers' willingness-to-pay for water to evaluate the economic impact of restrictions on water consumption and employs multi-replicate simulation, which accounts for uncertainty in future streamflows as well as future demand, to estimate a time stream of expected economic losses. Chapter 3 describes the computer software implementing this methodology in a way that maximizes portability. Chapter 4 concludes with a case study based on the Newcastle headworks system. It illustrates the identification and calibration of demand-price models and addresses the important issue of extrapolating the demand-price model beyond observed data. It demonstrates the use of multi-replicate simulation to estimate economic losses due to restrictions and makes use of this information to optimize restriction rules and to select an augmentation date.

2. METHODOLOGY

2.1 Selection of Augmentation Time

If the economic cost due to restrictions can be evaluated, multi-replicate simulation can be used to study the timing of a future augmentation. Two steps are implemented in a multi-replicate simulation:

- 1) N replicates of future inputs, namely streamflow, climate and socioeconomic variables, are generated by randomly sampling from their probability distributions. Each replicate represents an independent and identically distributed realization of future inputs.
- 2) For each replicate the headworks system is simulated and whenever shortfalls in demand occur the economic loss is evaluated. Let the economic loss for future month m, future year y, and replicate r be

$$\text{LOSS}(m,y,r), \quad m = 1, \dots, 12; \quad y = 1, \dots, Y; \quad r = 1, \dots, N$$

where Y is the planning horizon.

For any future month m and year y the probability distribution of economic losses due to demand shortfalls, defined by the probability density function $\xi[\text{LOSS}(m,y)]$, can be inferred from the N realizations $\text{LOSS}(m,y,r)$, $r = 1, \dots, N$. It needs to be stressed that the best we can do in describing the future performance of a water supply system is to infer the probability distribution of performance variables such as reliability, economic loss, severity and so on. This is because future inputs to the headworks system are random and unpredictable and hence system outputs (e.g. water delivered to consumers) are random and unpredictable. Multi-replicate simulation offers the only viable technique to infer the required distributions.

There is an extensive literature on decision making under uncertainty. Here we shall consider the simplest approach based on expected losses. Define the following terms:

- $\text{pw}[\text{AUG}(t)]$ = present worth of augmenting the system in future year t
- $\text{pw}\{E[\text{LOSS}|\text{AUG}(t)]\}$ = present worth of expected economic losses due to restrictions

with system augmented in future year t

Computation of the present worth of expected economic losses requires evaluation of expected losses from the simulation results. For month m and year y the expected loss is

$$\begin{aligned} E[\text{LOSS}(m,y)|\text{AUG}(t)] &= \int_0^{\infty} \text{LOSS}[m,y|\text{AUG}(t)] \xi\{\text{LOSS}[m,y|\text{AUG}(t)]\} d\text{LOSS} \\ &= \lim_{N \rightarrow \infty} \frac{1}{N} \sum_{r=1}^N \text{LOSS}[m,y,r|\text{AUG}(t)] \end{aligned} \quad (2.1)$$

We can now define the expected net economic benefit attributable to the augmentation in future year t as

$$E[\text{NB}(t)] = \text{pw}\{E[\text{LOSS}|\text{AUG}(\infty)]\} - \text{pw}\{E[\text{LOSS}|\text{AUG}(t)]\} - \text{pw}[\text{AUG}(t)] \quad (2.2)$$

The first two terms on the right hand side of eqn. (2.2) represent the reduction in expected economic losses due to the augmentation in future year t.

The preferred augmentation date can be determined by finding the future year t_{aug} which maximizes $E[\text{NB}(t)]$; that is,

$$t_{\text{aug}} = \begin{cases} t_{\text{amp}} \leftarrow \max_t E[\text{NB}(t)], & t = 1, \dots, Y \text{ if } E[\text{NB}(t_{\text{amp}})] > 0 \text{ and } t_{\text{amp}} < Y \\ \geq Y & \text{otherwise} \end{cases} \quad (2.3)$$

Of greater value will be the graph of $E[\text{NB}(t)]$ versus t. This will indicate the sensitivity of the economic criterion to different augmentation dates.

The maximum expected net benefit criterion of eqn. (2.3) is an intuitive criterion but, by no means, the only decision criterion that can be used. For risk averse decision makers it may be more relevant to consider some aspect of the right tail of $\xi\{\text{LOSS}[m,y|\text{AUG}(t)]\}$ such as the 95-percentile rather than the expected loss. In this study we shall confine our attention to the maximum expected net benefit criterion.

2.2 Economic Losses Due to Demand Shortfalls

To evaluate the probability density function $\xi[\text{LOSS}(m,y)]$ of future economic losses due to demand shortfalls, it is necessary to define a drought management plan (DMP) which defines the

actions taken by the water authority to reduce consumption during the drought storage drawdown. The DMP must be comprehensive in the sense that it must define actions for all contingencies. For example, if a water authority has a DMP based on restriction of water use during drought, it may consider at the beginning of a drought time restrictions on outdoor domestic consumption, progress to a total ban on outdoor water use, and, in the event of an extreme drought, progress to rationing indoor domestic, industrial and commercial use by regulation or by cutting supply.

Much of the Australian literature on DMPs (eg, Atherton, 1989) concentrates on restricting outdoor domestic consumption. This is inadequate if economic losses are to be meaningfully evaluated. Because there is a finite risk of the system being empty and consumers experiencing 100% shortfalls, the DMP must address such contingencies. Economic losses may have to be estimated for demand shortfalls ranging from 0 to 100% for all consumers. Without such a comprehensive approach there is a real prospect of seriously underestimating estimates of economic losses.

In the following sections a discussion is presented on the evaluation of economic losses for a number of urban demand sectors. In addition to the domestic sector, which can be further disaggregated into indoor and outdoor components, the industrial/commercial sector is considered because, in the event of an extreme drought, it would also have to be encompassed by the DMP.

2.2.1 Domestic economic losses

Domestic consumption is typically categorized into indoor and outdoor consumption. Following Narayanan et al. (1985) it can be argued that water use in the domestic sector, both indoor and outdoor, is a derived demand in the sense that it is one of a number of inputs used to produce a consumed output. For example, water along with labour, fertilizer, etc is used to produce the output "lawn and garden", while water along with labour, detergents and washing machines is used to produce the output "clean laundry". These outputs are directly consumed within the domestic sector rather than traded in a market. The economic benefit from domestic water use is given by the consumer surplus which is the difference between the consumer's willingness to pay for water and the price actually paid. When a DMP is implemented the domestic consumer experiences an economic loss in the sense that he forgoes consumption which, under normal circumstances, he was willing to pay for.

Evaluation of the consumer surplus relies on knowledge of the domestic demand-price function. In simple terms the estimation of the economic loss due to a demand shortfall can be explained by referring to the demand-price curve for a single household shown in Figure 2.1: For the price p_0 , consumption of water is q_0 . During periods of drought a DMP is implemented with consumption falling to $(1-R)q_0$ where R is the fraction by which consumption has been reduced. The region abcd represents the loss in the household's willingness to pay due to imposition of demand shortfalls. It has two parts, loss of revenue to the water authority and loss of consumer surplus.

The loss of willingness to pay for the i^{th} household, $i = 1, \dots, M$ is defined as

$$\Delta WTP_i = \int_{p_0}^{p_s} q_i(p) dp + p_0 q_0^i - p_s (1-R) q_0^i \quad (2.4)$$

where $q_i(p)$ is the i^{th} household's demand at price p , p_0 is the normal price and q_0^i is the normal household consumption. If restrictions are imposed reducing consumption to $(1-R)Q_0$ then p_s is the price at the reduced consumption level. This is called the shadow price of water because it is not actually charged.

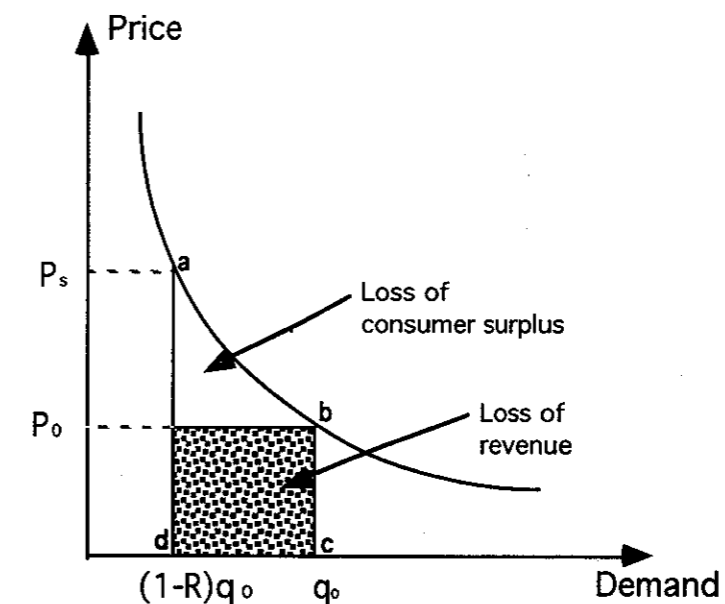


Figure 2.1. Household demand-price relationship showing loss of revenue and consumer surplus due to imposition of restrictions

For the domestic sector the total loss of willingness to pay due to imposition of restrictions is the sum of the willingness to pay losses over M households, namely

$$\begin{aligned}
\Delta WTP &= \sum_{i=1}^M \Delta WTP_i \\
&= \sum_{i=1}^M \left[\int_{p_0}^{p_s} q_i(p) dp + p_0 q_0^i - p_s(1-R)q_0^i \right] \\
&= M \int_{p_0}^{p_s} Q(p) dp + p_0 Q_0 - p_s(1-R)Q_0
\end{aligned} \tag{2.5}$$

where $Q(p)$ is the average household demand at price p , and Q_0 is the total domestic demand at price p_0 .

Offsetting this loss is the savings in costs of the water authority

$$\text{SAVING} = \int_{(1-R)Q_0}^{Q_0} MC(Q) dQ \tag{2.6}$$

where $MC(Q)$ is the short-run marginal cost function. The economic loss due to the demand shortfall is, therefore,

$$\begin{aligned}
\text{LOSS} &= \Delta WTP - \text{SAVING} \\
&= M \int_{p_0}^{p_s} Q(p) dp + p_0 Q_0 - p_s(1-R)Q_0 - \int_{(1-R)Q_0}^{Q_0} MC(Q) dQ
\end{aligned} \tag{2.7}$$

Dandy (1992) has shown that the above analysis underestimates the actual economic loss due to demand shortfalls. The underestimation arises for a number of reasons, two important ones being:

- i) Restrictions on outdoor domestic consumption may take the form of time restrictions such as limiting use of hoses to fixed periods during the day. In the calculation of loss of consumer surplus it is assumed that the reduction in consumption is equivalent to a quantity restriction. Dandy shows that time restrictions increase the opportunity cost of labour and so induce a shift in the demand-price relationship. The result of this is that eqn. (2.5) underestimates the loss of consumer surplus when time restrictions are in force.
- ii) Eqn. (2.5) makes use of an average household demand-price relationship. If short-run price increases are used to reduce consumption then eqn. (2.5) does produce the correct loss of consumer surplus. However, when quantity restrictions are imposed, the shadow

price will differ between households. Under quantity restrictions, Dandy shows that eqn. (2.5) is only correct when all households are the same. When there is inter-household variability in the demand-price relationship exists eqn. (2.5) underestimates the actual loss of consumer surplus.

We conclude from Dandy's work that eqn. (2.5) provides a lower bound on the economic loss due to restrictions when implemented in the form of time or quantity restrictions.

2.2.2 Industrial/commercial economic losses

As with the domestic sector, water use in the industrial/commercial sector is a derived demand in the sense that it is one of a number of nonproduced factors used to produce an output. However, unlike the domestic sector, outputs from the industrial/commercial sector are traded in a market to either be consumed or be intra-industry inputs. This complicates assessment of economic losses because not all the output is consumed.

One crude approach to estimating the economic loss due to shortfalls is based on the Leontief model, a linear multimarket analysis (Henderson and Quandt, 1971). Let x be the vector of gross output of n produced goods from the industrial/commercial sector and y be the final demand or net output for the n produced goods. In a multimarket equilibrium we have

$$x = Ax + y \tag{2.8}$$

where A is the coefficient matrix with a_{ij} ($i=1, \dots, n; j=1, \dots, n$) representing the amount of good i produced given one unit of good j . It follows that the value of final demand is

$$Y = p' (I - A) x \tag{2.9}$$

where p is the vector of prices for the n produced goods and I is the identity matrix.

If we assume that production of goods is linearly dependent on water use, the total derived demand for water is

$$Q_0 = w' x \tag{2.10}$$

where w is a vector of water use coefficients with w_i being the amount of water required to produce one unit of good i .

Suppose the DMP restricts the availability of water to $(1-R)Q_0$ and, furthermore, suppose each industry has its water availability reduced by the same fraction. Assuming in the short run that industry cannot adjust to the reduced availability of water it follows that production of goods will fall to $(1-R)x$. The economic loss will be the short-run reduction in the value of net output less savings made by the water authority; that is,

$$\begin{aligned} \text{LOSS} &= R p' (I-A) x - \text{SAVING} \\ &= R Y - \int_{(1-R)Q_0}^{Q_0} MC(Q) dQ \end{aligned} \quad (2.11)$$

It needs to be stressed that the analysis leading to eqn. (2.11) is simplistic in a number of respects, three of which are:

- 1) The implicit assumption is made that producers are using the best water-use technology and therefore there is no wastage. If this is not true, producers could, in the short run, be able to reduce wastage and so sustain production above $(1-R)x$. Under such conditions eqn. (2.11) would overestimate the economic loss.
- 2) A more sophisticated DMP would discriminate between high and low value industries resulting in an economic loss less than that predicted by eqn. (2.11).
- 3) The reduction in net output partly manifests itself as a reduction in regional household income. Eqn. (2.11) only accounts for the loss of income and makes no allowance for the loss of consumer surplus due to foregone consumption.

Nevertheless, eqn. (2.11) does provide a simple estimate of the economic loss by reducing the value of net output from the industrial/commercial sector to $(1-R)$ of its normal value. It is not clear whether a more sophisticated econometric analysis would yield an estimate above or below that predicted by eqn. (2.11).

In addition to goods and service traded in some kind of market, there are public goods and services which are not traded such as in the case of non-profit community groups, charities and public services (parks, street washing, ...). This non-trading sector may be a significant consumer of water and, therefore, needs to be considered.

3. SOFTWARE DEVELOPMENT

The methodology presented in Chapter 2 requires extensive computer simulation to realistically describe system behaviour and the effects of stochastic future inputs. In developing software to implement this methodology portability across different headworks systems was considered essential if the results of this study are to be accessible to most water authorities. To achieve this portability goal three objectives guiding the development of the software were established:

- i) The software must use a system-independent model so that it can be readily applied to a wide range of headworks systems.
- ii) The software must be capable of running on a wide range of computers.
- iii) Although Section 2.2 outlined a general approach for evaluating economic losses due to demand shortfalls, implementation to a particular system depends on available data and system characteristics. The economic loss software must, therefore, be capable of being customized for any headworks system.

Figure 3.1 presents a schematic of a software solution which provides the desired portability across IBM-compatible computers, Macintosh computers, and on computer systems running under Unix and supporting X Windows. This involves meshing WATHNET, an already developed generalized headworks simulation suite of programs (Kuczera, 1990 and 1992), with two new programs WATDEM and ECLOSS. In the schematic the oval shapes represent files, the rectangular shapes represent programs and the arrows denote the direction information flows.

The WATHNET suite consists of four programs. EDNET is used to interactively edit a network data file which describes the headworks system. WATSTRM is primarily used to generate synthetic streamflow and climatic data. SIMNET is the heart of the suite using network linear programming to simulate the operation of the headworks system. It uses information in the network, streamflow and demand data files and creates an output and a demand shortfall file. WATOUT is used to interactively examine the results in the output file.

The function of WATDEM is to generate a demand data file in a format that can be read by SIMNET. Moreover it is designed to implement the simulation methodology presented by Ng and Kuczera (1991, 1992) which explicitly allows for uncertainty in future demand forecasts as well as in future streamflow and climatic inputs. WATDEM accesses three files:

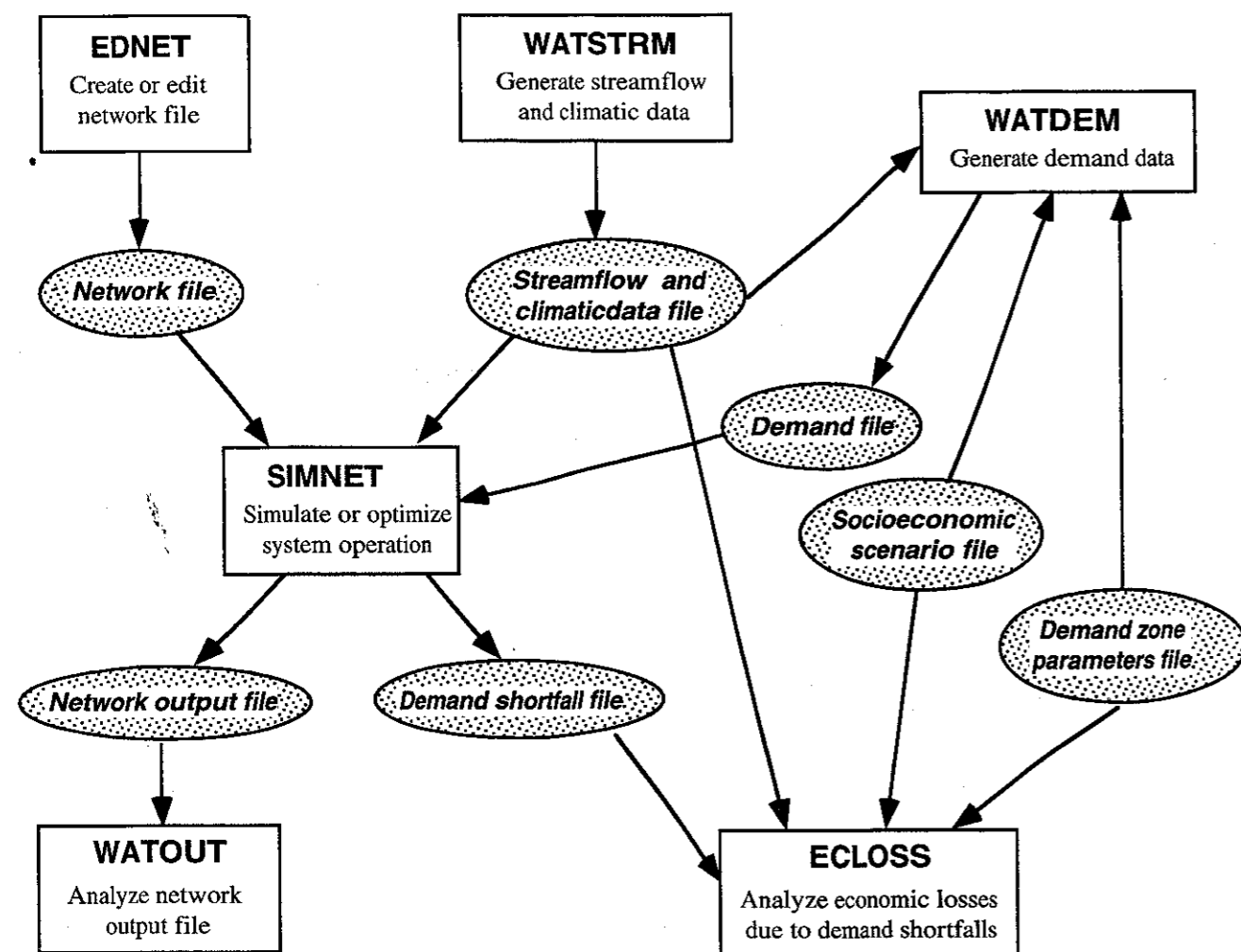


Figure 3.1. Schematic outlining program and file dependence between WATHNET, WATDEM and ECLOSS.

- i) The streamflow and climatic data file is read to obtain climatic data that influences seasonal demand variations. This same data file is used by SIMNET to simulate system behaviour. This guarantees that the important and significant cross-correlation between streamflow and climatic variables (such as rainfall) is preserved.
- ii) The socioeconomic scenario data file contains time series of the socioeconomic variables used to predict demand at each zone. The file format allows multiple scenarios for each variable. By specifying a (subjective) probability of occurrence for each scenario WATDEM will generate a demand data file that correctly allows for uncertainty in future socioeconomic scenarios. For example, future population, a major determinant of future demand, could be described by three scenarios consisting of low, medium and high growth rates. The probability assigned to each population scenario reflects the analyst's judgement about the likelihood of that scenario actually occurring.

- iii) The demand zone parameters file contains information about the parameters to be used for each zone. This format allows uncertainty about these parameters to be explicitly expressed. If requested, WATDEM will generate demand data that correctly allows for this uncertainty.

It needs to be stressed that WATDEM is a shell program requiring to be linked with a subroutine called MODELS which estimates monthly and yearly zonal demand given demand zone parameters, climatic and socioeconomic time series data. More specifically MODELS requires the following demand model to be implemented:

$$Q_{myk} = f(m, y, \Theta_k, CV_{my}, SV_y, \sigma_k) \quad (3.1)$$

where Q_{myk} is the demand in megalitres for month m , year y and demand zone k , Θ_k is a vector of the parameters for demand zone k , CV_{my} is a vector of the climatic variables for month m and year y , SV_y is a vector of the socioeconomic variables for year y , and σ_k is the standard deviation of demand model residuals for zone k . The user is free to code any function $f(\bullet)$ into MODELS. Q_{myk} is the output returned by MODELS. In Appendix A the prologue for subroutine MODELS is presented along with information on the formats on the demand zone parameters file and the socioeconomic scenario file. Although this design requires the user to write FORTRAN code, it does provide maximum flexibility in computing zonal demand. This is considered essential because presently there is no standard format for demand models.

The function of ECLOSS is to evaluate the present worth of the expected economic losses due to restrictions. ECLOSS accesses three files:

- i) The demand shortfall file created by SIMNET provides information about shortfalls occurring during the multiple replicate simulations.
- ii) Whenever a shortfall occurs ECLOSS reconstructs the unrestricted demand using the socioeconomic and climatic data and demand zone parameters obtained from the appropriate data files.

ECLOSS uses numerical integration to compute the loss in revenue and consumer surplus for a particular shortfall event. It evaluates eqn. (2.1) which averages economic losses over all the simulated replicates to produce tabular and graphical summaries of expected losses at nominated discount rates.

Like WATDEM, ECLOSS is a shell program requiring to be linked with a subroutine called PDFUNC. PDFUNC returns the shadow price given monthly demand, socioeconomic, climatic

and zonal parameter data. More specifically PDFUNC requires the following price-demand model to be implemented:

$$p_{myk} = g(Q_k, m, y, \theta_k, CV_{my}, SV_y) \quad (3.2)$$

where p_{myk} is the shadow price (\$/kilolitre) for month m , year y and demand zone k when the demand is Q_k megalitres for zone k , and θ_k is a vector of the parameters for demand zone k , CV_{my} is a vector of the climatic variables for month m and y , and SV_y is a vector of the socioeconomic variables for year y . The user is free to code any function $g(\bullet)$ into PDFUNC. p_{myk} is the output returned by PDFUNC. Its prologue can be found in Appendix A.

4. CASE STUDY: NEWCASTLE HEADWORKS SYSTEM

The purpose of the case study is to demonstrate the economic loss methodology of Chapter 2 highlighting problems with and insights arising from its application. The case study is based on the Newcastle headworks system but could have been applied to any other major urban system. All the data used was provided by the Hunter Water Corporation (HWC); no attempt was made to collect additional data. Because some simplifications were made in the analysis of the demand data, the simulation results should only be considered indicative of the actual situation. Nevertheless, for the purpose of this case study, this is considered to be more than sufficient.

After reviewing the Newcastle headworks system and the consumption data, simple demand models for the indoor domestic, outdoor domestic and industrial/commercial sectors are proposed and calibrated. The sensitivity of economic losses to assumptions about the demand models is examined. Finally the results of multi-replicate simulations are used to demonstrate the application of the economic loss methodology to selecting efficient restriction rules and to selecting an augmentation date.

4.1 Newcastle Headworks System

Figure 4.1 presents a schematic of the Newcastle headworks system. The system consists of four reservoirs which harvest water from the Williams River catchment:

- i) Chichester reservoir located on the Chichester river, a tributary of the Williams River, has a capacity of 21000 megalitres (ML). A gravity pipeline can deliver up to 95 ML/day to Newcastle via the Dungog treatment plant.
- ii) Seaham diversion weir located at the head of the tidal zone on the Williams river estuary, has a capacity of 3470 ML. It is used to divert water from the Williams river into Grahamstown reservoir via the Ballickera pumping station which has an effective maximum capacity of 40000 ML/month. At low flows high salinity may prevent pumping from Seaham weir.
- iii) Grahamstown reservoir has a capacity of 139000 ML. Local runoff from its 99 km² catchment is supplemented by diversions from Seaham weir; these diversions account for

less than half of the total inflow into Grahamstown. The present operating strategy pumps as much water from Seaham weir as is feasible until Grahamstown reservoir is within 10000 ML of full supply level. Water from the reservoir is treated at the Tomago treatment works before being distributed to Newcastle.

- iv) Tomago sand beds is an extensive unconfined aquifer. It is exploited primarily during droughts according to the following rule: When the combined capacity of Grahamstown and Chichester reservoirs falls below 50%, water is extracted and treated at a rate of 50 ML/day. This rate increases to 90 ML/day when the combined capacity falls below 40%. For simulation purposes Tomago sand beds are considered to have an infinite capacity.

Releases from Grahamstown and Chichester reservoir maintain, as closely as possible, the same percent stored volume.

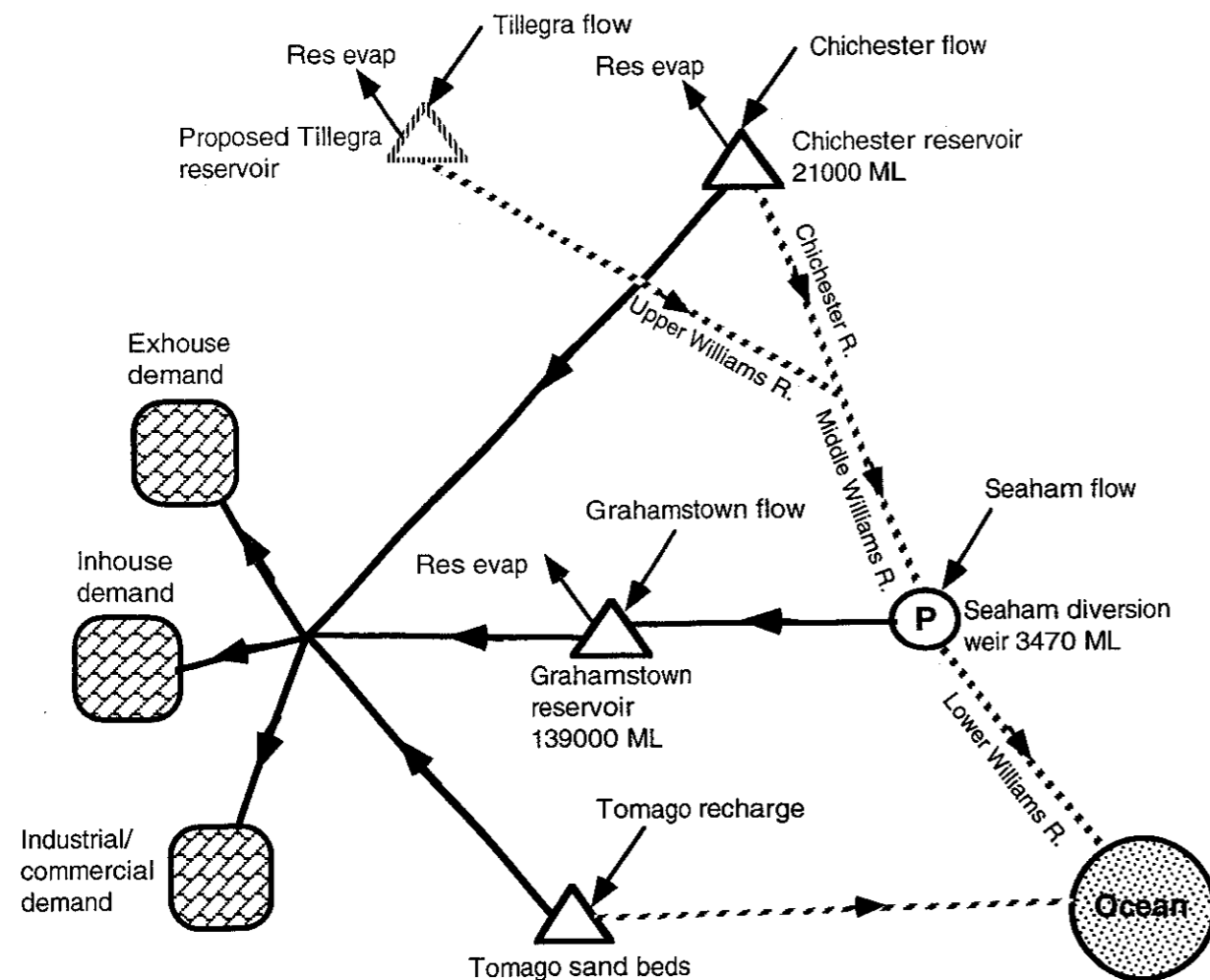


Figure 4.1 Schematic of Newcastle headworks system

Newcastle demand is disaggregated into three zones: outdoor domestic, indoor domestic and industrial/commercial. The present restriction policy is triggered when the the combined storage of Chichester and Grahamstown reservoirs falls below 60%. Restrictions apply to outdoor domestic use and progress through three stages reducing total demand 10% per stage. The second and third level restrictions are triggered when combined storage falls below 50% and 40% respectively.

Two augmentation options are considered most likely. The first involves the staged raising of Grahamstown dam to virtually double its present storage capacity. The second involves staged construction of Tillegra dam on the headwaters of the Williams river.

4.2 Historic Consumption and Socioeconomic Data

Two types of consumption data have been collected for the Newcastle headworks system:

- 1) **System-wide data:** These data consist of zonal consumption based on flow in major transfer mains to distributor reservoirs, and metered consumption of individual domestic and non-domestic connections. While monthly totals are available for the zonal data, meter readings, though taken at four month intervals, are spread uniformly throughout the year precluding the development of a monthly time series. Table 4.1 summarizes these data in annual form. Table 4.2 summarizes some socioeconomic data relevant to consumption. Figure 4.2 displays the trend in the number of metered connections and persons per domestic connection. A detailed discussion of historic water consumption patterns and forecasts can be found in Wilson (1990).
- 2) **Targeted data:** Since August 1976 outdoor (or exhouse) and indoor (or inhouse) water use has been separately metered at 27 domestic connections. From January 1987 this sample was increased to 130 domestic connections. For each connection new meters were installed to meter exhouse use but the main revenue meter was not replaced unless found defective. These meters are read at monthly intervals. Figure 4.3 displays the monthly time series of average inhouse and exhouse consumption (litres/day/connection) at targeted domestic connections. The average consumption of the 27 connections was found to overestimate that of the 130 connections. For example, Figure 4.4 presents a scatter plot of post-1986 average exhouse consumption based on the 27 and 130 connection samples; the slope of the least-squares regression line passing through the origin is 0.864. Accordingly the following least-squares adjustments were made to the pre-1987 data based on the 27 connections:

Table 4.1 Annual consumption data for Newcastle

Year	Annual consumption starting 1 July (ML)					
	Metered Domestic	Metered Non-Domestic	Metered Other	Scouring, Reservoir Cleaning	Net Unaccounted	Total
1974	25910	33290	2130	4100	19570	85000
1975	26020	29790	2560	2530	21620	82520
1976	28810	28230	900	1710	26010	85660
1977	28700	32190	620	1010	24450	86970
1978	33660	30260	470	2870	19570	86830
1979	33890	32220	2110	1540	23340	93100
1980	33780	29670	2610	1940	5510	73510
1981	29570	28170	630	5940	16460	80770
1982	26960	27720	880	2450	16330	74340
1983	26700	27900	700	5600	9400	70300
1984	30600	30300	700	3000	11600	76200
1985	26700	30500	600	6000	16600	80400
1986	30560	34000	770	3200	16040	84570
1987	28900	33000	700	2380	13070	78050
1988	30390	33310	680	740	15040	80160
1989	30140	31850	730	1550	13810	78080
1990	34027	32815	797	1042	15957	84638
1991	32040	30430	700	500	17470	81140

Table 4.2 Annual socioeconomic and rainfall data for Newcastle

Year	Population Supplied	Persons/connection	Marginal domestic water price c/kL	Sydney CPI (June quarter) base=100 Jan 81	Summer rain at Grahamstown (Nov to March) mm
1974	359009	3.23	0	--	409
1975	363011	3.19	0	--	847
1976	368207	3.17	0	--	623
1977	373402	3.14	0	--	670
1978	378598	3.12	0	--	562
1979	383793	3.09	0	85.5	269
1980	388989	3.07	0	94.9	430
1981	391839	3.04	0	103.3	746
1982	394690	3.01	60	114.6	310
1983	397540	2.98	67.5	127.4	755
1984	400391	2.95	75	131.2	419
1985	403241	2.92	84	139.7	609
1986	405043	2.90	90	152	403
1987	406846	2.88	98	166.1	744
1988	408648	2.85	104	178.3	572
1989	410450	2.83	116	192.5	926
1990	412252	2.81	123	208	241
1991	429300	2.79	129.8	213.9	692

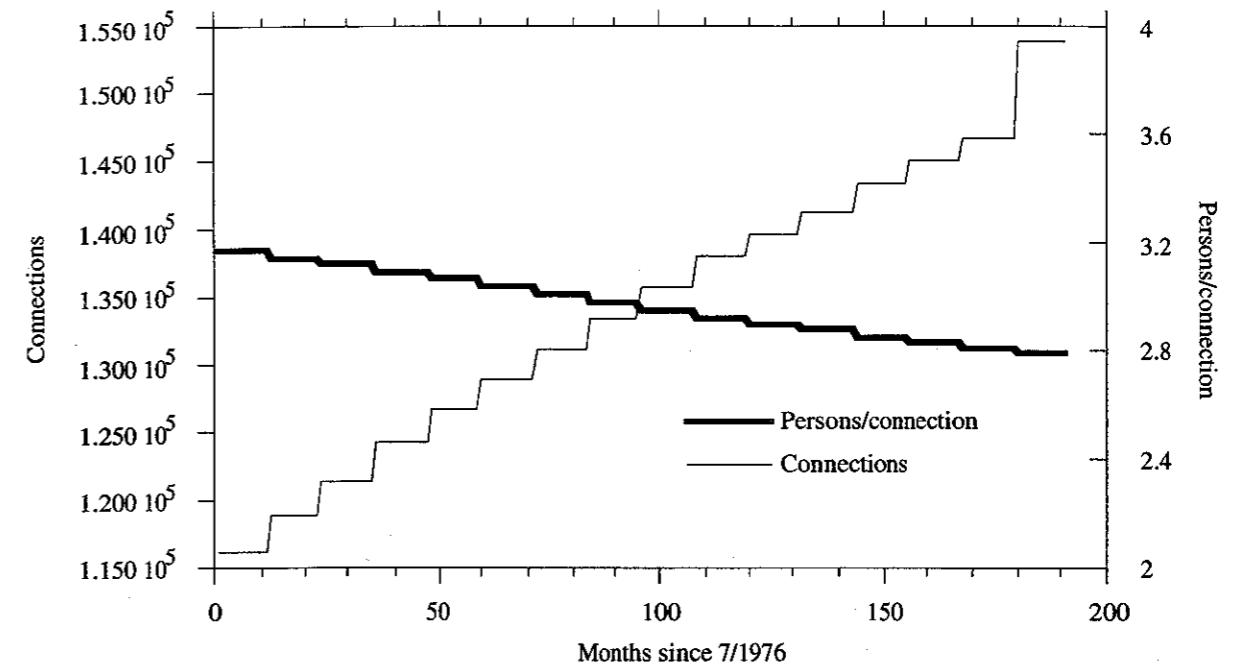


Figure 4.2 Trend in number of metered connections and persons per domestic connection

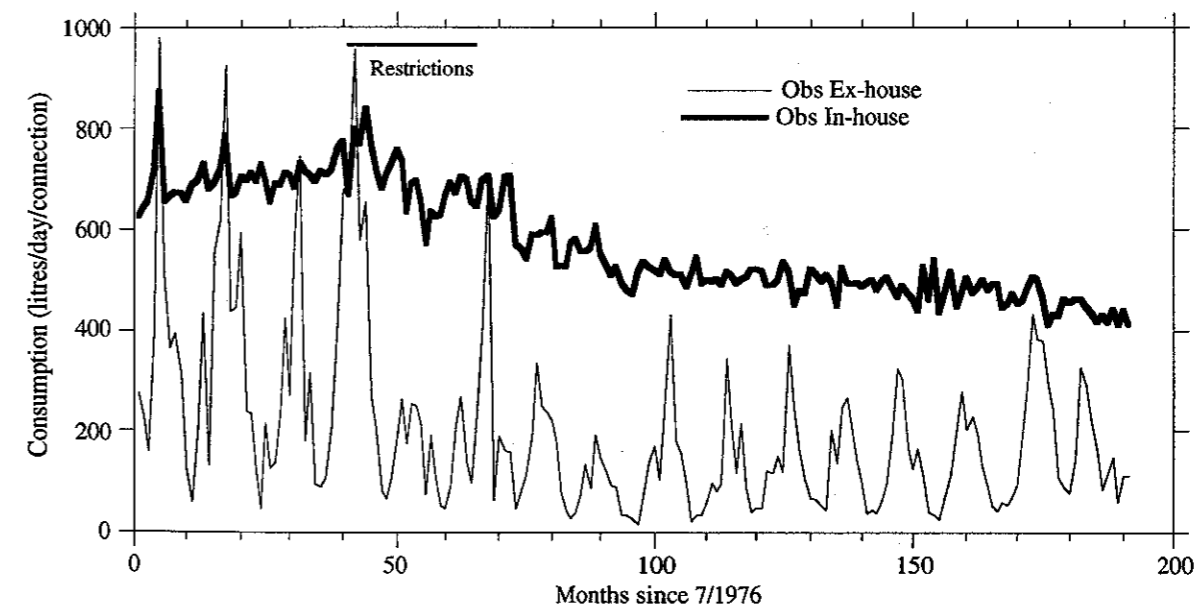


Figure 4.3 Monthly time series of average inhouse and exhouse consumption (litres/day/connection) at selected domestic connections

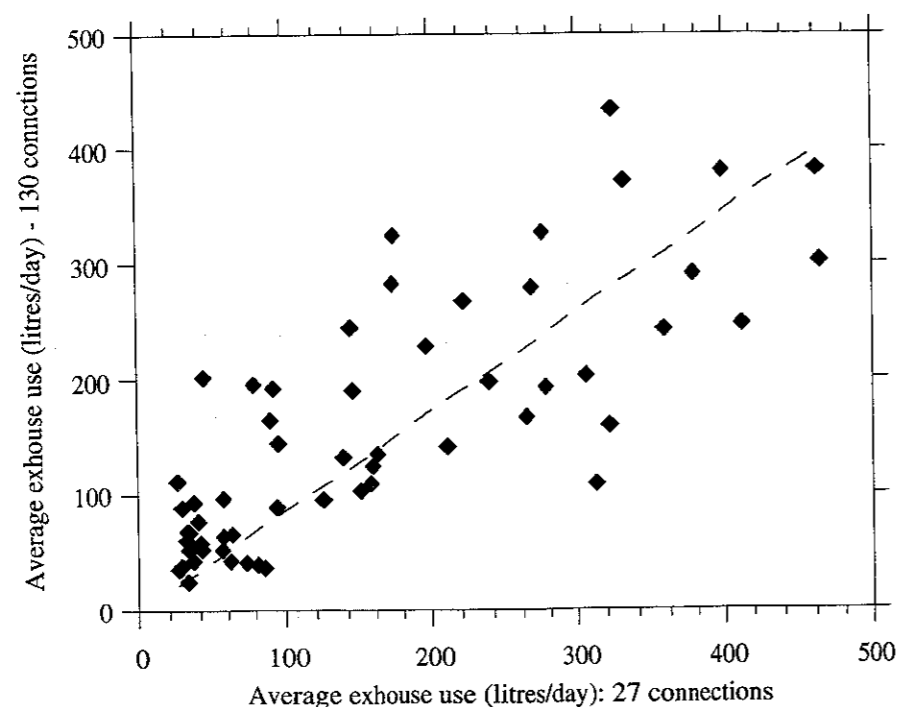


Figure 4.4 Scatter plot of post-1986 average monthly exhouse consumption for 27 and 130 connection samples

$$\text{Average exhouse use} = 0.864 * \text{Average exhouse use for 27 connections} \quad (4.1a)$$

$$\text{Average inhouse use} = 0.875 * \text{Average inhouse use for 27 connections} \quad (4.1b)$$

Several aspects of these data require discussion:

- i) Unlike the major Australian capital cities, metered domestic consumption represents only about one third of total consumption. The remainder is dominated by the industrial/commercial sector.
- ii) Net unaccounted consumption represents about a quarter of total consumption. This presents a problem when forecasting future consumption because there is no causal basis for making forecasts.

Considerable effort has been expended by the HWC (R.J. Wilson, personal communication, 1993) to resolve this anomaly. Extensive leak detection investigations have uncovered little evidence of major leakage within the distribution system. It is known that domestic flow meters are insensitive at low flow rates and tend to underestimate flows with age. Even new meters do not register at low flow rates. This means that uses such as a dripping tap, some drip irrigation systems and a fraction of every cistern refill will either

be underregistered or not registered at all. These factors could account for a significant proportion of the unaccounted consumption. For example, a single dripping tap in each serviced property could account for around 15% to 20% of the unaccounted consumption. If underregistrations due to defective meters are also allowed for, most of the unaccounted consumption could be attributed to the domestic sector which represents over 80% of all meters. On the other hand, an error in a very large meter supplying an industry could also account for a large amount of unaccounted consumption. Analysis of zonal consumption data reveals a pattern similar to that reported in Table 4.1 indicating unaccounted consumption is spread fairly uniformly across Newcastle's consumption zones. It is believed that most of the unaccounted consumption is due to metering problems rather than leakage.

At present there appears to be no satisfactory means for reconciling unaccounted consumption. Moreover, there appear to be anomalously low annual values in two of the years. It is noted that when the average consumption data based on 130 targeted connections are multiplied by the number of connections, the extrapolated domestic consumption agrees closely with the annual metered domestic consumption reported in Table 4.1. Accordingly in this study unaccounted consumption has been lumped with industrial/commercial demand primarily to maintain a direct relationship between the targeted and total metered domestic consumption data.

- iii) During the multi-year drought ending in early 1982 restrictions on outdoor water use were implemented. In July 1982 user-pays pricing was introduced in which the consumer pays for every kilolitre used. Prior to this domestic consumers were given a free entitlement which was sufficient, in most cases, to signal to the consumer the fact that, at the margin, the cost of water was zero. Figure 4.5 displays time series of average monthly percapita inhouse consumption and water price (1981 dollars). Two features are very evident. First, there is a marked initial drop in per capita inhouse consumption following the introduction of user-pays followed by a slight long-term decline. Second, the water price, expressed in 1981 dollars, has remained largely unchanged since introduction of user-pays pricing. This means that information on the domestic demand-price relationship is only effectively available for two points. As will be seen, this has major implications when extrapolating the demand-price curve to calculate the economic cost of restrictions.
- iv) Total consumption in 1991 had not yet recovered to mid-1970 totals. This is despite a growing population serviced by the HWC, growing at about 1.1% over the period 1974 to 1991. Figure 4.2 shows a steady growth in the number of serviced connections, and a contrasting decline in the number of persons per connection.

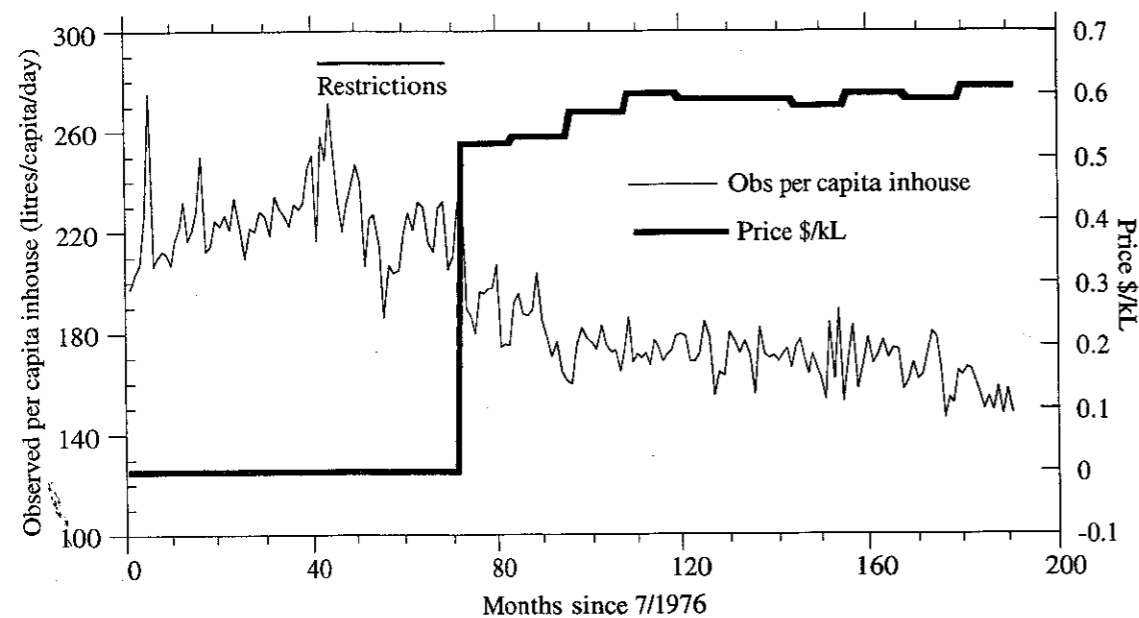


Figure 4.5 Time series of average monthly inhouse consumption and marginal water price (1981 dollars)

4.3 Development of a Domestic Demand-Price Model

Given the different price elasticities of demand for inhouse and exhouse use, separate demand-price models were developed for inhouse and exhouse use using the targeted connection data.

Inhouse domestic demand-price model

For the inhouse demand-price relationship two features were considered important:

- i) At zero price, there exists a finite maximum level of consumption; and
- ii) At high prices demand becomes inelastic as the household reduces consumption to its subsistence level, defined as the minimum amount required to maintain an acceptable living standard.

The following relationship satisfies these two requirements:

$$Q_{in} = D_{in} [d_{in} + (1 - d_{in}) \exp(-\gamma_{in}p)] \quad (4.2)$$

where Q_{in} is per capita inhouse consumption expressed as litres/person/connection/day, p is the water price (\$1981/kL), D_{in} is the maximum level of per capita consumption (litres/person/connection/day), d_{in} is the fraction of D_{in} defining the subsistence level of per capita consumption (litres/person/connection/day), and γ_{in} is the price parameter (kL/\$1981). Although the parameters d_{in} and D_{in} are implicit functions of socioeconomic status, this dependence was not explored in this study. The price elasticity of demand is

$$\epsilon_{in} = \frac{p}{Q_{in}} \frac{\partial Q_{in}}{\partial p} = -\gamma_{in} p \left[1 - \frac{D_{in} d_{in}}{Q_{in}} \right] \quad (4.3)$$

Eqn. (4.2) implies that consumers are willing to pay very high prices as supply approaches the subsistence level $d_{in}D_{in}$. In actuality, at sufficiently high prices, consumers would switch to alternative sources of water (provided it is available).

Exhouse domestic demand-price model

Outdoor water use is dependent on, inter alia, price and climate. The climate dependency is incorporated using the concept of a monthly water deficit defined as

$$\Delta = \begin{cases} \text{evap} - \text{rain} & \text{if evap} > \text{rain} \\ 0 & \text{otherwise} \end{cases} \quad (4.4)$$

where evap is monthly potential transpiration (mm) and rain is monthly rainfall (mm). The following relationship incorporates these two dependencies:

$$Q_{ex} = \Delta D_{ex} [d_{ex} + (1 - d_{ex}) \exp(-\gamma_{ex}p)] \quad (4.5)$$

where Q_{ex} is exhouse consumption expressed as litres/connection/day, p is the water price (\$1981/kL), D_{ex} is the maximum consumption level (litres//connection/day/mm deficit), d_{ex} is the fraction of D_{ex} defining the minimum level of outdoor use, and γ_{ex} is the price parameter (kL/\$1981). The price elasticity of demand is

$$\epsilon_{ex} = \frac{p}{Q_{ex}} \frac{\partial Q_{ex}}{\partial p} = -\gamma_{ex} p \left[1 - \frac{\Delta D_{ex} d_{ex}}{Q_{ex}} \right] \quad (4.6)$$

Calibration of the domestic demand-price models

The models given by eqns (4.2) and (4.5) were calibrated to the targeted inhouse and exhouse consumption data using least squares. Note that the 25 months during which restrictions were in force were excluded from the calibration.

Figure 4.6 displays the time series of residuals, defined as the difference between observed and predicted consumption, obtained from fitting the inhouse demand-price model to average monthly inhouse consumption. The residual plot suggests that the model fits the data reasonably well, though it is noted there exist systematic deviations from the predicted value. The model given by eqn. (4.2) implicitly assumes that consumers respond to price changes within one year. The long-term negative trend in the residuals following the introduction of user-pays may be the result of long-term price adjustments such as purchase of more efficient domestic appliances. On the other hand, the trend may be due to reductions in real household income. Despite the fact there is possible scope for further refinement of eqn. (4.2) the high coefficient of determination R^2 of 0.81 indicates most of the scatter in the data has been accounted for by the model.

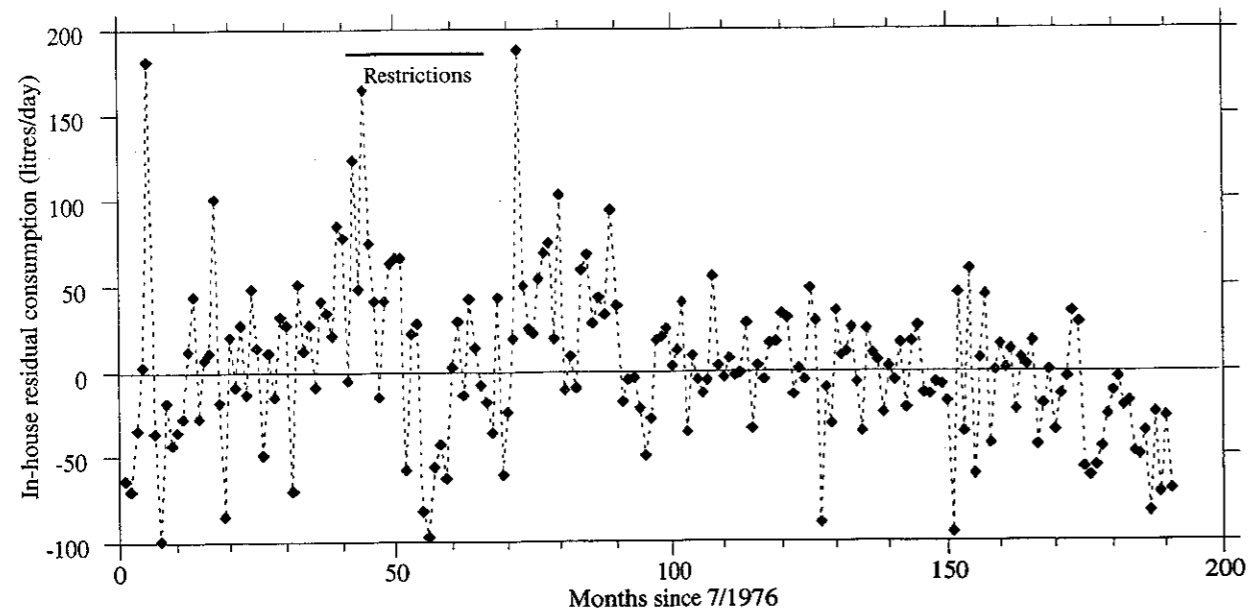


Figure 4.6 Time series of residuals obtained from fitting inhouse demand-price model to average monthly inhouse consumption

Figure 4.7 displays the time series of residuals obtained from fitting the exhouse demand-price model to average monthly exhouse consumption. Again the residual plot suggests that the model fits the data reasonably well. Unlike the residual plot of Figure 4.6 there is little evidence of systematic deviations from the predicted value. The R^2 was only 0.39 suggesting much of the

scatter in the data remains unexplained by the model given by eqn. (4.5). However, this is somewhat misleading as can be seen in Figure 4.7 which shows a major reduction in residual scatter following introduction of user-pays pricing.

A major problem arises when estimating the parameters of the inhouse and exhouse models. Because data are only available for effectively two water prices (when expressed in 1981 dollars), there is insufficient information to meaningfully infer the three parameters in the demand-price models given by eqns (4.2) and (4.5). The parameter Δ is well defined because there are several years of data with zero effective price. However, only one effective non-zero price is available to meaningfully infer the parameters γ and d . Therefore, prior information must be specified for at least one of these parameters. Tables 4.3 summarizes the fitted parameters and their standard deviations for the inhouse and exhouse models respectively using different prior values for the subsistence fraction parameter d . The choice of prior values for d represents nominal lower and upper bounds.

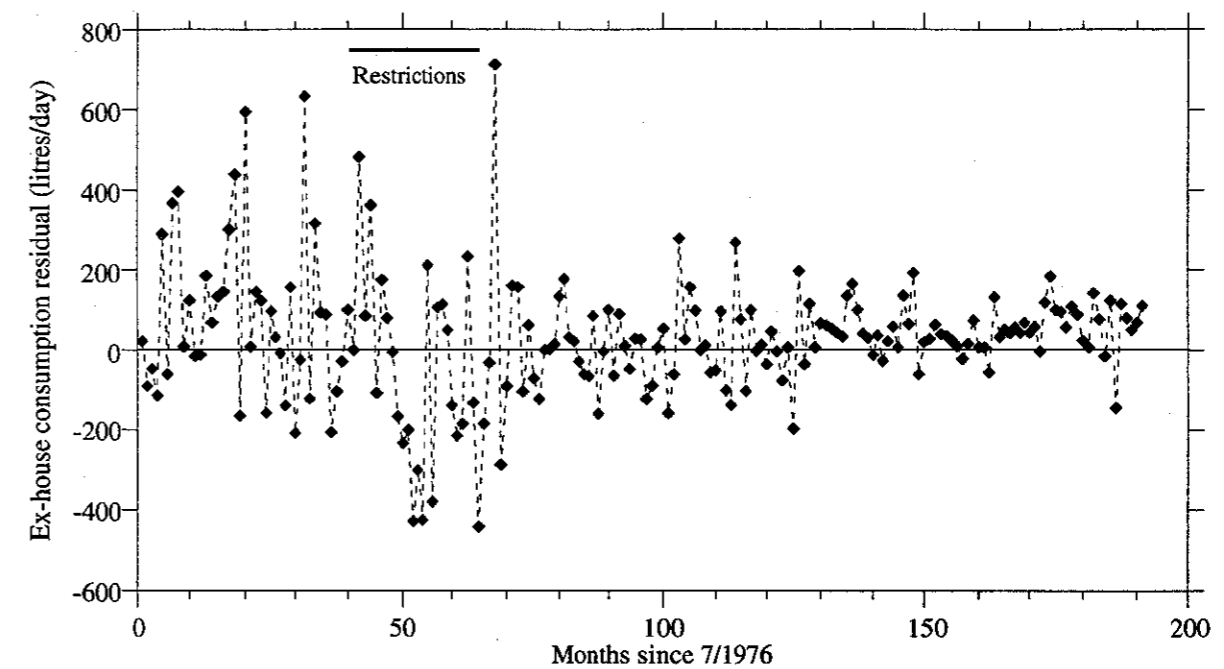


Figure 4.7 Time series of residuals obtained from fitting exhouse demand-price model to average monthly exhouse consumption

Table 4.3 Summary of fitted domestic demand model parameters for different values of the subsistence fraction parameter d

Inhouse				Exhouse			
Prior value of d_{in}	Parameter	Mean	Standard deviation	Prior value of d_{ex}	Parameter	Mean	Standard deviation
0.25	D_{in}	221	2	0.0	D_{ex}	3.43	0.22
	γ_{in}	0.615	0.031		γ_{ex}	1.32	0.19
0.45	D_{in}	222	2	0.25	D_{ex}	3.44	0.22
	γ_{in}	0.904	0.051		γ_{ex}	2.18	0.41

Economic loss due to demand shortfalls

To develop an insight about the magnitude of economic losses due to demand shortfalls the inhouse losses will be considered in some detail. Let Q_0 be the inhouse consumption at price p_0 . When restrictions are imposed consumption falls to $(1-R)Q_0$. From eqn. (4.2) it follows that the shadow price p_s is

$$p_s = \min \left\{ p_{max}, -\frac{1}{\gamma_{in}} \log_e \left[\frac{(1-R)Q_0 - d_{in}}{D_{in} - d_{in}} \right] \right\} \quad (4.7)$$

where $\min(x,y)$ is a function returning the minimum of x and y , and p_{max} is the price at which an alternative source of water becomes cost-effective. For example, the importation of water by road tanker to Goulburn was considered during the drought of 1979-82 (Anderson et al., 1986) at a cost of \$10/kL. Without specification of a finite p_{max} , the shadow price would approach infinity as $(1-R)Q_0$ approached $d_{in}D_{in}$. It can be shown that when $p_s < p_{max}$ the economic loss (\$/person/month) is

$$LOSS = \frac{30.5}{1000} D_{in} \left\{ d_{in} (p_s - p_0) + \frac{1-d_{in}}{\gamma_{in}} [\exp(-\gamma_{in} p_0) - \exp(-\gamma_{in} p_s)] \right\} + \frac{30.5}{1000} [Q_0 R p_0 - (1-R)Q_0 (p_s - p_0)] \quad (4.8)$$

Figures 4.8 and 4.9 display the shadow price, revenue loss and total economic loss as a function of percent restrictions for the respective cases of d_{in} equal to 0.25 and 0.45. In both cases the

restrictions reduce consumption below the level given by the current water price of \$0.60/kL (1981 dollars); the cost of alternative supplies p_{max} is \$10/kL. Two features deserve comment:

- i) For small restriction percents (up to 30%) the economic loss is small being of the order of \$5/person/month (1981 dollars). However, for higher restriction percentages, the economic loss can grow dramatically depending on the value of d_{in} . Moreover, the divergence between loss of revenue to the water authority and total economic loss becomes marked.
- iii) The sensitivity of the severe economic losses to the choice of d_{in} is evident. The economic losses are derived from extrapolating the demand-price curve well beyond observed prices and are clearly sensitive to the choice of d_{in} . Unfortunately the historic consumption data for Newcastle provide no clue as to what is an appropriate value for d_{in} . Clearly prior information on d_{in} is required before economic losses can be meaningfully evaluated. It is, however, beyond the scope of this study to explore this issue.

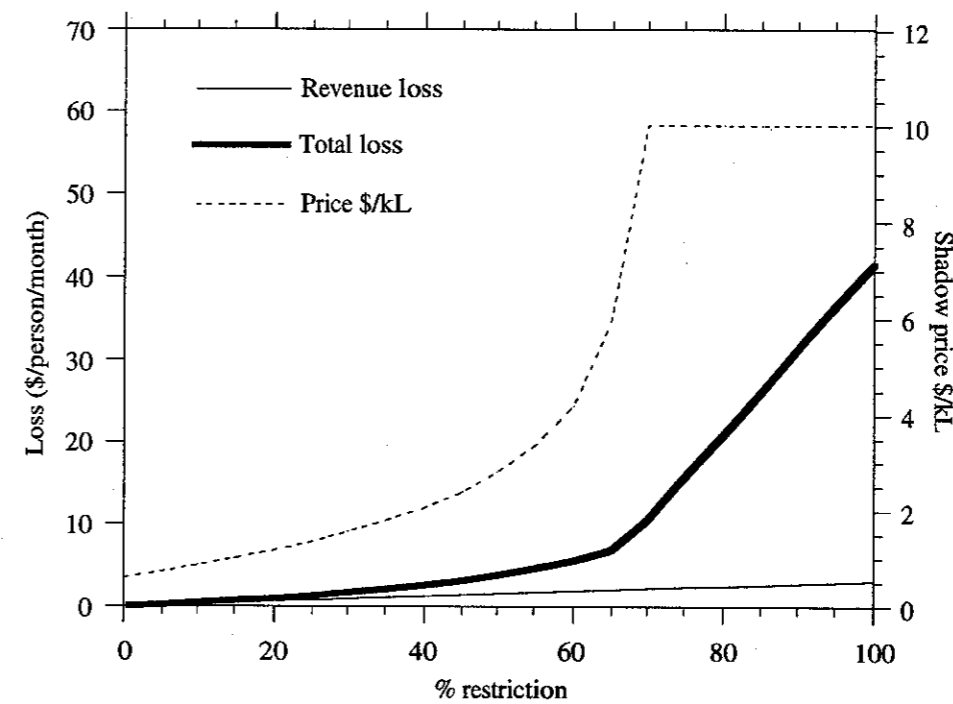


Figure 4.8 Inhouse economic total and revenue losses and shadow price as a function of percent restriction: $d_{in} = 0.25$; $p_{max} = \$10/kL$

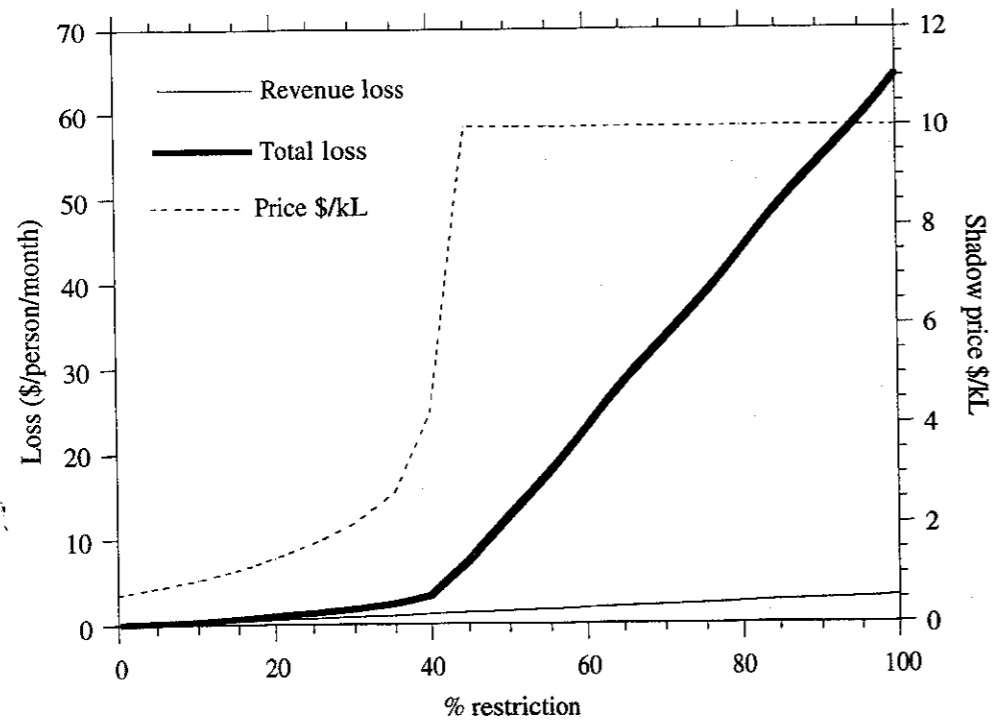


Figure 4.9 Inhouse economic total and revenue losses and shadow price as a function of percent restriction: $d_{in} = 0.45$; $p_{max} = \$10/kL$

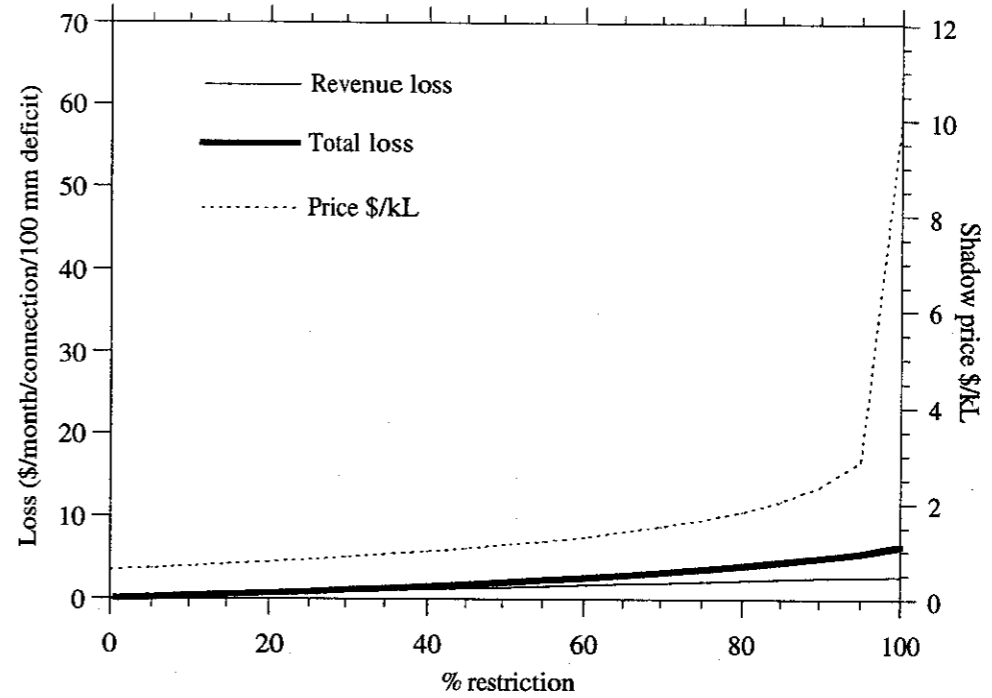


Figure 4.10 Exhouse economic total and revenue losses and shadow price as a function of percent restriction: $d_{ex} = 0.0$; $p_{max} = \$10/kL$; 100 mm deficit

A similar analysis is repeated for exhouse consumption with a 100 mm water deficit. Figures 4.10 and 4.11 display the shadow price, loss in revenue and total economic loss as a function of percent restrictions for the respective cases of d_{ex} equal to 0.0 and 0.25. In both cases the restrictions reduce consumption below the level given by the current water price of \$0.60/kL (1981 dollars); the cost of alternative supplies p_{max} is \$10/kL. More striking than the inhouse examples is the extreme sensitivity of total economic losses to the choice of d_{ex} . With the introduction of user pays eqn. (4.5) predicts that exhouse consumption has fallen from 344 to 155 litres/month/connection/100mm deficit. For the case of d_{ex} equal to 0.25, the imposition of restrictions pushes the domestic consumer into the highly inelastic region of the demand-price relationship where loss of consumer surplus is very significant.

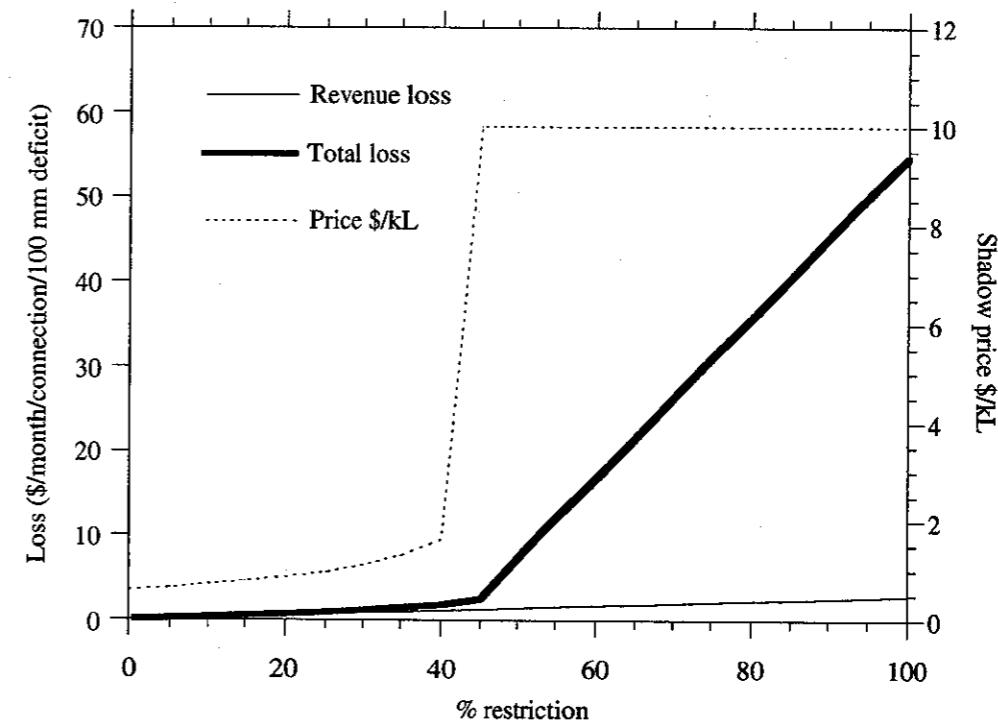


Figure 4.11 Exhouse economic total and revenue losses and shadow price as a function of percent restriction: $d_{ex} = 0.25$; $p_{max} = \$10/kL$; 100 mm deficit

4.4 Calibration of a Industrial/Commercial Demand Model

A simple model for industrial/commercial consumption was adopted:

$$Q_{ic} = [a + b (yr-1992)] * \{1.0 + amp * \sin[\frac{2\pi}{12}(mth+phase)]\} + c * rain \quad (4.9)$$

where Q_{ic} is consumption in ML for month mth and year yr , parameters a and b define the long-term trend in consumption, parameters amp and $phase$ define the seasonal cycle, and parameter c makes allowance for the effect of monthly rainfall $rain$. A more suitable model would have disaggregated the industrial/commercial sector into industry-specific sectors and undertaken an econometric analysis of the sector's water use, its price elasticity and its net output. However, this was considered well beyond the scope of this study.

The model given by eqn. (4.9) was fitted using least squares to monthly data starting in April 1982. The observed data were derived by subtracting targeted domestic consumption, adjusted for the total serviced population, from monthly total consumption. This means all unaccounted consumption has been lumped into the industrial/commercial sector.

Figure 4.12 displays monthly time series of observed and fitted consumption. Despite considerable scatter (the R^2 was only 0.43) there is a well-defined long-term trend. The residual time series plot shown in Figure 4.13 reveals the presence of a low-frequency cycle possibly related to the business cycle of economic activity.

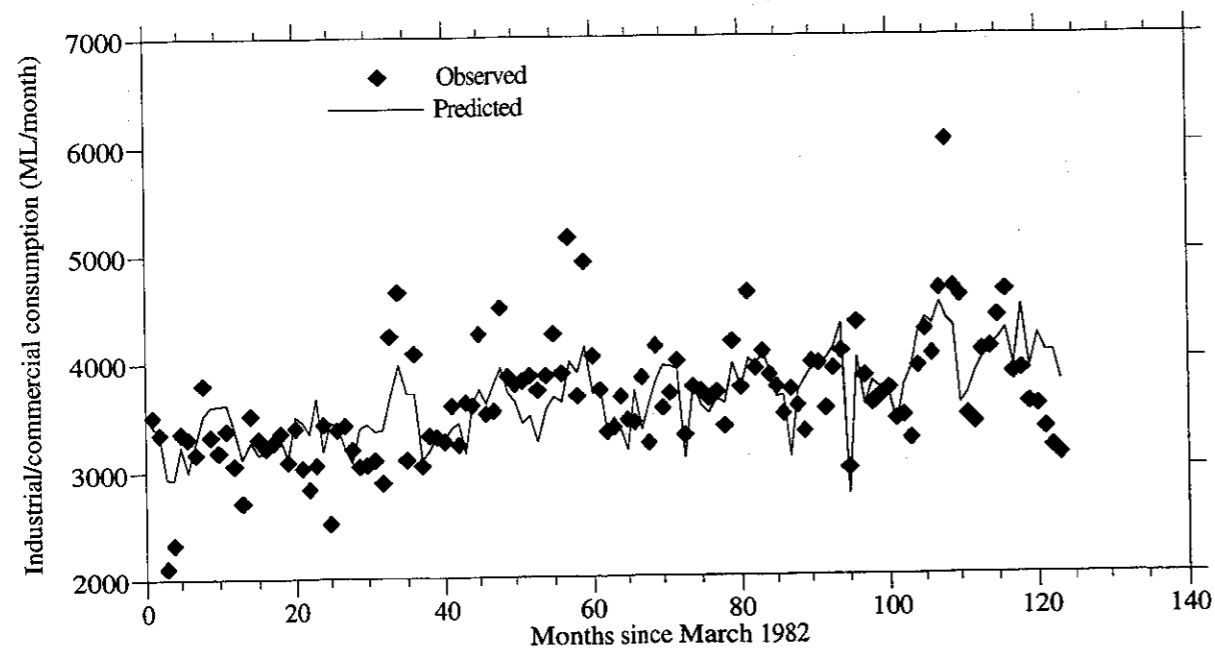


Figure 4.12 Monthly time series of observed and fitted industrial/commercial consumption

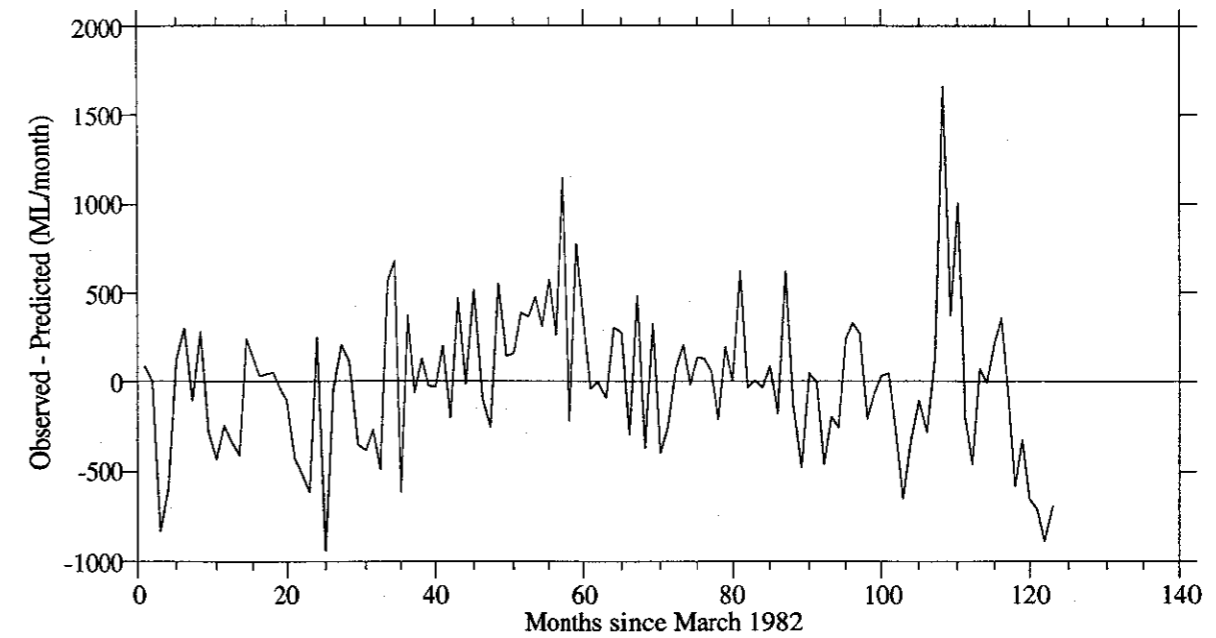


Figure 4.13 Monthly time series of residual industrial/commercial consumption

Table 4.4 summarizes the fitted parameters and their standard deviations. Parameter b gives the long-term growth in consumption as 2.1% with 95% confidence limits being 1.5% and 2.7%. Contrast this growth with the historic 1.1% growth in population.

Table 4.4 Summary of industrial/commercial consumption model parameters

Parameter	Mean	Standard deviation
a	4377	92
b	91.5	12.5
amp	0.068	0.013
$phase$	1.83	0.38
c	-2.96	0.52

4.5 Simulation Analysis

Several simulation runs will be presented and discussed. Common to all the runs are the following features:

- i) The behaviour of the headworks system is simulated using several thousand replicates of future streamflow and rainfall. Each replicate starts in January 1993.
- ii) At the start of each replicate all existing reservoirs are full. A newly commissioned reservoir starts empty.

iii) Program WATDEM was used to generate 5000 replicates of future demand. Appendix B presents a listing of the socioeconomic scenario data file for the Newcastle system. Three socioeconomic variables were used: serviced population, persons per domestic connection, and domestic water price (\$/kL 1981 dollars). For each variable only one future scenario was used, though it needs to be stressed that WATDEM can accept multiple future scenarios provided the probability of occurrence is specified. The water price was kept constant in 1981 terms at \$0.60/kL. Serviced population was assumed to increase at 3560 per year being 0.8% of the present population.

Industrial/commercial losses were arbitrarily valued at \$5/kL.

Appendix B presents source code listings of subroutines MODELS and PDFUNC..

The simulation runs will illustrate the sensitivity of economic losses to assumptions about subsistence consumption, the sensitivity of economic losses to the choice of restriction rules, and the sensitivity of augmentation timing. It needs to be stressed, that because simplifications were made in the analysis of the demand data, the simulation results should only be considered indicative of the actual situation.

4.5.1 Sensitivity of economic losses to choice of restriction rules

This Section illustrates the use of economic losses to assist in the selection of restriction rules. Two simulation runs will be presented. Each run uses 5000 replicates simulating the system from 1993 to 2010. Run 1 describes the present Newcastle headworks system. Run 2 describes the same system as Run 1 except that exhouse restrictions are triggered later in the storage drawdown.

Run 1: Present system

The HWC's drought management plan (DMP) triggers restrictions on exhouse consumption when the combined storage in Grahamstown and Chichester reservoirs falls below 60%. There are no formal restrictions on inhouse and industrial/commercial consumption, although restrictions on exhouse use would probably induce voluntary reductions in consumption in other sectors. In this case study the HWC's DMP has been modified to formally restrict inhouse and industrial/commercial consumption when the headworks system is nearing empty; no allowance is made for voluntary reductions following initiation of exhouse restrictions. Figure 4.14

summarizes this DMP. When the combined storage falls below 15%, restrictions on inhouse consumption are triggered; they could be implemented by cutting off water for a fraction of each day to selected zones. When the combined storage falls below 10%, industrial/commercial consumption would be restricted possibly by closing down non-essential industrial/commercial activity on selected weekdays. The purpose of this strategy is to reduce the risk of the system being empty and consequent draconian restrictions.

Drought management plan: Run 1 - Present system

Restriction rules:

Demand sector	Trigger percent storage	Percent reduction in demand	Possible implementation mechanisms
Exhouse	60	33	Time restriction on sprinklers
	50	66	Sprinkler ban
	40	100	Total ban on outdoor use
Inhouse	15	20	Cut off water to selected zones
	10	40	for a fraction of each day
	5	60	Seek alternative supplies
Industrial/commercial	10	20	Close down non-essential activity one workday a week
	5	40	Close down non-essential activity two workdays a week

Rationing: If system runs out of water and shortfalls exceed reductions brought about by restriction rules, prorate excess shortfall between inhouse and industrial/commercial sector.

Operation: If combined Chichester and Grahamstown storage falls below 50%, supply water from Tomago sand beds at a rate of 50 ML/day. This rate increases to 90 ML/day when the combined capacity falls below 40%.system

Figure 4.14 Drought management plan used in Run 1

Figures 4.15 to 4.19 summarize the statistical behaviour of the system. Figure 4.15 presents 1, 2 and 5 percentiles for total storage as well as the lowest storage volume in the 5000 replicates. Two features deserve comment:

- i) The system never emptied in the 5000 replicates. This does not mean the system will never empty but does suggest the risk of the system emptying is less than about 1 in 5000 in any year. This risk may be judged to be unacceptably high.
- ii) Because all replicates started with the system full the reservoir percentiles plunge in the first two years, and, thereafter, follow a gradual negative trend associated with the long-term growth in future consumption.

Figure 4.16 presents the probability of having restrictions for one or more months in any future year. By the year 2010 this probability has climbed to over 25% which by most standards would justify augmentation. Figures 4.17 to 4.19 present the probability of experiencing a first level restriction in any month for the exhouse, inhouse and industrial/commercial sectors respectively. It is clear that virtually all the restriction events are confined to the exhouse sector with the remaining two sectors facing risks of less than 0.05% in any month. In fact the number of restriction events in the inhouse and industrial/commercial sectors is so few, the risk estimates are considered to be of low accuracy.

Despite the apparently poor reliability of the Run 1 system, evaluation of total economic losses presents a somewhat different perspective. Table 4.5 lists lower and upper bounds on the total economic losses due to restrictions. The losses are expressed in present worth terms using a social discount rate of 4% and are in 1981 dollars. The losses are only indicative because there is insufficient data to reliably estimate the subsistence fractions d_{in} and d_{ex} . The lower bound represents nominally low subsistence fractions while the upper bound represents nominally high subsistence fractions. These losses, dominated by exhouse losses, are small. If an augmentation were commissioned in 1993 and totally eliminated restrictions in the period 1993 to 2010, it would only produce benefits in the range \$3 to \$8.5 million (1981 dollars). These low losses are indicative of frequent nuisance restrictions on exhouse consumption.

System lowest volume & percentiles: 1, 2, 5

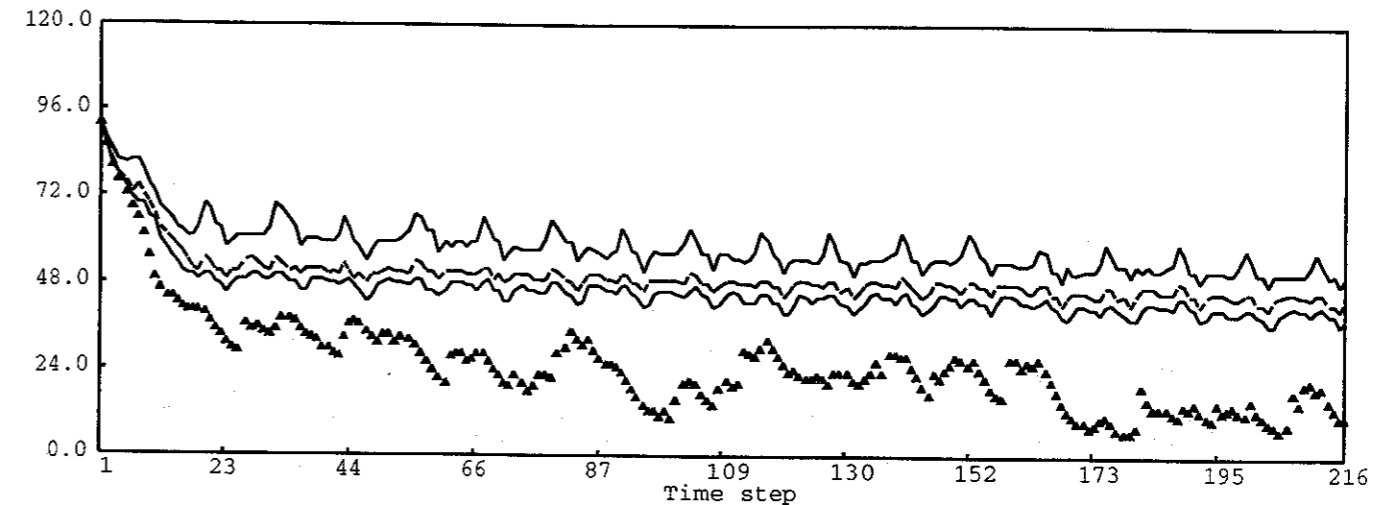


Figure 4.15 Monthly time series of minimum total storage and 1, 2 and 5 total storage percentiles: Run 1

System Annual Failure Probability (%)

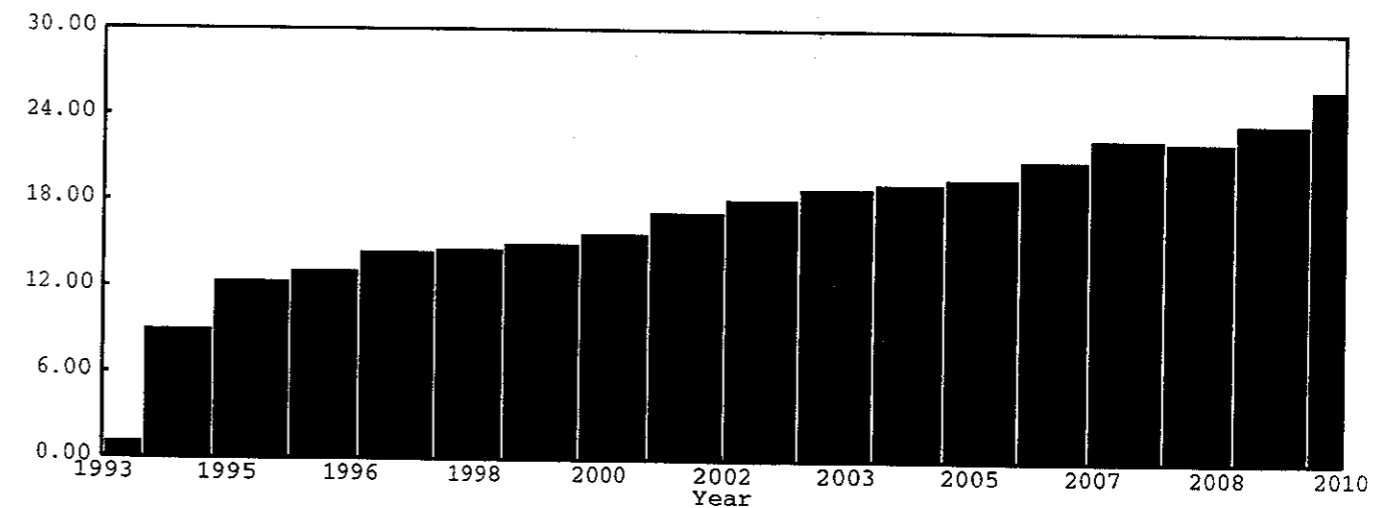


Figure 4.16 Annual time series of probability of having restrictions: Run 1

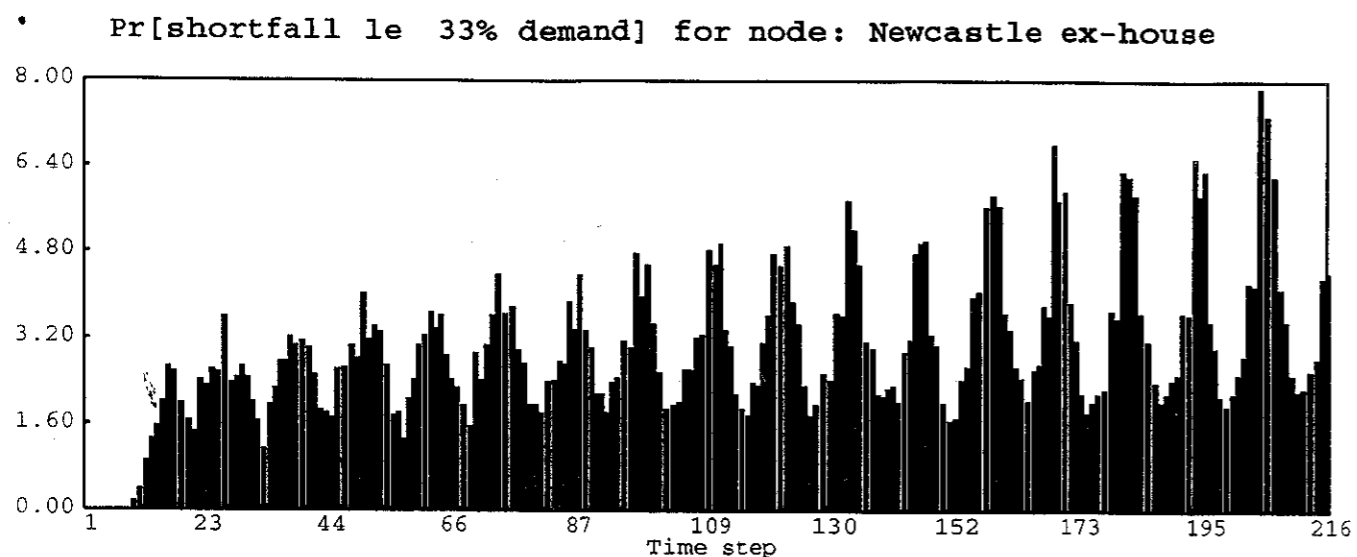


Figure 4.17 Monthly time series of probability of exhouse consumption being restricted \leq 33%: Run 1

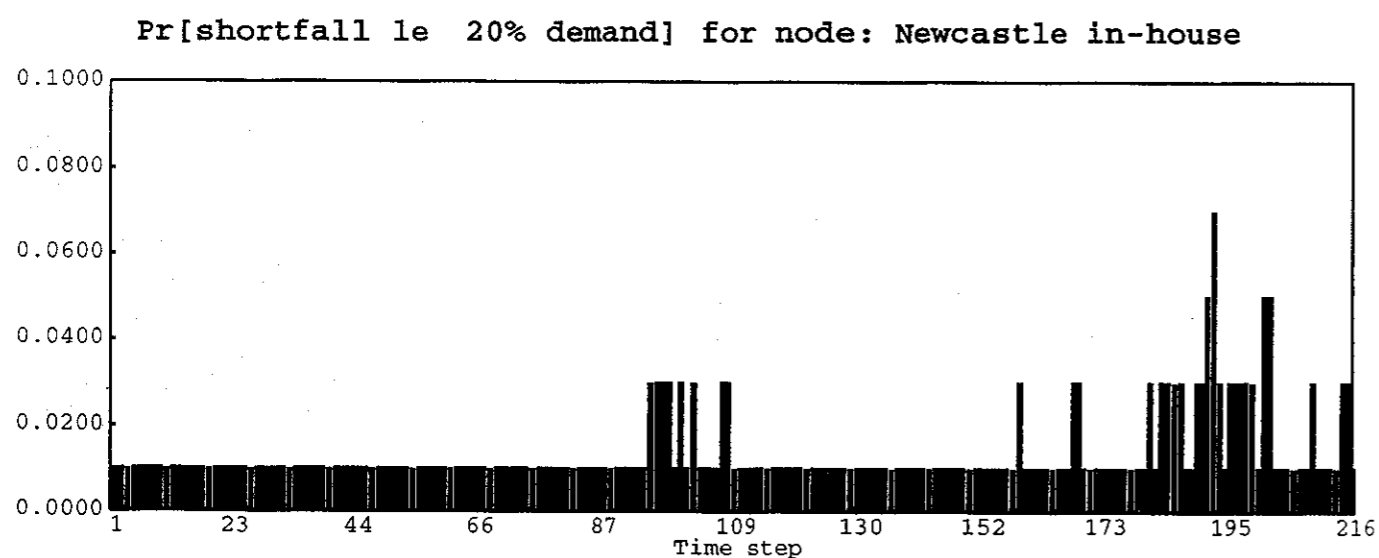


Figure 4.18 Monthly time series of probability of inhouse consumption being restricted \leq 20%: Run 1

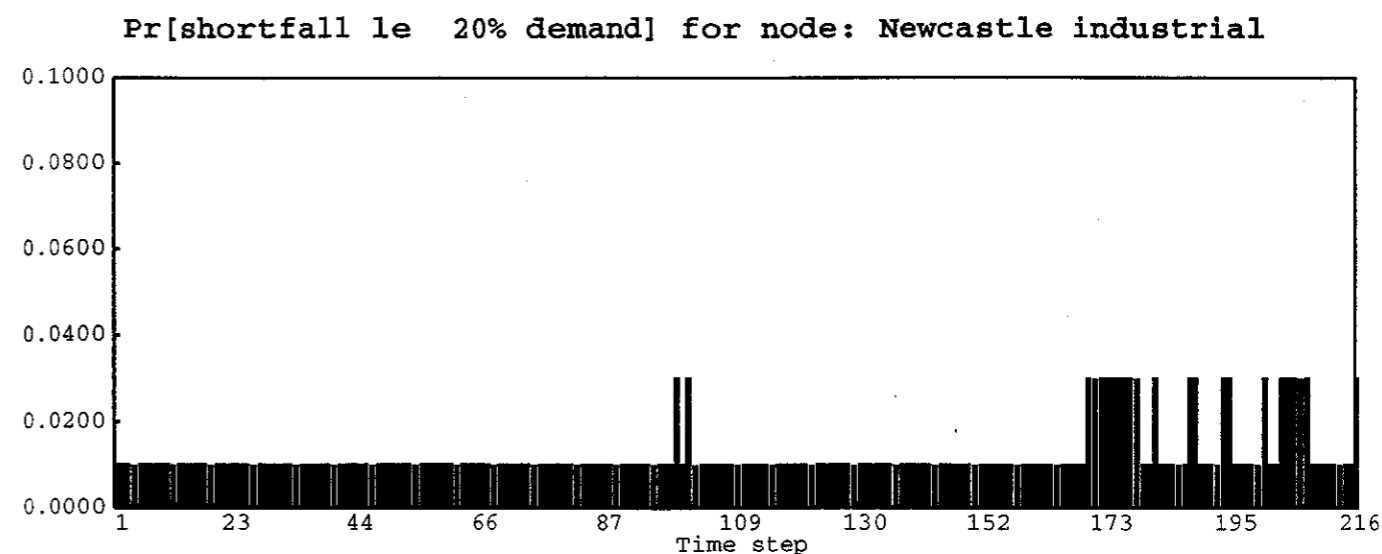


Figure 4.19 Monthly time series of probability of industrial/commercial consumption being restricted \leq 20%: Run 1

Table 4.5 Total economic losses due to restrictions: Run 1

Year	Present worth of expected total economic loss due to restrictions (\$, million 1981; 4% discount rate)	
	Lower bound $d_{in} = 0.25; d_{ex} = 0.0; p_{max} = \$10/kL$	Upper bound $d_{in} = 0.45; d_{ex} = 0.25; p_{max} = \$10/kL$
1993	0.006	0.010
1994	0.099	0.238
1995	0.122	0.317
1996	0.144	0.372
1997	0.142	0.373
1998	0.153	0.408
1999	0.166	0.454
2000	0.175	0.490
2001	0.176	0.486
2002	0.193	0.554
2003	0.193	0.556
2004	0.186	0.533
2005	0.178	0.510
2006	0.204	0.587
2007	0.229	0.673
2008	0.207	0.604
2009	0.226	0.677
2010	0.225	0.662
Total	3.025	8.503

Run 2: Present system with restrictions triggered at 40% storage

The analysis of Run 1 results revealed a rapidly deteriorating reliability but restrictions were virtually confined to the exhouse sector with expected losses in the range of \$3 to \$8 million over the planning horizon. This suggests that a less conservative DMP should be considered. Figure 4.20 summarizes a revised DMP in which the trigger storage for exhouse restrictions is lowered to 40%.

Figure 4.21 presents 1, 2 and 5 percentiles for total storage as well as the lowest storage volume in the 5000 replicates. Again the system does not empty in the 5000 replicates, but, when compared with Figure 4.15, there is a downward shift in the percentile traces.

Figure 4.22 presents the probability of having restrictions for one or more months in any future year. By the year 2010 this probability has climbed to only 8% compared with 25% for Run 1. Figures 4.23 to 4.25 present the probability of experiencing a level-one restriction in any month for the exhouse, inhouse and industrial/commercial sectors respectively. When compared with their Run 1 counterparts, these Figures reveal that the risk of level-one restrictions in the exhouse sector falls at the expense of higher risks in the inhouse and industrial/commercial sectors.

Despite the near trebling of the risk of restrictions for the inhouse and industrial/commercial sector, expected economic losses fall appreciably when compared with Run 1. Table 4.6 lists lower and upper bounds on the total economic losses due to restrictions for Run 2. The total losses over the planning period range from \$0.80 to \$1.96 million (1981 dollars), which is about a quarter of the total losses for Run 1. As Table 4.7 reveals, the reduction of the trigger storage for exhouse restrictions has brought about major savings in exhouse economic losses at the expense of only a small increase in inhouse and industrial/commercial sector losses. Note these savings are underestimated because of the short planning horizon used in the simulation runs. This example illustrates Dandy's (1989) argument that there is scope to tune restriction rules to minimize economic losses. It highlights the need to consider not only the probability of having restrictions, but also the risk of having severe restrictions. The choice of the subsistence fractions d_{in} and d_{ex} and the price of alternative supplies p_{max} controls the relative importance of frequent but minor restrictions and rare but severe restrictions.

Drought management plan: Run 2 - Present system with restrictions triggered at 40%

Restriction rules:

Demand sector	Trigger percent storage	Percent reduction in demand	Possible implementation mechanisms
Exhouse	40	33	Time restriction on sprinklers
	30	66	Sprinkler ban
	20	100	Total ban on outdoor use
Inhouse	15	20	Cut off water to selected zones
	10	40	for a fraction of each day
	5	60	Seek alternative supplies
Industrial/commercial	10	20	Close down non-essential activity one
	5	40	workday a week Close down non-essential activity two workdays a week

Rationing: If system runs out of water and shortfalls exceed reductions brought about by restriction rules, prorate excess shortfall between inhouse and industrial/commercial sector.

Operation: If combined Chichester and Grahamstown storage falls below 40%, supply water from Tomago sand beds at a rate of 50 ML/day. This rate increases to 90 ML/day when the combined capacity falls below 30%.system

Figure 4.20 Drought management plan used in Run 2

Table 4.6 Total economic losses due to restrictions: Run 2

Year	Present worth of expected total economic loss due to restrictions (\$, million 1981; 4% discount rate)	
	Lower bound	Upper bound
	$d_{in} = 0.25; d_{ex} = 0.0; p_{max} = \$10/kL$	$d_{in} = 0.45; d_{ex} = 0.25; p_{max} = \$10/kL$
1993	0.000	0.000
1994	0.008	0.013
1995	0.016	0.032
1996	0.021	0.041
1997	0.027	0.065
1998	0.035	0.085
1999	0.037	0.083
2000	0.043	0.096
2001	0.044	0.105
2002	0.044	0.113
2003	0.054	0.148
2004	0.049	0.127
2005	0.050	0.123
2006	0.055	0.133
2007	0.080	0.200
2008	0.079	0.188
2009	0.080	0.204
2010	0.080	0.201
Total	0.801	1.960

Table 4.7 Sector economic losses due to restrictions for Run 1 and Run 2

Sector	Present worth of expected total economic loss due to restrictions (\$, million 1981; 4% discount rate)			
	Lower bound		Upper bound	
	Run 1	Run 2	Run 1	Run 2
Exhouse	3.006	0.690	8.484	1.844
Inhouse	0.004	0.027	0.004	0.032
Industrial/commercial	0.015	0.084	0.015	0.084
Total	3.025	0.801	8.503	1.960

System lowest volume & percentiles: 1, 2, 5

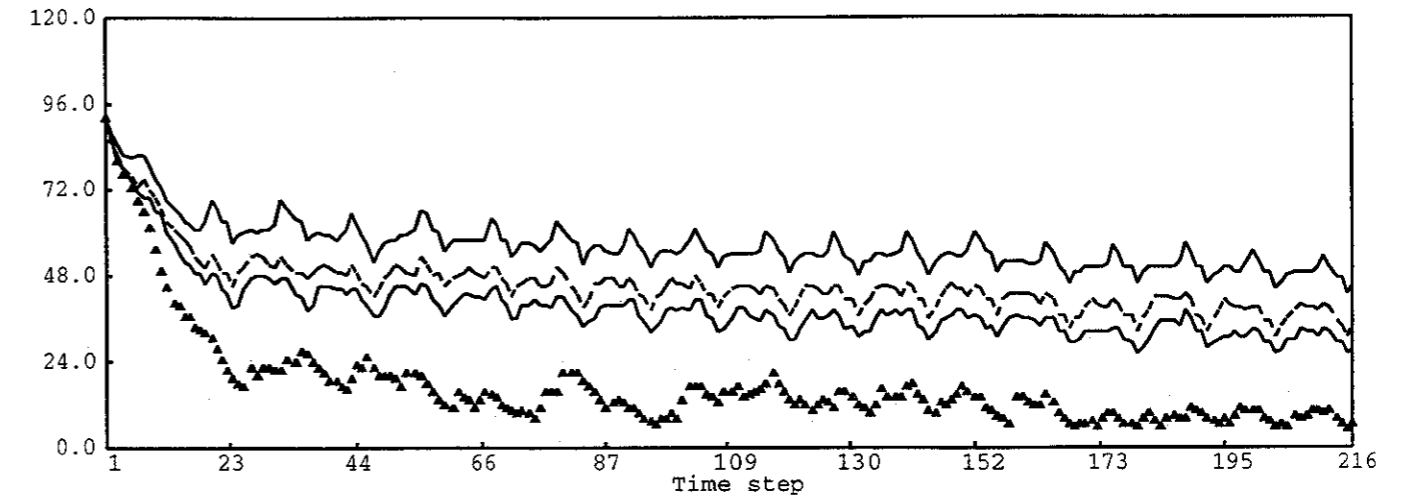


Figure 4.21 Monthly time series of minimum total storage and 1, 2 and 5 total storage percentiles: Run 2

System Annual Failure Probability (%)

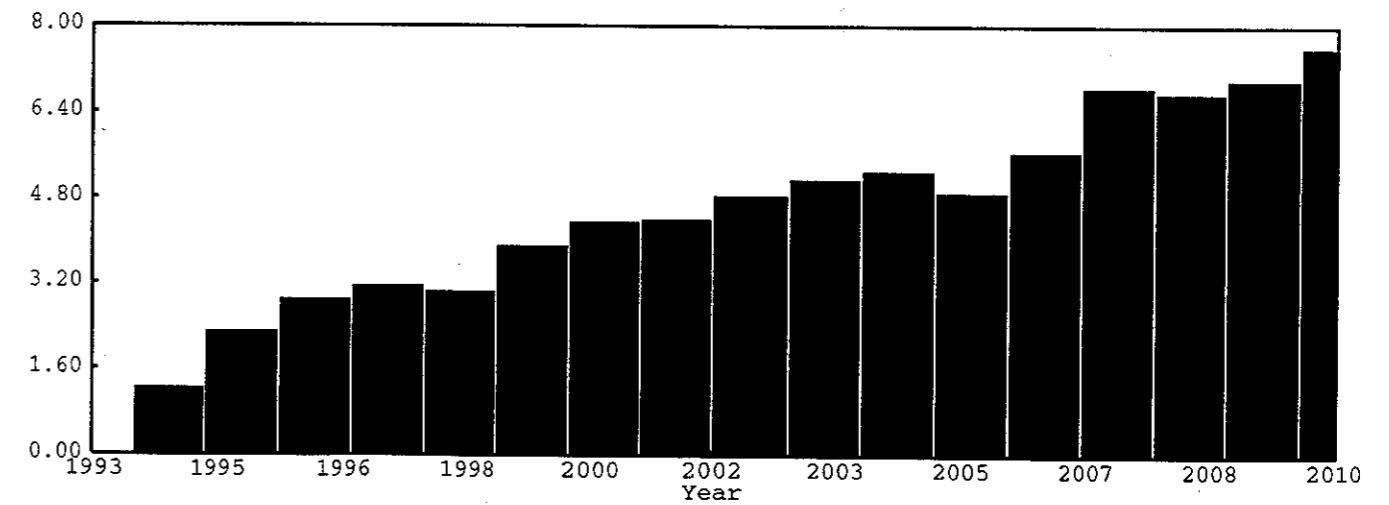


Figure 4.22 Annual time series of probability of having restrictions: Run 2

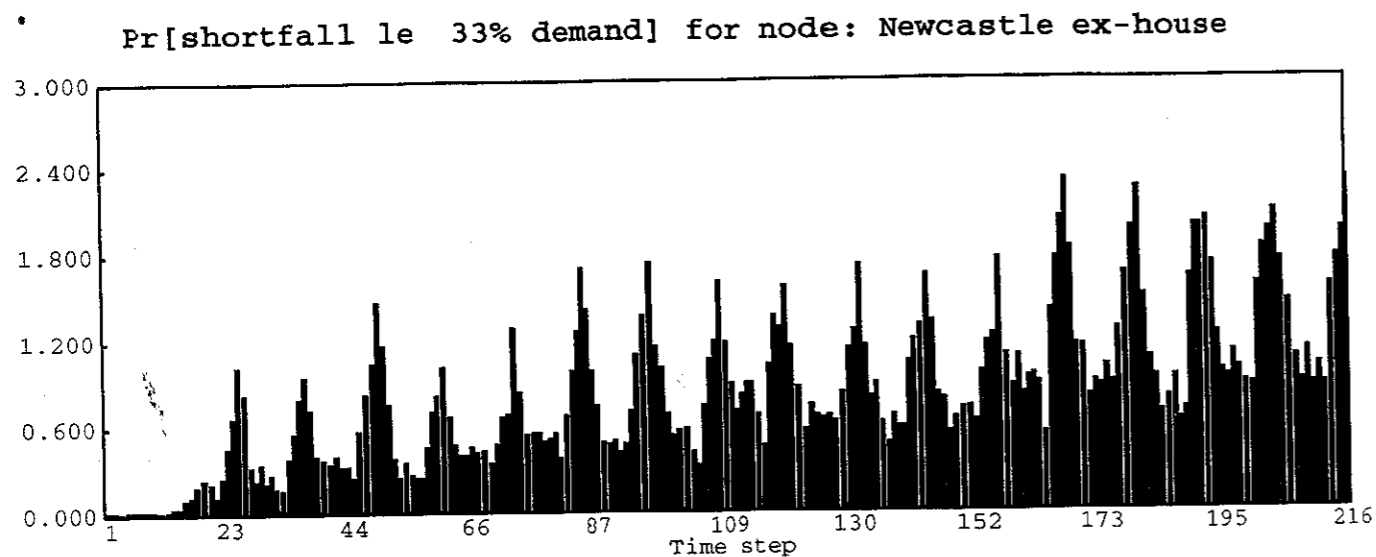


Figure 4.23 Monthly time series of probability of exhouse consumption being restricted \leq 33%: Run 2

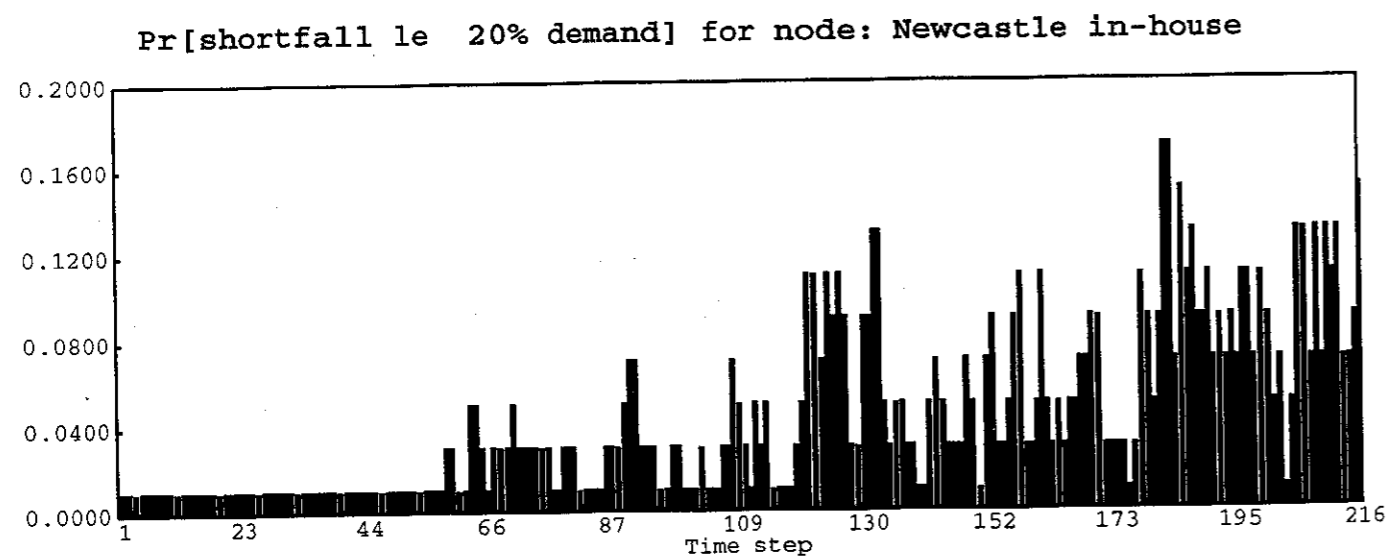


Figure 4.24 Monthly time series of probability of inhouse consumption being restricted \leq 20%: Run 2

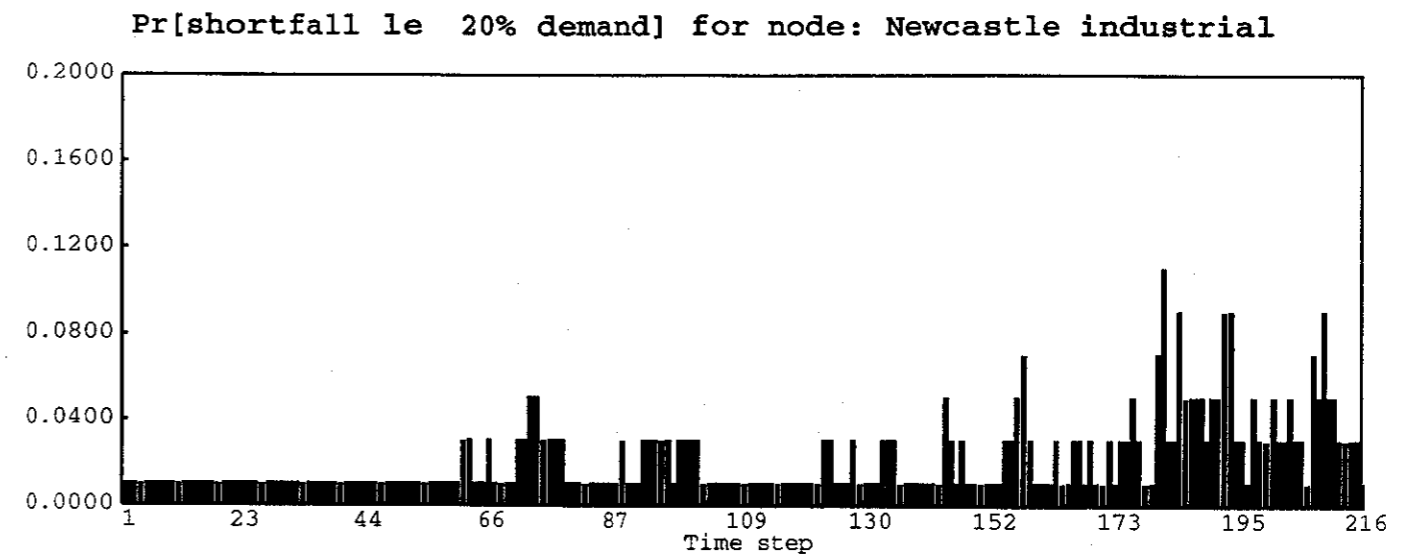


Figure 4.25 Monthly time series of probability of industrial/commercial consumption being restricted \leq 20%: Run 2

4.5.2 Augmentation timing

This Section illustrates the use of economic losses to assist in determining the preferred timing of an augmentation. Six simulation runs are presented. Run 3 simulates the hypothetical present system which is the same as the system in Run 2 except that Grahamstown reservoir has a water supply capacity of only 60000 ML (with the remaining capacity reserved for flood storage). Runs 4 to 8 simulate the augmentation of the Run 3 system in which Grahamstown reservoir's capacity is raised to 100000 ML at some future date. The simulations were performed using 2500 replicates each 50 years long.

Run 3: Run 2 system with Grahamstown capacity at 60000 ML

The DMP is the same as for Run 2 (see Figure 4.20). Figure 4.26 presents 1, 2 and 5 percentiles for total storage as well as the lowest storage volume in the 2500 replicates. Figure 4.27 presents the probability of having restrictions for one or more months in any future year. Both Figures reveal a steadily worsening level of performance. The annual probability of restrictions exceeds 10% near the end of the century and continues to steadily climb to over 50% by the end of the 50-year planning horizon.

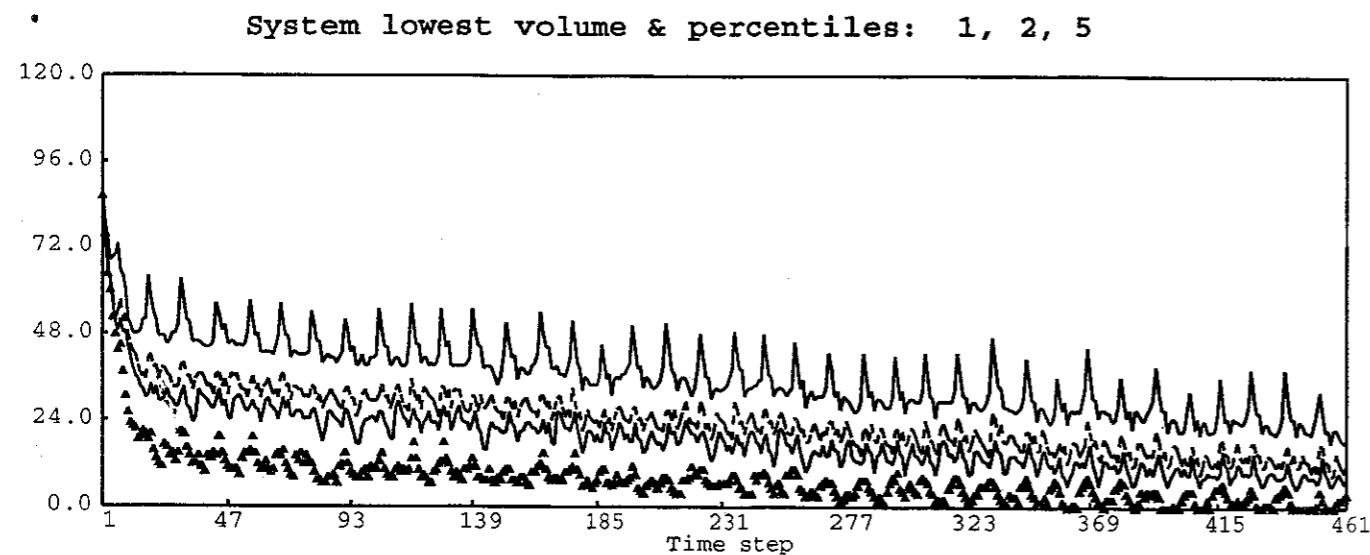


Figure 4.26 Monthly time series of minimum total storage and 1, 2 and 5 total storage percentiles: Run 3

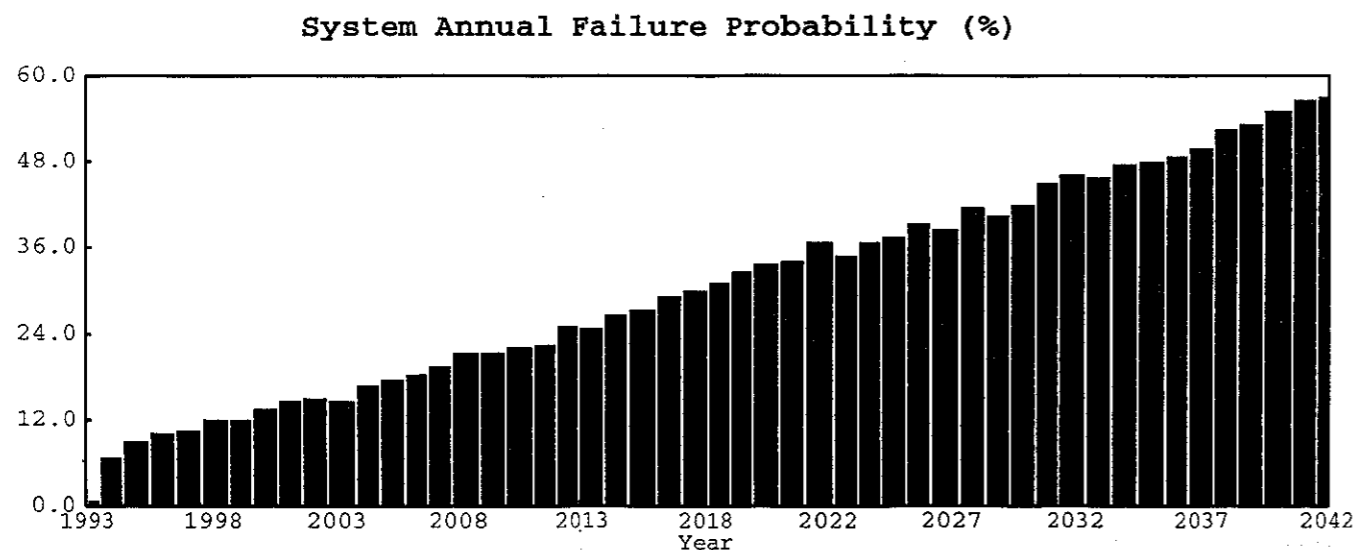


Figure 4.27 Annual time series of probability of having restrictions: Run 3

Figure 4.28 presents the lower and upper bounds for the undiscounted inhouse and exhouse economic losses. The major divergence between the lower and upper bound economic loss estimates highlights the sensitivity of the losses to assumptions about household subsistence behaviour.

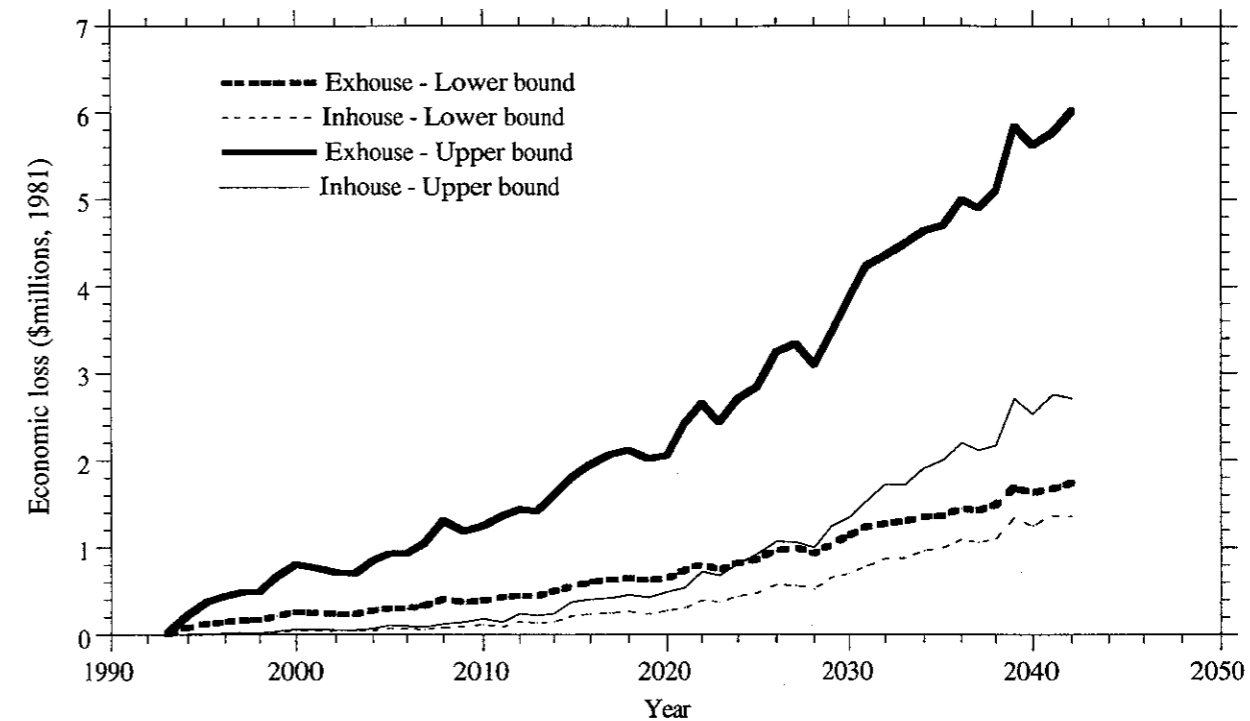


Figure 4.28 Time series of lower and upper bounds for undiscounted inhouse and exhouse economic losses: Run 3

Runs 4 to 8: Run 3 system with Grahamstown capacity increased to 100000 ML

In Runs 4 to 8 the capacity of Grahamstown is increased from 60000 to 100000 ML. The commissioning year ranges from 1993 to 2013 in five year increments. The DMP is the same as for Run 2. Tables 4.8a and 4.8b present the savings in expected economic losses due to restrictions for different discount rates, augmentation years and for lower and upper bounds on economic losses. These savings are sensitive to the choice of discount rate and subsistence assumptions. Note that these savings underestimate the actual savings because the 50-year planning horizon is not sufficiently long for the present worth of losses to converge to zero, particularly at low discount rates.

Figures 4.29 and 4.30 present plots of augmentation year versus net benefits, calculated using eqn. (2.2), for lower and upper bound economic losses. The augmentation capital cost is assumed to be \$40 million (1981 dollars). Three features deserve mention:

- i) The net benefits are sensitive to the choice of discount rate. This is because benefits are actually increasing with time due to a rapid deterioration in the performance of the Run 3 system.

Table 4.8a Present worth of economic loss savings due to augmentation using lower bound economic losses

Augmentation year	Present worth of economic loss savings (\$million, 1981)					
	0%	1%	2%	3%	4%	5%
1993	84.7	58.3	40.7	28.9	20.9	15.3
1998	83.9	57.6	40.0	28.2	20.2	14.7
2003	83.2	56.8	39.2	27.5	19.5	14.0
2008	81.1	55.0	37.7	26.1	18.3	13.0
2013	78.0	52.5	35.6	24.4	16.9	11.8

Table 4.8b Present worth of economic loss savings due to augmentation using upper bound economic losses

Augmentation year	Present worth of economic loss savings (\$million, 1981)					
	0%	1%	2%	3%	4%	5%
1993	148.8	103.8	73.6	53.1	39.0	29.1
1998	146.3	101.5	71.4	51.0	37.0	27.2
2003	144.1	99.2	69.1	48.9	35.0	25.4
2008	139.1	94.9	65.4	45.6	32.2	23.0
2013	132.3	89.3	60.9	41.9	29.1	20.4

- ii) In the vicinity of the optimum augmentation year the net benefit function is flat. This means that for the Run 3 system there is a wide window (of the order of 10 years) in which the net benefits of the augmentation are very similar. Consequently the planner has considerable latitude in selecting an augmentation year whilst maintaining a near optimal level of net economic benefits.
- iii) The magnitude of net benefits and the preferred augmentation year are sensitive to assumptions about household subsistence behaviour. The upper bound economic losses bring forward substantially the 'optimal' augmentation year.

Figures 4.31 and 4.32 present plots of augmentation year versus net benefits for an augmentation capital cost of \$20 million. As would be expected comparison with Figures 4.29 and 4.30 shows that the preferred augmentation year moves closer to the present.

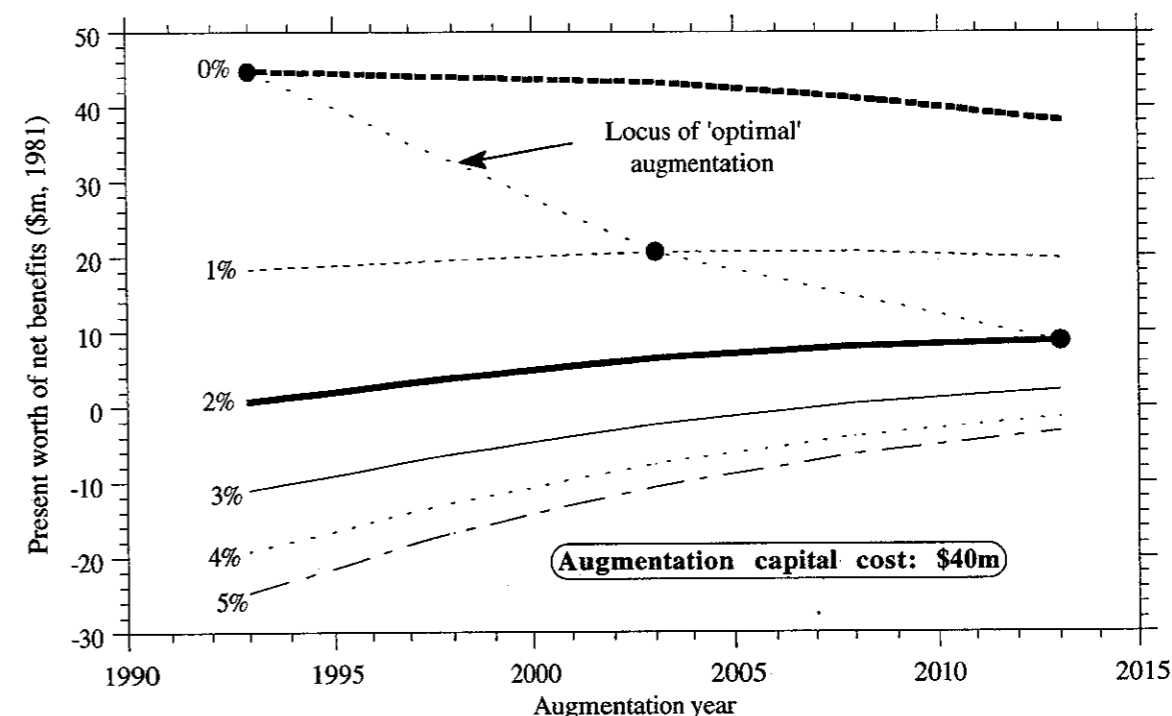


Figure 4.29 Plot of augmentation year versus present worth of net benefits for discount rates from 0% to 5%: Lower bound economic losses; Runs 4 to 8; augmentation cost = \$40m

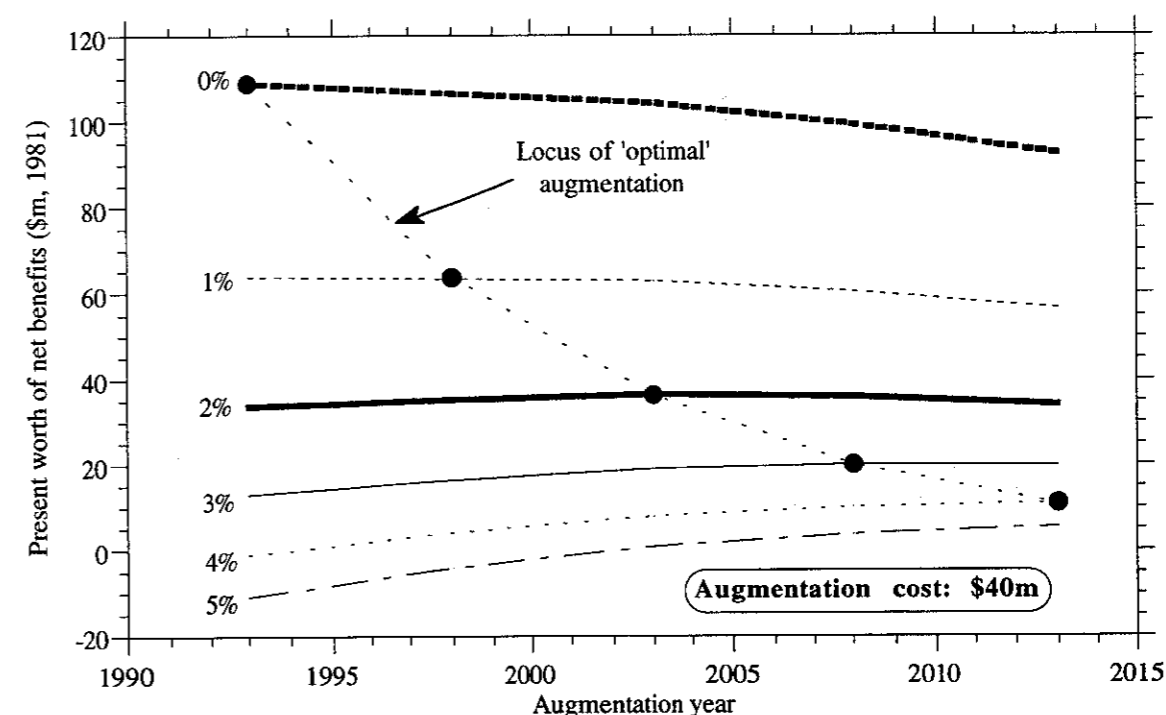


Figure 4.30 Plot of augmentation year versus present worth of net benefits for discount rates from 0% to 5%: Upper bound economic losses; Runs 4 to 8; augmentation cost = \$40m

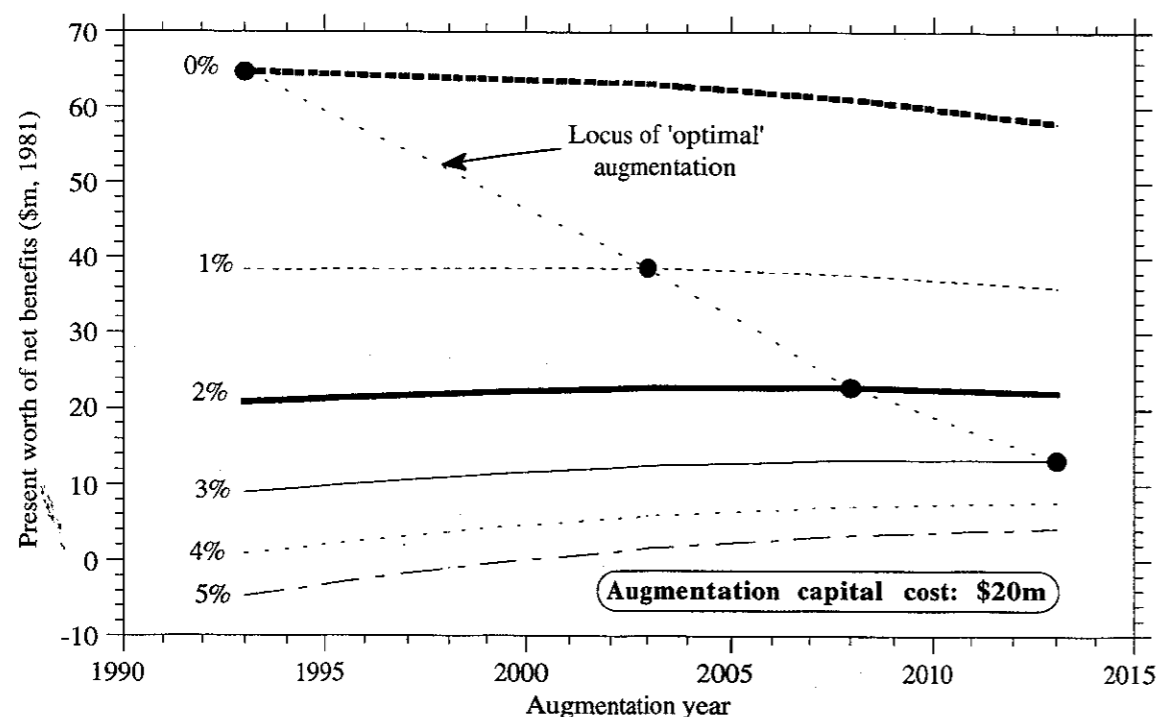


Figure 4.31 Plot of augmentation year versus present worth of net benefits for discount rates from 0% to 5%: Lower bound economic losses; Runs 4 to 8; augmentation cost = \$20m

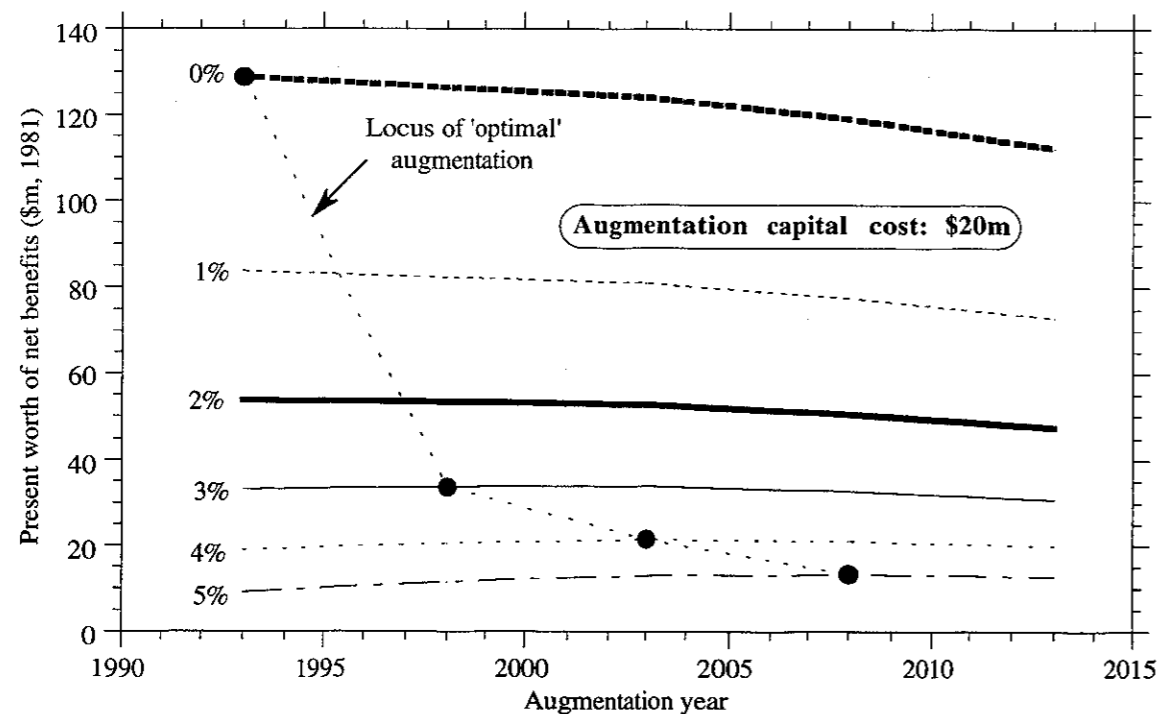


Figure 4.32 Plot of augmentation year versus present worth of net benefits for discount rates from 0% to 5%: Upper bound economic losses; Runs 4 to 8; augmentation cost = \$20m

5. CONCLUSIONS

This study develops and demonstrates a stochastic economic approach for deciding when a headworks augmentation should commence and for optimizing restriction rules. The approach uses information about consumers' willingness-to-pay for water to evaluate the economic impact of restrictions on water consumption. Multi-replicate simulation, which accounts for uncertainty in future streamflows as well as future demand, is used to estimate future expected economic losses due to restrictions for a given drought management plan and operating policy. Computer software for implementing this methodology was developed around the WATHNET generalized headworks simulation model and can be run on IBM-compatible and Macintosh computers and on Unix workstations supporting X Windows.

A case study based on the Newcastle headworks system demonstrated the methodology. Several major findings based on this case study are summarized below:

- i) The methodology relies on sufficient information being available to define the demand-price relationship. In particular, the economic loss due to restrictions depends on knowing the shape of the demand-price curve near the subsistence region where prices, well beyond those currently set by water authorities, force the consumer to drastically reduce consumption. In the Newcastle case study, price-demand data only provided information about two points on the inhouse and exhouse demand-price curves and thus were unable to reliably identify the subsistence region. Therefore, economic loss calculations had to rely on making an assumption about the shape of the demand-price curve in the subsistence region.

Two assumptions about the subsistence region representing nominal lower and upper bounds were illustrated. It was found that economic losses were very sensitive to these assumptions.
- ii) The estimation of expected economic losses requires specification of a comprehensive drought management plan for all demand sectors. Because there is a finite risk of running out of water, the capability has to be provided for estimating economic losses in all demand sectors, not just in the outdoor domestic demand sector. Failure to address all sectors could lead to serious underestimation of losses.

- iii) The case study showed that the augmentation date which maximizes the present worth of expected net benefits, defined as the difference between savings in economic losses due to restrictions and the cost of the augmentation, was sensitive to assumptions about the subsistence region of the demand-price curve and to the choice of the discount rate.
- iv) In the vicinity of the preferred augmentation date the expected net benefit function was quite flat indicating that a wide range of augmentation dates could be selected without major losses in economic efficiency. This result may be in part due to the availability of large sand bed aquifers in the Newcastle system which cushion the severity of restrictions during severe droughts. A system totally reliant on surface storage may be more vulnerable to severe drought.
- v) The economic loss methodology provides a rational means for tuning the restriction rules in the drought management plan. It was shown that a less conservative restriction policy led to unambiguously lower expected economic losses and would, in addition, justify deferral of an augmentation. This highlights the importance of jointly optimizing operating policy as well as augmentation timing.

In summary, the viability of the economic loss methodology depends critically on having reliable demand-price information. Given such information the tools developed in this study are capable of giving planners an economic perspective on system performance, which, together with current risk-based measures, should assist in the search for good solutions in managing headworks systems.

The main research priority lies in better definition of the demand-price relationship in the subsistence region, not only for the outdoor domestic sector but for all sectors. Willingness-to-pay surveys and cross-sectional studies may better define this subsistence region. A sufficient outcome of such studies would be an objective description of the uncertainty of the demand-price curve in the subsistence region. Because the software developed in this study implements Ng and Kuczera's (1992) approach for allowing for uncertainty in the demand-price curve, such information will lead to meaningful estimates of economic losses.

ACKNOWLEDGEMENTS

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APPENDIX A: WATDEM AND ECLOSS PROGRAM DETAILS

This Appendix presents program details for programs WATDEM and ECLOSS which were described in Chapter 3. In Figures A1 and A2 respectively the prologues for subroutines MODELS and PDFUNC are presented. These subroutines implement eqns (3.1) and (3.2). Sample source code for these subroutines can be found in Appendix B.

The socioeconomic scenario data file is an ASCII file providing information about the socioeconomic scenarios used in the demand model. Its FORTRAN format is described in Table A1. An example can be found in Appendix B. A feature of this format is the capability to allow multiple scenarios for each socioeconomic variable.

The demand zone parameters file is an ASCII file summarizing information obtained from a regression analysis about the parameters in the demand model used to predict demand at a particular zone or centre. One file must be provided for each demand zone. Its FORTRAN format is described in Table A2. The format is more complicated than is strictly necessary to maintain consistency with the posterior moments file produced by the nonlinear regression program NLFIT (Kuczera, 1989); there is no need, however, to use NLFIT to perform the regression as the information can be obtained from any regression package. If NLFIT is not used, it is recommended that the variable neq assigned in the third record be given a value of 1 and that all dummy variables be given a value of 0. An example can be found in Appendix B.

```

subroutine models (mndem, yrдем, ndem, par, npar, std, sevar,
&
nsevar, selag, senyr, sestyr, clvar, nclvar,
&
cllag, clnyr, clstyr, clstmn, styear, nyear,
&
stmwly, npx, dmx, nsx, ncx, ytx, mtx, ylx, mnx)
*-----
* Routine computes monthly demand at selected demand zones.
*
* Input variables
* *****
* Name          Type          Description
* ----          -
* npx           INT           Dimension variable defines max. number of
*                    parameters in a demand model.
* dmx           INT           Dimension variable defines max. number of demand zones
* nsx           INT           Dimension variable defines max. number of
*                    socioeconomic (SE) variables.
* ncx           INT           Dimension variable defines max. number of
*                    climatic and streamflow variables.
* ytx           INT           Dimension variable defines max. simulation yrs
* mtx           INT           Dimension variable defines max. simulation months
* ylx           INT           Dimension variable defines max. no of lag years
*                    prior to start of simulation
* mnx           INT           Dimension variable defines number of months in year (ie 12)
* par(npx,dmx) DBLE          Values of the demand zone parameters.
* npar(dmx)     INT           No. of parameters for each demand zone.
* std(dmx)      DBLE          Std.Dev. of demand natural uncertainty.
* sevar(ytx,nsx) DBLE          Socioeconomic (SE) variables scenarios.
* nsevar        INT           No. of socioeconomic var.
* selag         INT           Order of lag of SE var.
* senyr         INT           Length of SE var data in years passed into MODELS.
* sestyr        INT           Starting year of SE data passed into MODELS
* clvar(mtx,ncx) DBLE          climatic variables.
* nclvar        INT           No. of the climatic (CL) variables.
* cllag         INT           Order of lag of CL var.
* clnyr         INT           Length of CL data in year passed into MODELS
* clstyr        INT           Starting year of CL data passed into MODELS
* clstmn        INT           Starting month of CL data passed into MODELS. Same as the
*                    starting month of the simulation.
* stmwly        INT           First month in simulation year; if equal to 1 then simulation
*                    year corresponds to calendar year.
* styear        INT           First year of the simulation.
* nyear         INT           No. of years to be simulated.
*
* Output variables
* *****
* Name          Type          Descriptions
* ----          -
* mndem(ytx,mnx,dmx) DBLE          Monthly demand (megalitres) indexed by year, month
*                    and zone
* yrдем(ytx,dmx)   DBLE          Yearly demand (megalitres) indexed by year and zone
* ndem          INT           Number of demand zones defined. This will be checked
*                    against the number of demand sites read in by WATDEM
*
integer npx, dmx, nsx, ncx, ytx, mtx, ylx, mnx, nsevar, nclvar, clnyr, clstyr,
&
nyear, styear, stmwly, senyr, selag, sestyr, cllag, clstmn, ndem, ifirst
integer npar(dmx)
double precision mndem(mnx,ytx,dmx), yrдем(ytx,dmx), par(npx,dmx),
&
sevar(ylx:ytx,nsx), clvar(mnx,ylx:ytx,ncx), std(dmx)

```

Figure A1. Prologue for subroutine MODELS in WATDEM

```

subroutine pdfunc (lprice, ldeman, dmctr, ndmctr, sevar, nsevar,
+
clvar, nclvar, par, npar, shseas, shyear,
+
nyear, styear, dmx, nsx, ncx, mnx, npx )
*-----
* Routine computes the water price given the demand, climatic and socioeconomic variables
* for a given demand centre at a given season and year
*
* Input variables
* *****
* Name          Type          Description
* ----          -
* dmx           INT           Dimension variable for number of demand sites.
* nsx           INT           Dimension variable for number of socioeconomic variables
* ncx           INT           Dimension variable for number of climatic variables
* mnx           INT           Dimension variable for number of seasons. (i.e. 12).
* npx           INT           Dimension variable for number of parameters.
* ldeman        DBLE          Given monthly water demand (ML) for a demand site.
* dmctr         INT           Index identifying the demand center being considered
* ndmctr        INT           Total number of demand centres
* sevar(nsx)    DBLE          Socioeconomic variables for demand centre dmctr
* nsevar        INT           Number of socioeconomic variables
* clvar(ncx)    DBLE          Climatic variables for demand centre dmctr
* nclvar        INT           Number of climatic variables.
* par(npx)      DBLE          Demand model parameters for demand centre dmctr
* npar          INT           Number of demand model parameter.
* shseas        INT           Season
* shyear        INT           Year
* nyear         INT           Number of year to be simulated
*
* Output variables
* *****
* Name          Type          Descriptions
* ----          -
* lprice        DBLE          Shadow price ($/kL) for demand given by ldeman
*
integer dmx, nsx, ncx, mnx, npx, dmctr, ndmctr, shseas, shyear,
&
nyear, styear, nsevar, nclvar
integer npar(dmx)
double precision lprice, ldeman, sevar(nsx), clvar(mnx,ncx), par(npx,dmx)

```

Figure A2. Prologue for subroutine PDFUNC in ECLOSS

The following listing describes subroutine MODELS for the Newcastle headworks case study. The code implements eqns (4.2), (4.5) and (4.9). See the prologue in Figure A1 for a description of the subroutine arguments:

```

*
*+++++72
*
  subroutine models (mndem, yrdem, ndem, par, npar, std, sevar,
    & nsevar, selag, senyr, sestyr, clvar, nclvar,
    & cllag, clnyr, clstyr, clstmn, styear, nyear,
    & stmnwy, npx, dmx, nsx, ncx, ytx, mtx, ylx,
    & mnx, ifirst)
*-----
* This routine defines demand models used in the Newcastle
* headworks simulation.
*
  implicit none
  integer npx, dmx, nsx, ncx, ytx, mtx, ylx, mnx, nsevar, nclvar,
    & nyear, styear, stmnwy, senyr, selag, sestyr, cllag,
    & clnyr, clstyr, clstmn, ndem, ifirst
  integer npar(dmx)
  double precision mndem(mnx,ytx,dmx), yrdem(ytx,dmx),
    & par(npx,dmx), sevar(ylx:ytx,nsx),
    & clvar(mnx,ylx:ytx,ncx), std(dmx)
*
  integer i, j, num, izero, month, year
  double precision evap(12), rzero, inhouse, exhouse, random,
    & conns, znorm, rain
*
* Suppress generation of disturbances
*
  logical genran
  parameter( izero = 0, rzero = 0.0d0, genran=.false. )
  save
*
* Grahamstown monthly pan evap (mm)
*
  data (evap(i),i=1,12)/212.0, 174.0, 155.0, 121.0, 89.0, 80.0,
    & 78.0, 98.0, 121.0, 171.0, 197.0, 221.0/
*-----
* Demand site 1 - Newcastle inhouse domestic demand
* This implements eqn. (4.2)
*
  num = 1
  do i = 1, nyear
    yrdem(i,num) = rzero
    conns = sevar(i,1)/sevar(i,2)
    do j = 1, 12
*
* Get calendar month; stmnwy gives first month in simulation year
*
      if (stmnwy+j-1.le.12) then
        month = stmnwy + j - 1
      else
        month = stmnwy + j - 13
      end if
*

```

```

* Order of SE variables: 1) Population, 2) Persons per lot, 3) Price
*
* Order of climate variables: 1) Gtown rain
*
* Subroutine indom computes monthly inhouse demand
*
      call indom (par(1,num), sevar(i,3), conns, sevar(i,2),
        & inhouse)
*
* Add natural uncertainty to in-house demand
*
      if (genran) then
        random = min(2.5d0*std(num),max (-2.5d0*std(num),
          & znorm (rzero, std(num), num, izero)))
      else
        random = rzero
      end if
*
* Assign monthly inhouse demand to mndem and accumulate in yrdem to get annual demand
*
      mndem(j,i,num) = max (rzero, inhouse + random)
      yrdem(i,num) = yrdem(i,num) + mndem(j,i,num)
    end do
  end do
*-----
* Demand site 2 - Newcastle exhouse domestic demand
* This implements eqn. (4.5)
*
  num = 2
  do i = 1, nyear
    yrdem(i,num) = rzero
    conns = sevar(i,1)/sevar(i,2)
    do j = 1, 12
*
* Get calendar month
*
      if (stmnwy+j-1.le.12) then
        month = stmnwy + j - 1
      else
        month = stmnwy + j - 13
      end if
*
* Order of SE variables: 1) Population, 2) Persons per lot, 3) Price ($/kL)
*
* Order of climate variables: 1) Gtown rain obtained by dividing Grahamstown
* runoff by 32.26
*
      rain = clvar(j,i,1)/32.26d0
      call outdom (par(1,num), evap(month), rain, sevar(i,3),
        & conns, sevar(i,2), exhouse)
*
* Add natural uncertainty to ex-house demand
*
      if (genran) then
        random = min(2.5d0*std(num),max (-2.5d0*std(num),
          & znorm (rzero, std(num), num, izero)))
      else
        random = rzero
      end if

      mndem(j,i,num) = max (rzero, exhouse + random)

```

```

        yrdem(i,num) = yrdem(i,num) + mndem(j,i,num)
    end do
end do
*-----
* Demand site 3 - Newcastle industrial, commercial, scour and
* unaccounted-for demand
* This implements eqn. (4.9)
*
num = 3
do i = 1, nyear
    yrdem(i,num) = rzero
    year = styear + i - 1
    do j = 1, 12
*
* Get calendar month
*
        if (stmnwy+j-1.le.12) then
            month = stmnwy + j - 1
        else
            month = stmnwy + j - 13
        end if
*
* Order of climate variables: 1) Gtown rain
*
        rain = clvar(j,i,1)/32.26d0
        call indus (par(1,num), month, year, rain,
        &          sevar(i,1), mndem(j,i,num))
*
* Add natural uncertainty
*
        if (genran) then
            random = min(2.5d0*std(num),max (-2.5d0*std(num),
            &          znorm (rzero, std(num), num, izeo)))
        else
            random = rzero
        end if
        mndem(j,i,num) = max (rzero, mndem(j,i,num) + random)
        yrdem(i,num) = yrdem(i,num) + mndem(j,i,num)
    end do
end do
*-----
* Define number of demand zones; WATDEM checks this value for consistency
*
ndem = num
end
*
*-----
*-----72
*
subroutine indom (par, price, conns, plot, inhouse)
implicit none
integer year, month
double precision par(8), price, conns, plot, zero, inhouse,
&          one, cons
parameter (zero=0.0d0, one=1.0d0, cons=30.5d-6)
*-----
* Compute monthly inhouse demand according to eqn. (4.2):
*
* Parameter list:
* 1 = Ex-house zero price consumption
* 2 = In-house zero price consumption
* 3 = Ex-house price exponent
* 4 = In-house price exponent

```

```

* 5 = Pan evap multiplier
* 6 = Price lag (years)
* 7 = Subsistence as a fraction of max in-house
* 8 = Subsistence as a fraction of max ex-house
*
* Get total monthly inhouse consumption ML
*
    inhouse = plot*conns*par(2)*cons*
    &          (par(7) + (one-par(7))*exp(-par(4)*price))
end
*
*-----72
*
subroutine outdom (par, evap, rain, price, conns, plot, exhouse)
implicit none
integer i
double precision par(8), evap, rain, price, conns, plot, zero,
&          exhouse, deficit, cons, one
parameter (zero=0.0d0, cons=30.5d-6, one=1.0d0)
*-----
* Compute monthly exhouse demand according to eqn. (4.5):
*
* Parameter list:
* 1 = Ex-house zero price consumption
* 2 = In-house zero price consumption
* 3 = Ex-house price exponent
* 4 = In-house price exponent
* 5 = Pan evap multiplier
* 6 = Price lag (years)
* 7 = Subsistence as a fraction of max in-house
* 8 = Subsistence as a fraction of max ex-house
*
* Get irrigation requirement based on simple cumulative water deficit
* evap - rain
*
    deficit = max (zero, par(5)*evap - rain)
*
* Get ex-house consumption
*
    if (deficit.gt.zero) then
        exhouse = deficit*conns*par(1)*cons*
        &          (par(8)+(one-par(8))*exp(-par(3)*price))
    *
* Update water deficit based on actual garden watering
*
    else
        exhouse = zero
    end if
end
*
*-----72
*
subroutine indus (par, month, year, rain, pop, monindus)
implicit none
integer year, month
double precision par(6), monindus, rain, cons, pop
parameter (cons=2.0d0*3.141592654d0/12.0d0)
*-----
* Compute predicted monthly non-domestic demand according to eqn. (4.9):
*
* Parameter list:

```

```

* 1 = Monthly demand in 1992
* 2 = Annual trend
* 3 = Seasonal amplitude
* 4 = Phase shift in months
* 5 = Rain effect
* 6 = population effect

```

```

monindus = (par(1) + par(2)*dble(year-1992) +
&          par(6)*pop) *
&          (1.0d0 + par(3)*sin(const*(dble(month)+par(4)))) +
&          par(5)*rain
end

```

The following listing describe subroutine PDFUNC for the Newcastle headworks case study. For inhouse and exhouse demand the code rearranges eqns. (4.2) and (4.5) so that price is on the left hand side; for the non-domestic sector a fixed price of \$5/kL is used. See the prologue in Figure A2 for a description of the subroutine arguments:

```

*
*+++++72
*
subroutine pdfunc( lprice, ldeman, dmctr, ndmctr, sevar, nsevar,
+               clvar, nclvar, par, npar, shseas, shyear,
+               nyear, styear, dmx, nsx, ncx, mnx, npx )
*-----
* Routine computes the water price given the demand, climatic and socioeconomic variables
* for a given demand centre at a given season and year
implicit none
integer dmx, nsx, ncx, mnx, npx, dmctr, ndmctr, shseas, shyear,
&       nyear, styear, nsevar, nclvar
integer npar(dmx)
double precision lprice, ldeman
double precision sevar(nsx), clvar(mnx,ncx), par(npx,dmx)
*
double precision evap(12), rain
integer i
save
*
* Grahamstown monthly pan evap (mm)
*
data (evap(i),i=1,12)/212.0, 174.0, 155.0, 121.0, 89.0, 80.0,
&      78.0, 98.0, 121.0, 171.0, 197.0, 221.0/
*-----
if (dmctr.eq.1) then
*
* In-house domestic demand
*
call indom (par(1,dmctr), sevar(1), sevar(2), lprice, ldeman)
if (lprice.lt.0.0d0) then
call prompt('Negative inhouse price')
call finish
end if

else if (dmctr.eq.2) then
*
* Ex-house domestic demand
*
rain = clvar(shseas,1)/32.26d0
call outdom (par(1,dmctr), sevar(1), sevar(2), lprice,
&           evap(shseas), rain, ldeman)
if (lprice.lt.0.0d0) then
call prompt('Negative exhouse price')
call finish
end if

else if (dmctr.eq.3) then
*
* Industrial, commercial, scour and unaccounted-for demand
*
rain = clvar(shseas,1)/32.26d0

```

```

        call indus (par(1,dmctr), shseas, shyear, rain, ldeman,
&                lprice, sevar(1))
    end if
end
*
*+++++72
*
subroutine outdom (par, pop, perlot, price, evap, rain, mondem)
implicit none
double precision par(8), mondem, perlot, price, pop, delta,
&                evap, rain, zero, deficit, exhous, cons,
&                maxprice, minhouse
parameter (zero=0.0d0)
parameter (delta=1.0d-8, cons=30.5d-6, maxprice=10.0d0)
*-----
* Compute price given monthly ex-house demand for Newcastle given:
* rain = Grahamstown rainfall
* evap = Grahamstown pan evap
* mondem = water demand in ML
* pop = population connected
* perlot = persons per connection
*
* Code implements eqn. (4.5) rearranged to have price on LHS
*
* Parameter list:
* 1 = Ex-house zero price consumption
* 2 = In-house zero price consumption
* 3 = Ex-house price exponent
* 4 = In-house price exponent multiplier
* 5 = Pan evap multiplier
* 6 = household exponent
* 7 = Subsistence as a fraction of max in-house
* 8 = Subsistence as a fraction of max ex-house
*
* Get irrigation requirement based on simple water deficit = evap - rain
*
deficit = max (zero, par(5)*evap - rain)
*
* Get price $/kL
*
if (deficit.gt.zero) then
    exhous = mondem/(deficit*cons*pop/perlot)
    minhouse = par(1)*par(8)
    if (exhous.gt.(1.0d0+delta)*minhouse) then
        price = log((exhous-minhouse)/(par(1)*(1.0d0-par(8))))
&        /(-par(3))
        price = min (price, maxprice)
    else
        price = maxprice
    end if
else
    price = zero
end if
end
*
*+++++72
*
subroutine indom (par, pop, perlot, price, mondem)
implicit none
double precision par(8), mondem, perlot, price, minhouse, pop,
&                inhouse, delta, maxprice, cons

```

```

parameter (delta=1.0d-8, maxprice=10.0d0, cons=30.5d-6)
*-----
* Compute price given monthly in-house demand for Newcastle given:
* mondem = water demand in ML
* pop = population connected
* perlot = persons per connection
*
* Code implements eqn. (4.2) rearranged to have price on LHS
*
* Parameter list:
* 1 = Ex-house zero price consumption
* 2 = In-house zero price consumption
* 3 = Ex-house price exponent
* 4 = In-house price exponent multiplier
* 5 = Pan evap multiplier
* 6 = household exponent
* 7 = Subsistence as a fraction of max in-house
* 8 = Subsistence as a fraction of max ex-house
*
* Get monthly consumption per capita in ML
*
inhouse = mondem/(cons*pop)
*
* Get price $/kL
*
minhouse = par(2)*par(7)
if (inhouse.gt.(1.0d0+delta)*minhouse) then
    price = log((inhouse-minhouse)/(par(2)*(1.0d0-par(7))))
&        /(-par(4))
    price = min (price, maxprice)
else
    price = maxprice
end if
end
*
*+++++72
*
subroutine indus (par, month, year, rain, actdem, price, pop)
implicit none
integer year, month
double precision par(5), monindus, rain, actdem, price,
&                iomult, pop
parameter (iomult=5.00d0)
*-----
* Assume fixed value of loss $ of net output per KL of water restricted
price = iomult
end

```

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