STOCHASTIC DYNAMIC PROGRAMMING FOR SALINITY MANAGEMENT IN RESERVOIR OPERATION

by

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ABSTRACT

A stochastic dynamic programming technique for the optimal operation of a reservoir to control salinity in the reservoir and thereby also in the releases, and to meet irrigation and municipal demands is developed. The technique defines the optimal policy for releases to meet salinity and irrigation water supply requirements. The problem for which the approach was specifically developed is characterised by the presence of a strongly stratified, essentially two-layer, condition in a reservoir used to supply irrigation water. The two-layer condition exists over the winter months when cold and heavy saline flows enter the reservoir and flow to the bottom of the reservoir. The two-layer condition continues until mixing of the reservoir occurs in early summer. While the reservoir is stratified, it is possible to flush the saline water out of the reservoir by low level intakes. This flushing reduces the overall salinity level in the reservoir when mixing occurs at the end of winter, and thereby reduces the salinity of irrigation water withdrawn from the reservoir over the summer. However, removing the saline bottom layer also reduces the volume of water available for irrigation. Hence there are limitations on the amount that can be withdrawn to reduce the salinity. The technique is an approach to optimising the performance of the reservoir to meet irrigation demands, while minimising salt concentration in the irrigation water.

Stochastic dynamic programming is used to reflect the uncertainty in the inflows while chance-constraints are used to control the level of salt in the reservoir at the beginning of the irrigation season. Three different conditions or assumptions are considered in modelling the probabilistic nature of the salt inflows to the reservoir: 1) salt load is directly related to the volume of inflow, 2) salt load is independent of the volume of the inflow, and 3) salt load is conditioned on the volume of inflow. The model is demonstrated by application to the Wellington Reservoir in Western Australia for the case in which the salt load is conditioned on the inflow. The results of the application of the model for a range of different combinations of maximum allowable salt concentration and probability of exceeding that are compared to each other and to the release policy generated in an earlier simulation analysis undertaken to manage the salinity question.

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CHAPTER - 1

INTRODUCTION:

WATER RESOURCES PLANNING AND MANAGEMENT

The task of water resource planners may be broadly described as the identification or development of water resource system designs or management plans and the evaluation of their ecological, environmental and social aspects. There are two basic approaches for solving planning models: simulation and optimisation. The efficient management of a water resource system requires the determination of optimal operation policies. Simulation relies on trial-and-error to identify near optimal solutions. The difficulty with the simulation approach is that there is often a large number of feasible solutions or plans. In recent times optimal operation policies have often been identified through a suitable optimisation technique.

Uncertainty has always been an important element in the planning process for water resource projects or systems. Uncertainty arises in these systems because of the variability in the values of many factors that affect the performance of the control system. For example, how well a reservoir performs in any given year cannot be known with certainty when an operation is planned. The success and performance of operation of the reservoir depend on future (unknown and variable) meteorological, social and technical conditions. More specifically the uncertainty in each of these categories arises from the stochastic nature of hydrological processes such as inflow of the water to a reservoir, from the uncertainty in future market and economic conditions, and from an incomplete understanding of the outputs and the impacts of developments. This thesis is directed specifically towards the problem of managing the salinity in a reservoir used to supply irrigation and domestic water, under explicit recognition of the uncertainty about the inflows of water and salt to the reservoir.

RESERVOIR ANALYSIS

Historically, management of reservoir systems has generally had the primary, and sometimes the sole objective, of maintenance of water supply to achieve one or more demand targets. However, more recently reservoirs have become multi-purpose units, e.g., being used for flood control, irrigation water supply and hydro-electric generation simultaneously. This change in emphasis has required the application of multi-objective analysis to determine how to operate the system so as to best meet the often conflicting demands. With the new emphasis on environmental issues, maintenance of water quality in the reservoir itself and in the releases from the reservoir has also assumed greater importance in the operation of reservoirs, adding further to the multi-objective nature of the reservoir management problem. As noted earlier, the historical emphasis on meeting demands in reservoir operation has been based on meeting supply demand targets. In this kind of planning, maximising reliability or minimising risk of failure also became another major objective or issue of concern.

These complexities in the operation of a multi-purpose reservoir have increasingly required the application of models to develop optimal operating procedures which meet demands while simultaneously also meeting other requirements such as maintenance of water quality. These reservoir operation models must also be formulated to account for hydrological uncertainty in the inputs in order to produce realistic results.

A considerable amount of work on the development and application of models for the optimal operation of reservoirs has been done by a number of researchers. A good review by Yeh (1985) cites some 224 references related to models for reservoir management and operation. Deterministic models based on average or mean value of inputs, for example inflows, have usually been found to be optimistic (Nemhauser, 1966) with system benefits being overestimated and costs and losses underestimated. Furthermore, the results of such deterministic models are based only on the expected value of each variable. Hence, even for the preliminary identification of efficient project design, and operating policies prior to a detailed simulation study, deterministic models are of limited value. These limitations of deterministic planning models resulted in the development of stochastic programming methods able to account for many of the effects of uncertainties, such as hydrologic uncertainty, that characterise reservoir operation planning.

Hydrologic uncertainty inherent within the reservoir operation problem can be handled and incorporated into both simulation and optimisation models for planning and evaluation of reservoir operation systems. However, simulation models are not a very efficient means of choosing (from among the alternative plans, designs and operating policies), that policy which will maximise system performance indices. Optimisation models are theoretically a more efficient means of identifying 'optimal' solutions. From the range of optimisation techniques available, the stochastic dynamic programming algorithm is one of the most popular techniques for deriving the optimal operation policy of reservoir when stochastic inputs have to be considered.

However, despite extensive research effort, no single solution technique appears to be capable of comprehensively optimising the operation of a real multipurpose reservoir system which includes multiple uses, multiple time periods and stochastic inflows. Furthermore, very few studies of reservoir operation have included water quality considerations.

Previous work on the water quality aspects of reservoir operation has generally been oriented around the development and use of predictive models rather than operation research/systems analysis techniques. Most of these models have also been developed only to investigate rather than optimise water quality.

The development and application of a stochastic dynamic programming model for managing water quality, or more specifically salinity levels, in a reservoir and thereby in the releases from that reservoir while still meeting the demands for the water in the reservoir is reported in this study. The model is developed specifically for the Wellington Reservoir in Western Australia which is experiencing problems with salinity levels in the irrigation water supplied from the reservoir.

In this thesis, three variations of a stochastic reservoir operation model are proposed. Each incorporates hydrologic uncertainty, seasonal variability of inflows of water and salt, and mixing of the reservoir. Each solution is structured for solution by the technique of stochastic dynamic programming. All three model types have the following general characteristics,

1] A number of possible discrete inflows of water, inflows of salt and their associated probabilities, storage volumes, and salt concentrations can be defined in each time interval,

2] The conditions of a single layer non-stratified reservoir, double layer stratified reservoir, and the transition between these two conditions can be considered in the model,

3] Chance constraints can be imposed on the salt concentration in the reservoir.

CHAPTER - 2

PROBLEM DESCRIPTION:

The Wellington Reservoir is located approximately 160 km south of Perth in Western Australia as shown in Figure 2.1. The reservoir, which lies in the incised valley of the Collie River, has a capacity of a 186 gigalitres (GL). The surface water resources of the region of Western Australia in which the Wellington Reservoir lies are drawn mainly from the Darling range and flow down to the coast of the Indian Ocean (Imberger and Hebbert, 1980). It is now well recognised that agricultural development following the clearing of natural vegetation in the catchment of the Wellington Reservoir, has increased the salinity levels of the streams flowing through the area (Peck and Hurle, 1973). These increases in salinity level are attributed to the reduction in evapotranspiration that occurs after the clearing of the natural vegetation in the area. This reduction in evapotranspiration causes an increase in recharge to the ground water system. The increased groundwater recharge in turn raises the ground water table and changes the existing salt balance by flushing large quantities of salts, previously stored in the upper section of the soil profile, directly into the stream. Salt which has accumulated on the ground surface over the summer from evapo-transpiration processes from the raised groundwater table is also flushed into the streams by the winter rainfalls.

Figure 2.2 shows the salinity levels of the inflows corresponding to the cleared catchment area of the Wellington Reservoir. As shown in this Figure 2.2, with only 5% of the catchment cleared, average annual inflow salinities were below 300 mg/l total disolved solids (T.D.S). With 20% of the catchment cleared, in 1970 average inflow salinities were 600 mg/l. In 1977, with about 24% catchment cleared, average inflow salinities were 750 mg/l. The World Health Organisation recommends an allowable limit for the human consumption of 500 mg/l. In Australia the maximum limit recommended by the Australian Water Resource Council for domestic water supply is 1500 mg/l (Green, 1985). Despite this allowable level of 1500 mg/l it is highly desirable to maintain the salinity level below 1000 mg/l in water used for domestic purposes.

Considering the seriousness of the salinity problem in the region of the Wellington Reservoir, clearing was restricted by legislation to about 25% of the total catchment area.

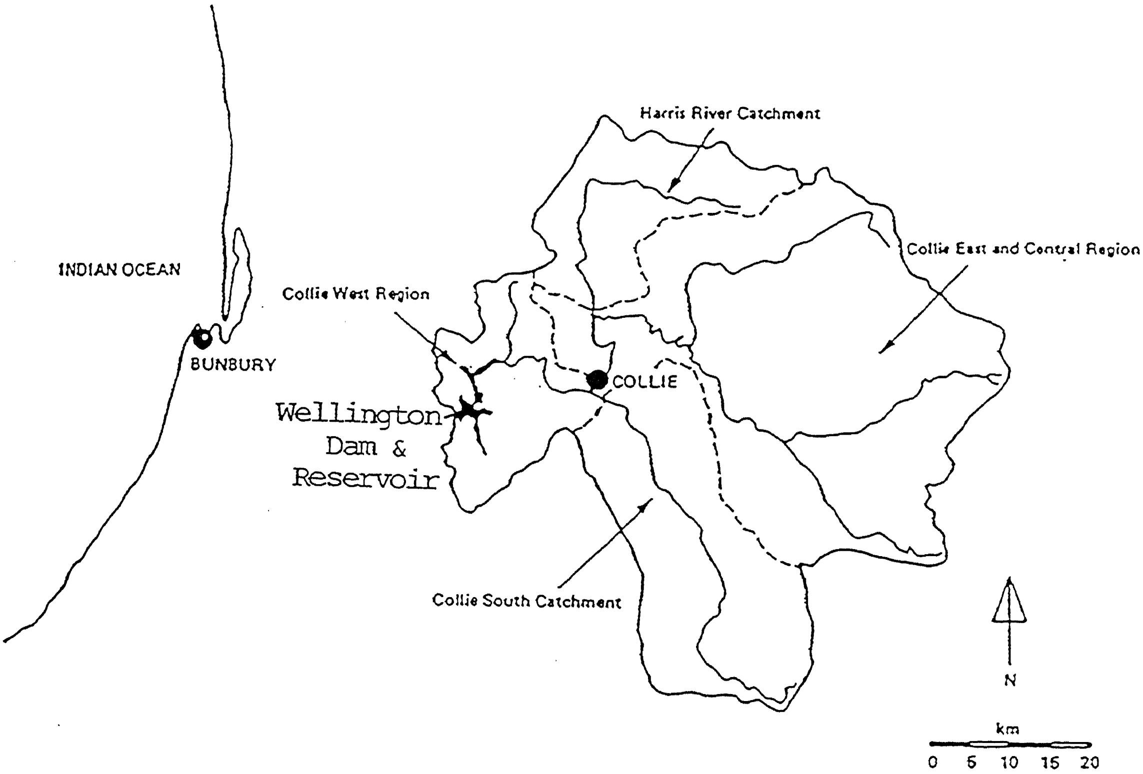


FIGURE 2.1

Location of Wellington Reservoir

(Source: Imberger and Hebbert, 1980)

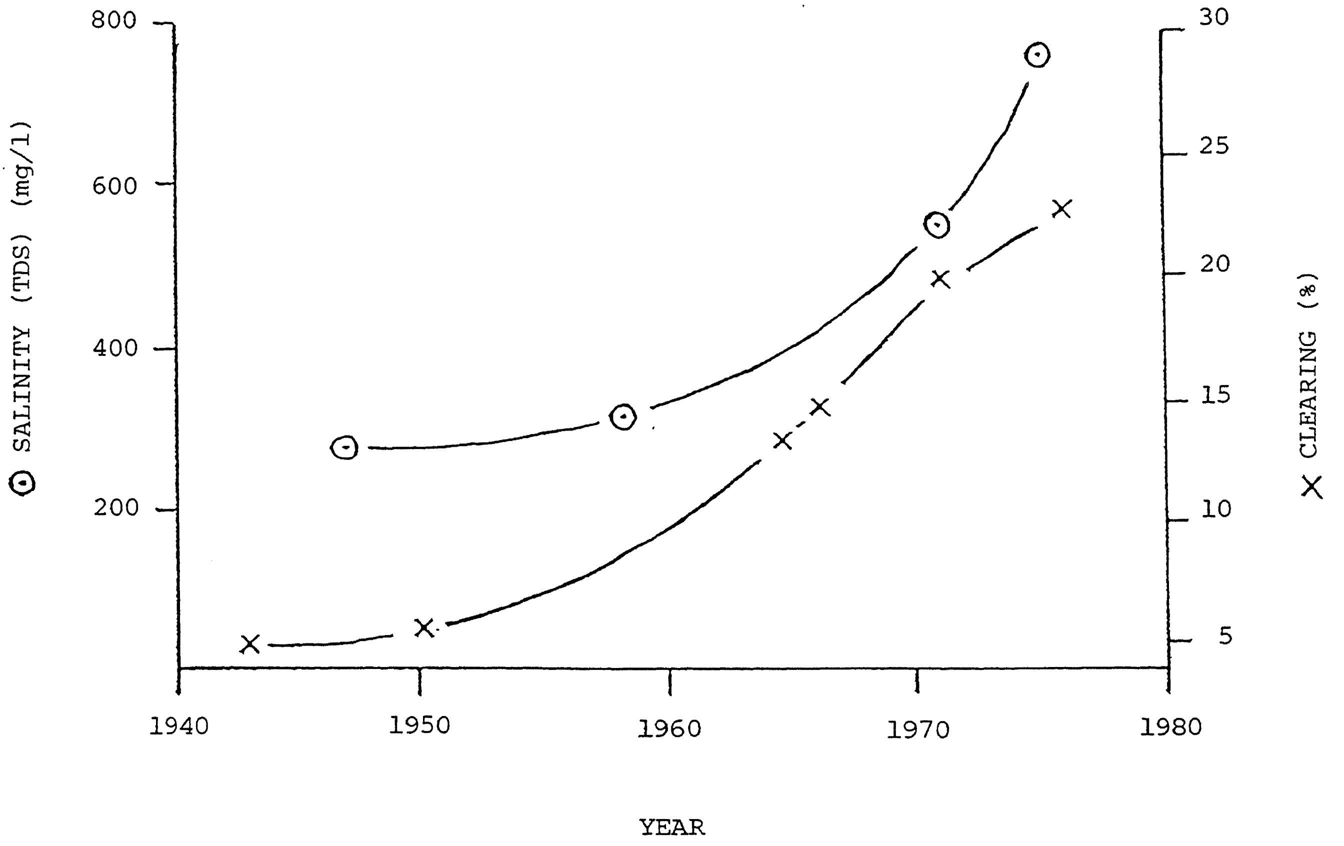


FIGURE 2.2 - Catchment clearing and mean annual inflow salinity to the Wellington Reservoir (Source: Loh and Hewer, 1977)

However, because of the slow response of the ground water system, the salinity levels in the inflows (reservoir) continued to rise. In 1977, Loh and Hewer (Loh and Hewer, 1977) felt that the full effect of previous and recent clearing was not yet felt.

Apart from the overall increases in stream salinity attributed to catchment clearing, the stream salinities and the volumes of inflow vary significantly between seasons and from year to year. Generally winter inflows are greater and carry higher salt concentrations and therefore have higher total salt loads than the summer inflows. This seasonal variation in salinity level of the inflows can be used to advantage in the operation of the reservoir for management of the salinity problem.

The first winter inflows carry surface salts accumulated over the previous summer. Later winter flood flows are generally fresher, as most surface salts have been flushed off the land by the first inflows. Low flows, however, which are in part due to ground water flows, may remain highly saline. The yearly fluctuation in salinity level in inflow can be noted in the following values. The high annual inflows of 1974 averaged only 325 mg/l while the inflows of 1975 averaged 860 mg/l T.D.S. (Imberger and Hebbert, 1980).

This variation in salt concentration of the inflows between the summer and winter months can be exploited to manage the salinity level in the reservoir in the following manner. The colder and highly saline winter inflow is more dense than the water remaining in the reservoir from the previous summer. This dense saline cold water therefore flows into the bottom of the reservoir as a cold saline wedge, resulting in the development of a strong vertical stratification with a relatively less saline warmer upper layer called the epilimnion and a highly saline bottom layer called the hypolimnion. This bi-layer situation exists until early in the summer season when the reservoir turns over and is effectively mixed to a single-layer homogeneous reservoir.

The Wellington Reservoir itself has three outlets; a low level outlet at the bottom of the reservoir, a mid level off-take and the spillway. The low level outlet can be used in the winter to extract as much of the highly saline water as possible by selective withdrawal from the bottom layer before the reservoir turns over and is mixed. The removal of the saline water in the winter does, however, reduce the amount of water available to meet irrigation, domestic and municipal demands during the summer. On the other hand, while holding the saline water in the winter can be helpful in meeting demands in summer, it increases the amount of salt in water released during the summer. Extending the policy of not releasing saline water in the winter months will then result in the water in the reservoir becoming progressively more saline with corresponding direct and indirect 'costs' for irrigation and domestic uses.

The problem in the operation of this reservoir is therefore, how much saline water should be removed from the low level off-take in winter months so that the total salt in the reservoir is reduced before the reservoir is mixed, while still maintaining sufficient water to meet irrigation, municipal and domestic demands in the irrigation season. Since saline inflow generally occurs in the winter months, the question arises whether this saline water in the reservoir should a) be released to keep the salinity level of the reservoir down, or b) be held back, in spite of its high salinity, in order to provide sufficient water for the summer to meet the high irrigation demands occurring in that season.

A further issue complicating the reservoir operation is the problem of predicting not just the inflow over a year but also the salt loads imposed by these inflows. There is no identifiable fixed relation between salt and water inflows. Although inflow of salt is related to the inflow of water, high salt inflows do not necessarily coincide with high inflow volumes. As noted previously, small inflow volumes occurring early in the winter may have relatively high salt concentrations, and later, high inflow volumes to the reservoir may contain lower salt concentrations with a correspondingly reduced salt load. Thus it appears salt and water inflows are somewhat independent, and the whole process of salt and water inflow is somewhat stochastic in nature.

CHAPTER - 3

LITERATURE REVIEW:

During the last twenty years, one of the most important advances made in the field of water resource engineering has been the application of optimisation techniques to the planning, design and management of complex multipurpose reservoir systems. The problem being addressed in this thesis, namely, management of a salinity affected reservoir, fits into this category. As dynamic programming (DP) is the solution chosen in this study, only optimisation/system analysis literature related to the DP approach is reviewed in detail.

DYNAMIC PROGRAMMING (DP):

Dorfman (1962), Hall and Shephard (1967), and Becker and Yeh (1974) proposed linear programming (LP) techniques for the reservoir operation problem (for quantity aspects of reservoir operator). Manne (1962) introduced the application of LP for Markov process optimisation with a hypothetical single reservoir example. However, a review of the literature over the last two decades reveals that, in spite of numerous attempts to apply optimisation techniques such as linear programming (LP) and non-linear programming (NLP), dynamic programming appears to be the most popular and effective optimisation technique for reservoir operation. One reason for this popularity is that non-linear, discrete and stochastic features can be easily incorporated into a DP formulation. An indication of the dominance of dynamic programming is that Yeh (1985) authored a complete paper on the role of dynamic programming in reservoir operation.

Dynamic Programming, a method formulated initially largely by Bellman (1957), for whom "Bellman's Principle of Optimality" is named, is a procedure for optimising a multistage decision process. The approach is used extensively in the optimisation of all types of water resource systems (Buras,1966). It has the important characteristic of being able to effectively decompose highly complex problems, with a large number of variables, into a series of smaller, less complex sub-problems which are able to be solved sequentially. In this context, the key feature of DP applications is that the solution can usually be identified as a serial, or progressive, directed network for an operation or planning problem (Hastings,1973).

It is the ability of dynamic programming to handle problems with a sequential structure, e.g., monthly operation of a reservoir, that makes it particularly appropriate in the problem of reservoir operation. The first applications of dynamic programming to reservoir operation used conventional discrete dynamic programming with deterministic inflow data, e.g., Little (1955), Young (1967), and Hall et al. (1968). These models were generally single-state variable techniques with volume of storage being the most common, and in most cases, the only state variable.

To handle situations requiring more than one state variable, the technique of incremental dynamic programming with successive approximation was used by Larson (1968) in conjunction with Bellman's concept of successive approximations which decomposes an original multiple state variable problem into a series of optimisation problems. The two approaches are combined in such a manner that the sequence of optimisations over the sub-problems converges to the solution of the original problem. Trott and Yeh (1973) and Giles and Wunderlick (1981) used this technique for problems involving multiple reservoirs.

For the purpose of obtaining good convergence, Hall et al. (1969) suggested two procedures for defining parameters of the state variables. The first was to keep the parameters small but constant throughout the iterations. The second was to reduce the increments as the iteration proceeded. However, Turgeon (1982) has demonstrated that incremental dynamic programming may converge to a non-optimal solution if the same state increment is used for each stage.

STOCHASTIC DYNAMIC PROGRAMMING (SDP):

With the exception of Turgeon (1982), all the procedures discussed above used deterministic estimates of inflows. In an attempt to recognise the true probabilistic nature of the hydrologic inputs such as inflows, stochastic dynamic programming was introduced to the problem by such researchers as Butcher (1971), Torabi and Mobasheri (1973) and Dudley and Burt (1973).

Much of the work on the application of stochastic dynamic programming to reservoir operation is based upon early developments by Howard (1960), who introduced the concept of the returns related to the transition matrix into a Markov process. In a multistage Markovian model, the objective is generally to maximise the expected return.

The studies by Butcher (1971) and Torabi and Mobasheri (1973) used a first order Markov process to predict the probability of particular flows in an upcoming month, given an observed flow in the current (or depending on the point of view, the previous) month. Arunkumar and Yeh (1973) used the SDP approach to maximise the firm power output in reservoir operation, using a penalty function for not meeting the specified firm power demand. Their study used the decomposition approach suggested by Ross (1970) for a parallel two-reservoir system.

An operating model developed by Loucks et al. (1981) also used an SDP algorithm for reservoir operation. At each stage or time period in that model, the optimal release, or equivalently the final storage volume, depends on the two state variables, initial storage volume and the most recently observed inflow. The objective function in this case is to maximise the expected performance of the complete system. This maximisation is performed by maximising, at each time period, the expected performance associated with an initial storage and inflow observed in the previous time period. The decision used to maximise returns is the amount of water to release in each time period. As the recursive equations in the Loucks et al. (1981) approach are solved for each period in successive years, if the stochastic process is stationary, the policy defined in each period will eventually repeat in successive years. When this condition is satisfied, and when the expected annual performance is constant for all states and all periods within a year, the policy reaches what is termed as a steady-state condition. This steady-state condition is attained only if the transition probabilities themselves are stationary on an annual basis, e.g., if they do not change from year to year. The probability distributions of releases and storage in each time interval can then be defined at this steady-state condition. The model has a number of other attributes useful for the proposed salinity management model and is described in more detail in the following chapter.

Stedinger et al. (1984) developed a stochastic dynamic programming model for reservoir operation optimisation by employing the best forecast of the current period's inflow instead of the preceding period's inflow to define a reservoir release policy. The steady-state reservoir policies developed by the modification resulted in a substantial improvement in simulated reservoir operations.

Turgeon (1981) proposed a SDP model using the concept of successive approximation for the optimisation of the weekly operating policy of a multi-reservoir hydroelectric system. Goulter and Tai (1985) (1987) developed an SDP model for the operation of a serial two-reservoir hydroelectric system, and identified the practical considerations and implications of the use of SDP. Other applications of SDP to reservoir operation have been reported by Yarkowitz (1982), Loaiciga and Marino (1986), Bogardi et al. (1990), Paudyal and Shahi (1990), and Eiger and Shamir (1991). Most recently, Yeh et al. (1991) also used a SDP model for optimisation of a multi-reservoir system.

CHANCE-CONSTRAINED DYNAMIC PROGRAMMING :

Another stage in development of dynamic programming for reservoir operation, taken in parallel to the development of stochastic dynamic programming, was the introduction of chance-constrained dynamic programming. Chance-constraints were first proposed by Charnes et al. (1958), for general mathematical programming problems. Chance-constraints are applied in optimisation procedures because they admit the variation of random data and permit constraint violations up to specified probability limits.

Chance-constrained models for reservoir operation applications were first developed by Revelle et al. (1969), followed by many others, such as Eisel (1972) and Loucks and Dorfman (1975). All developed a linear decision rule (LDR) for the use of chance-constrained linear programming as a practical means of obtaining the simultaneous optimum solution for design and operation of a reservoir. Sneidovich (1980), however, noted that the LDR model proposed by Eisel (1972) performed poorly.

Askew (1974a) investigated probabilistic DP models incorporating reliability constraints. He recognised that, in previous stochastic formulations, there was no direct control over the probability of failure of the reservoir system being modelled. Through use of penalty functions, a chance-constrained approach which helped in defining a more appropriate optimum release policy was then developed. Sneidovich and Davis (1975) subsequently introduced additional system variables to the approach. Takeuchi (1986) also developed a chance-constrained model for real-time reservoir operation using drought duration curves.

RELIABILITY PROGRAMMING IN RESERVOIR MANAGEMENT:

Reliability and chance-constraints were used by Askew (1974b) to derive the reservoir operating rules in dynamic programming applications. However, it is not always necessary to predetermine a level of reliability in reservoir operations. In some cases reliability may be incorporated as a variable and optimised through reliability programming. ReVelle and Kirby (1970) first suggested reliability programming which was subsequently used by Colorni and Fronza (1976) and Moy et al. (1986) in various reservoir operation models. Simonovic and Marino (1980) examined reliability programming in reservoir management using constraints on reliability (probability) of maximum and minimum reservoir volume levels and measures for flood risk and drought risk respectively.

It should be noted that the above discussion was focussed on reservoir models whose primary concerns or objectives were related to returns arising from the quantity of water supplied rather than the quality of that water.

The work proposed in this thesis is related to both quality and quantity of water. Work on managing the reservoir to improve the quality of the water in the reservoir and in the reservoir releases is, however, far less common than that on optimising reservoir performance for the objectives related primarily to quantity of water supplied.

WATER QUALITY MODELS:

A number of models have been constructed for the simulation of water quality in lakes. One of the more significant of the early studies was the review and subsequent development of a comprehensive formulation of heat exchange processes at the air-water interface of reservoirs performed by Wunderlich et al. ("Tennessee Valley Authority", 1972). In that study Wunderlich et al. used the Wunderlich - Gras formulation to develop a temperature model for streams and reservoirs, (California Department of Fish and Game, 1967). Later Chen et al. (1975) extended the approach by including a wide range of water quality state variables.

Markofsky and Harleman (1973) developed a one dimensional temperature model for reservoirs and a DO-BOD model for impoundments was subsequently produced. These models use the one dimensional slab model first proposed by Raphael (1962) as a basis for the hydro-dynamic computations. Chen and Orlob (1975) developed a lake ecologic one-dimensional model LAKECO, which was incorporated into a comprehensive water quality model for river-reservoir systems.

Volleweider and Dillon (1974) discussed the management of phosphorous in a reservoir through the use of a lake process model. O'Connor and Mueller (1970) examined the management of chlorine in the reservoir through the same lake process model. Baca et al. (1967) developed a generalised water quality model for eutrophic lakes and reservoirs while Snodgrass and O'Melia (1975) developed a model in which the management of phosphorus in stratified and non-stratified reservoirs was considered. More recently Patterson et al. (1984) examined the classification and dynamic simulation of the vertical density structure of lakes.

Gillard (1984) used the concept of multilevel selective withdrawal to manage dissolved oxygen levels in a reservoir. A dissolved oxygen model described by Martin et al. (1985) was also placed in the context of management of the water quality in the reservoir. In more recent work, Hookey and Loh (1985) considered the hydrologic simulation of the mixing process in the Wellington reservoir and thereby examined the salinity of water supply of the Harris - Wellington system.

In terms of optimisation models for managing the water quality in reservoirs, Loucks et al. (1967) and Dorfman et al. (1972) used linear programming. Fontaine et al. (1981)

examined the issue of water quality of release through the development of an optimisation-simulation approach for the optimum control of the temperature of release from a reservoir. While the approach only has a single objective, namely control of temperature of release, it is important in that it exploits the strengths of simulation and optimisation techniques in the development of optimal operating strategies for water quality management. Green (1985) also reported on the application of an integration of simulation and optimisation techniques for the problem of managing the salinity in the Wellington Reservoir.

A comprehensive review of models for streams, lakes, and reservoirs was sponsored by the International Institute for Applied Systems Analysis (IIASA) in the early 1980s. The review was published as a part of IIASA's State of the Art Series (Orlob, 1984).

The above reservoir operation models were primarily concerned with the quality of the water in the reservoir with relatively little concern for joint consideration of the both quality and quantity aspect of the reservoir operation. Dandy and Crawley (1990) developed a linear programming based optimisation model which considered both quality and quantity aspects of reservoir operation to define an operating policy for the Adelaide headworks system. However practical use of the model in the Adelaide situation appears to be hampered by a relatively poor ability to forecast catchment inflow and system demands.

In spite of this degree of research effort, there appears to be no single, comprehensive, solution strategy capable of optimising the operation of a multipurpose reservoir system in which both water quality and water quantity issues are objectives. This statement also holds true for even the specific case of a single salinity affected reservoir such as Wellington reservoir in Western Australia which is the focus of this study. The following section will discuss the work related to understanding and modelling the salinity conditions in that reservoir and previous attempts on developing optimisation models for management of the salinity problem.

PREVIOUS RESEARCH ON THE WELLINGTON RESERVOIR:

Loh and Hewer (1977) examined salinity and flow conditions in the catchment of Wellington reservoir system. In measuring the effect of catchment clearance on the increase of salinity in the inflows to the reservoir, Loh and Hewer (1977) noted that not all inflow is completely mixed with the water in the reservoir. However, in the simulation model used in that study to calculate salinity of the reservoir, the summer mixing of the winter stratified reservoir is not considered in a realistic fashion.

Imberger and Patterson (1981) proposed the dynamic reservoir simulation model known as DYRESM. The DYRESM model is one dimensional in nature but can provide very useful predictions of vertical temperature and salinity profiles. As such, it can also predict temperature and salinity conditions for withdrawals from the different levels of the reservoir. The model is based on a simple variable grid with spatial and temporal resolution being determined by the length and time scale of the process being simulated. The model has been applied to the Wellington reservoir in Western Australia. Based on the reported applications, DYRESM appears to be a good base for water quality modelling and its relatively simple computational basis helps ensure economic operation.

Patterson et al. (1977) have also monitored salinity and temperature profiles of the reservoir. These measurements were then used with the physically based mathematical model (DYRESM) for an understanding of the internal dynamics of the reservoir. In their subsequent work on the simulation of the Wellington reservoir, Patterson et al. (1978a) applied DYRESM specifically to evaluate the benefit of winter scour policies on long term reservoir salinities. Their approach exploited the ability of DYRESM to recognise the two different layers of the reservoir that occur as a result of "winter" stratification in which colder inflows, because of their high densities arising from lower temperature and high salinities, flow to the bottom of the reservoir and form a separate 'lower' layer. This layer has both a different temperature and salinity from the top layer of the reservoir which is derived from the water remaining in the reservoir after the summer irrigation season.

In a subsequent paper on the management of the same reservoir, Patterson et al. (1978b) investigated and applied a number of strategies for the management of salinity in the Wellington reservoir. The strategies included scouring of excess high salinity water from the bottom of winter stratified reservoir via an off-take near the base of the reservoir wall, the combining of midlevel and base off-take supply for irrigation and diversion of the most saline flows.

Patterson et al. (1978a), Imberger and Hebbert (1980) and Imberger (1981) examined the salinity of the release water from the Wellington reservoir as well as the salinity level in the reservoir itself. Their approach, while not being developed in a pure multi-objective context, did in fact consider the dual objectives of maximising the supply from the reservoir and maximising the water quality in the reservoir itself and in the release from the reservoir.

Although all this attention has been given to the salinity problem of Wellington Reservoir, management of the salinity problem in the Wellington reservoir, is not yet solved. The following chapters describe the development and application of a new approach to address management of this salinity problem.

CHAPTER - 4

MODEL DEVELOPMENT:

4.1

GENERAL DESCRIPTION OF DYNAMIC PROGRAMMING:

Before discussing the application of stochastic dynamic programming to the problem of salinity management in the Wellington reservoir, the dynamic programming approach itself will be briefly summarised. Dynamic programming is an optimisation procedure that is particularly applicable to problems requiring solution of a sequence of interrelated decisions such as monthly releases from a reservoir. Each decision transforms the current situation of the system into a new situation. A sequence of decisions, such as monthly reservoir releases, in turn yields a sequence of situations or states of the system, e.g., volumes of water remaining in a reservoir over a sequence of months.

The dynamic programming approach seeks to identify the sequence of decisions that provides the optimal (maximum or minimum depending on the problem) sum (or in some cases, product) of the values of individual decisions for each of the possible sequential conditions or states of the system. From this complete set of decision sequences the optimal sequence for the system as a whole is identified. Thus, a first step in the dynamic programming approach is to structure the problem as a multi-stage decision-making procedure. In the case of reservoir operation, this multi-stage decision making is a multi-period release problem.

Stages in the dynamic programming context are the intervals or points in the sequence of time, or space, as appropriate at which the decisions are applied to transfer the system from one state to the next. The stages for the dynamic program in the reservoir problem are time periods such as months or weeks of the year.

States in the dynamic programming context define the status or condition of the system of a particular stage, e.g., storage in the reservoir at the beginning and end of the month. Decision variables are those variables which can be directly manipulated or controlled at each stage in the system. For a reservoir operation problem the decisions might be the amounts to release from the reservoir in a particular time period or stage.

The basic principle behind dynamic programming is the framing of a sequential or multi-stage decision process containing many interdependent variables and converting it into a series of single stage problems, each containing a few variables. The conversion is based on, and must comply with, Bellman's principle of optimality for dynamic programming which states that:

> "An optimal set of decisions has the property that whatever the current decision, the remaining decisions must be optimal with respect to the outcome which results from the current decision".

As such, the net benefits resulting from each decision at each stage of the problem are dependent only on the stage and state at which the decision is being made and the decision itself, and are otherwise independent of any decisions made at previous stages. Thus, if the returns at any stage are dependent on the decisions made at another stage in a way not captured by the state variables, then dynamic programming is not an appropriate solution strategy.

The return at any stage in a dynamic program is the direct consequence or outcome of the decision made at that stage. As such, each decision at each stage must have a clearly identified consequence and direct contribution to the overall objective function that can be associated with it. For example, the release of water from a reservoir might represent the amount of water supplied to an irrigation district and the return might be the economic benefit arising from the supply of that amount of water. If this feature can not be assured dynamic programming is again an inappropriate model for the system.

As indicated in Chapter 2, given the uncertainties in the prediction of hydrologic parameters and other factors affecting the performance of water resource systems, deterministic planning models are often inadequate for modelling these systems. In deterministic models the return is given unambiguously by specifying values for the decision variables. There are no uncontrollable or random variables.

In contrast, models which address uncertainties explicitly contain random variables which can not be controlled and whose values are specified through probability distributions. Hence optimisation techniques applied to these types of problems require some form of description or representation of the various random processes.

A process in which either the transitions between conditions or states of the system, or the returns generated from decisions, are controlled by a probabilistic law is called a stochastic process. Transition from one state at a given stage to another state in the following stage in this situation depends not only on the current state of the system, i.e., the state for which the decision is being made, but also on random events, such as inflow to the reservoir, that fall outside the control of the decision maker.

All decision making in such an environment of uncertainty is based on the outcomes, e.g., storage in a reservoir at the end of month, of alternative actions, e.g., reservoir releases. These actions, such as releases of water, when combined with events, e.g., inflows, which occur with known probabilities, result in a range of possible states or conditions, each condition (storage) occurring with a probability derived from the probability of the event (inflow) which caused it.

A major attraction of dynamic programming is the almost trivial ease with which it can be adapted, both mathematically and computationally, to these stochastic situations. No other technique of operations research can make a comparable claim. As will be demonstrated later in this thesis, this ease of transfer to stochastic situations stems from the necessity in deterministic dynamic programming of solving, implicitly rather than explicitly, a large number of subproblems in order to solve a given problem. All that is required for extension of dynamic programming to the analysis of stochastic systems is that, when determining the return or value of the decisions, a range of possible outcomes arising from each decision must be evaluated with consideration of their associated probabilities of occurrence. This requirement is in contrast to deterministic dynamic programming where, because the outcome of each decision is certain, it is only necessary to evaluate one outcome, rather than a range of outcomes, for each decision.

Another important issue to note is that the purpose of optimisation in a stochastic environment is not to identify the single best sequence of decisions, and thereby series of states, even if a single well defined planning objective can be agreed upon. Rather the purpose of a model such as stochastic dynamic programming (SDP) is to develop an optimal policy (set of decisions) in which the optimal decision, i.e., the decision which gives the optimal return, is specified for each possible state or outcome in every stage.

This aspect of SDP is in contrast to the results of deterministic dynamic programming which give an explicit optimal sequence of decisions. In deterministic dynamic programming a single outcome is clearly and uniquely defined for each decision for each state in each stage. Thus, because each decision results in a known outcome, all that is needed to specify the optimal solution for the deterministic case is the single optimal decision for each stage, i.e., an optimal sequence of decisions.

Chance constraints can also be used in the framework of stochastic dynamic programming to identify and constrain the probability of either the state variables or other outcomes falling outside a specified range. In the proposed model for salinity management in a reservoir, chance constraints are used to identify and constrain the salt concentration in the reservoir. In this way the model is able to identify the operating (release) policy that ensures that the salt concentration in the reservoir will remain within specified limits with a given probability.

The underlying objective of the approach proposed in this study for management of the salinity in the Wellington Reservoir is minimisation of the salinity in the irrigation water released from the reservoir. However, in the actual formulation of the model, the mathematical objective function is minimisation of shortfall in meeting irrigation targets, while simultaneously constraining the salinity level in the reservoir. (Municipal and domestic demands are assumed to be mandatory and no deviation between demand and actual supply for these uses is permitted). In this way the salinity issues are addressed through compliance with chance constraints rather than by making decisions to achieve explicit minimum salt levels.

The reason behind the strategy for selection of this objective function and the placement of the salt objective in constraints lies in the need for separability. It is not possible to associate or isolate the specific contributions (returns) for any particular release decision to an objective of minimisation of the salinity in the reservoir or in irrigation release at any stage, as would be required if the minimisation of irrigation water salinity, or reservoir salinity just prior to irrigation season, was the formal mathematical objective. Thus, the salinity issue must be incorporated on a stage by stage basis in the constraints rather than in the objective function.

The multi-objective nature of the problem arising from the conflict between releasing winter inflows to minimise salinity in the reservoir and the need to store those winter inflows to meet summer irrigation demands is also able to be examined using the SDP model. The issue is discussed later in this thesis.

Although the proposed model is developed primarily for the Wellington Reservoir situation, it is formulated in such a way that, it is easily adapted to reservoir problems having the same or similar characteristics to those of the salinity affected Wellington Reservoir.

4.2

FORMULATION OF MODEL:

4.2.1

TRANSFORMATION EQUATIONS

Months of the year were chosen as stages in the model in order to reduce the computational requirements of the model as well as to reflect the planning level type of operating policy of the Wellington Reservoir. The decision variable is therefore the volume of water to release from the reservoir during each month. Although the model is formulated on a monthly basis there is no conceptual difficulty in going to smaller time intervals, such as weeks, if a greater level of operational precision is required and the input data are available for the smaller intervals. Use of smaller time intervals (stages) does, however, increase the computational burden.

As noted in Chapter 1, in the summer months the reservoir is in a single layer condition. In this non stratified single layer condition, the reservoir operating model has two state variables, one being the total volume of water in the reservoir with the other representing the salinity level or salt concentration in the reservoir. The single decision variable is release from the reservoir. In determining the impacts of a particular release decision the inflow volume occurring in a particular time period (month) is added to the initial storage volume. The release volume and any losses, for example due to evaporation, are then deducted from the total of the initial storage volume and inflow volume, to give the final total storage volume at the end of the time period (month). (This final storage volume is equivalent to the initial storage volume for the next time period).

Similarly salt load in the inflow is added to the initial salt load in the reservoir, and salt load released in the release volume is deducted to give the final total salt load at the end of the month. The total final salt load is then divided by total final storage volume to give the salt concentration in the reservoir at the end of month.

The transformation equation for transition from t month to month t+1 for the single layer reservoir can be expressed as follows.

Storage equation: $St+1 = St + It - Rt$ (1)

Salt load equation: $SAt+1 = SAt + ISt - Rt * SCt$ (2)

Salt concentration equation: $SCt+1 = SAt+1/St+1$ (3)

Where $St+1$ = final storage at the end of time period (month) t

St = initial storage volume at the beginning of the time period (month) t

SC_t = salt concentration at the beginning of time period t

I_t = inflow volume in the time period (month) t

R_t = release volume in the time period (month) t

SC_{t+1} = salt concentration at the end of time period (month) t

SA_t = salt load in the reservoir at the beginning of time period (month) t

IS_t = inflow of salt load in time period (month) t

In the winter months, the reservoir is a stratified double layer system with the stage to stage transition being one of double layer to double layer. In this stratified double layer condition the dynamic programming model has four state variables, namely volume of water and salt concentration in each of the upper and lower layers of the reservoir. Theoretically the model has two decision variables representing release from each of these two layers. However, in application, during the winter months the objective is to withdraw water, i.e., make releases, such that salinity in the reservoir is reduced by the greatest amount. In effect, this requirement restricts the release to come from the bottom, more saline, layer of the stratified reservoir. Hence other than the fixed, and essentially non variable, domestic and municipal withdrawals, releases from the top layer can be neglected and the process effectively reverts to a single decision problem. The storage and salt concentration in the bottom layer at the end of each period are calculated in the same manner as for storage and salt concentration for the single layer reservoir discussed above. The salt concentration in the top layer remains constant and the storage in the top layer is simply changed (reduced) by volume required for domestic and municipal uses.

The transformation equation for transformation (transition) from month t to month t+1 for the double layer reservoir can be expressed as follows.

For the reservoir lower layer

Storage equation:	$St+1 = St + It - Rt$	(4)
Salt load equation:	$SAt+1 = SAt + ISt - Rt^* Sct$	(5)
Salt concentration equation:	$SCt+1 = SAt+1/St+1$	(6)

where the terms in this case refer to lower layer conditions rather than overall reservoir condition in the single layer condition.

For the reservoir upper layer

Storage equation:	$SUt+1 = SUt - Rut$	(7)
Salt load equation:	$SAUt+1 = SAUt - RUt*SCUt$	(8)
Salt concentration equation:	$SCUt+1 = SAUt+1 / Sut+1$	(9)

where SUt = initial upper layer storage at beginning of time period (month) t

SAUt = initial upper layer salt load at beginning of time period (month) t

SCUt = initial upper layer salt concentration at beginning of time period (month) t.

RUt = release volume from the upper layer in the time period (month) t.

= mandatory domestic and municipal releases.

All other variables as defined previously.

At the beginning of the winter months, the reservoir changes from a single layer non-stratified reservoir to the double layer stratified reservoir. At the beginning of the month of the year in which the stratification first occurs, the reservoir operating model has two state variables consistent with the single layer reservoir model. At the end of the month it has four state variables consistent with the double layer reservoir model. Modelling of the transition between the non-stratified single layer reservoir and final stratified double layer winter reservoir can be achieved in the following manner. The salt concentration and storage volume of the single layer non stratified reservoir become the salt concentration and storage volume of the top layer of the double layer stratified winter reservoir. Recall that inflow of water and salt during winter months contributes solely to the salt concentration and storage of the lower layer of stratified reservoir. Hence the salt concentration and volume in the lower layer in this transition month are those associated with the inflow during the month. Mathematically the process for the lower layer of the reservoir can be written as follows.

$$St+1 = It - Rt \tag{10}$$

$$SAt+1 = SAt + ISt - Rt * SCt \tag{11}$$

$$SCt = SAt+1 / St+1 \tag{12}$$

where SAt = 0

For the upper layer of the reservoir on the other hand the transition is written simply

$$SUt+1 = SUt - RUt \tag{13}$$

$$SAUt+1 = SAUt - RUt * SCUt \tag{14}$$

$$SCUt = SAUt+1/SUt+1 \tag{15}$$

At the beginning of the summer months the reservoir mixes throughout its depth, resulting in a transition from a stratified double layer to a single layer essentially non stratified condition, consistent with the summer month conditions described previously. Modelling of this transition between a stratified double layer winter reservoir and non stratified single layer reservoir can be achieved in the following manner. The salt concentration of each layer is multiplied by the volume of the water in that layer to give the total salt content. The volumes of water in each layer are then added to give the total volume of the non stratified reservoir. This volume becomes that associated with the state variable for storage volume for the single layer reservoir occurring at the end of the month. The total salt is divided by this total volume of water to calculate the new salt concentration of the single layer summer reservoir.

Mathematically this transition can be written,

$$St+1 = SUt + St + It - Rt \tag{16}$$

$$SAt+1 = SAt + SAUt + ISt - (Rt * SCt) \tag{17}$$

$$SCt = SAt+1 / St+1 \tag{18}$$

As discussed in Chapter 1, inflow of salinity shows a seasonal variation. There does not appear to be a very strong relationship between inflow of water and the inflow of salt. Three possible relationships between inflow of water and inflow of salt have therefore been considered in this reservoir operating model and a different model has been developed for each possible relationship. The models based on each of these assumed relationships are described below.

4.2.2

GRAPHICAL REPRESENTATION:

SINGLE LAYER TO SINGLE LAYER COMPONENT:

In the summer months the reservoir remains a single layer non stratified reservoir. Hence the transition over the summer period is that of a single layer to single layer reservoir. The total storage volume of reservoir water is discretized into a number of storage levels to give the storage state variables in the dynamic program. Similarly the salt concentration of the reservoir is discretized into a number of salt concentration levels which act as the second set of state variable for the dynamic program. Each level of the storage state has the complete range of salt concentration states associated with it. In other words the salt concentration states at each stage are repeated for each of the potential storage levels at that stage.

A graphical depiction of the problem in the summer non-stratified single layer reservoir as it relates the dynamic programming formulation is shown in Figure 4.1. This figure shows how the states of storage and states of salt concentration at the beginning of each time period (month) are integrated in the formulation, and how the decision of what amount of the water to release from the reservoir in that period transforms the storage and salt concentration at the beginning of the period to the storage and salt concentration at the end of that period. (Recall that the storage and salt concentration at the end of period is the storage and salt concentration at the beginning of the next period.)

The operating policy for the reservoir specifies the reservoir release in a particular period as a function of initial (observed) storage volume and initial salt concentration in that period, and on the basis of known or estimated probability distributions of water (and salt) inflows in that time period.

As shown in Figure 4.1, for each stage or time period (month) each release decision results in a range of possible subsequent storage states each occurring with known probability. Each storage state has a range of salt concentration states associated with it

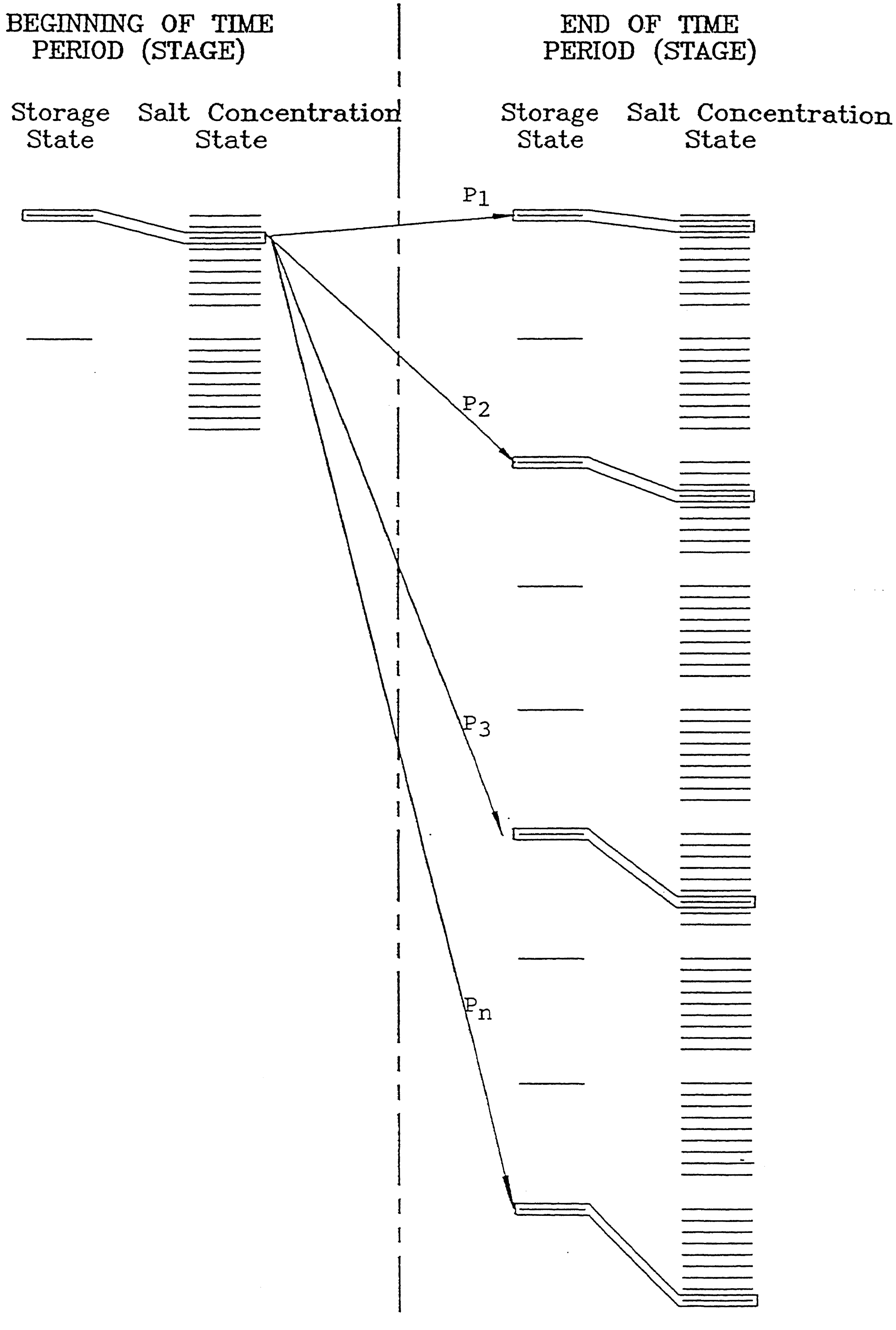


FIGURE 4.1 Single layer to single layer case

The expected return for a given release decision is then calculated by multiplying each sum of the immediate returns resulting from the release and the long range returns associated with the storage and salt concentration states occurring at the end of the stage as a result of the outcome of the decision, by the corresponding probabilities of the inflows that caused those outcomes and then adding the resulting values together.

The decision, or more precisely the optimal decision, for a given month is selected for each combination of level of storage and salt concentration at the beginning of a month, from the range of possible release decisions for that storage and salt concentration in that month.

All possible outcomes of storage and salt states for each stage resulting from release decisions, are also subjected to a number of constraints, e.g., minimum and maximum level of release, minimum and maximum level of storage, and maximum allowable salt concentration in the reservoir. More detailed definition of these constraints is given later in the section on chance constraints.

DOUBLE LAYER TO DOUBLE LAYER COMPONENT:

During the winter months the reservoir is in a double layer stratified reservoir condition. As noted earlier, the primary difference between the single layer to single layer model described above and this double layer to double layer model is that, in the double layer to double layer case, cold saline inflow goes to the bottom layer of the reservoir. In this condition, the reservoir remains in the double layer stratified condition with a less saline relatively warm upper layer and a more saline and cool lower layer.

As discussed earlier, the reservoir model in this case has the four state variables of storage and salt concentration in each layer. The storage volume in the lower layer of reservoir is discretized into a number of lower layer storage levels which act as the first set of storage state variables in the dynamic program. Similarly the storage volume in the upper layer of reservoir is also discretized into a number of upper layer storage levels which act as the second set of storage state variables for the dynamic program. The salt concentrations of the upper layer and lower layer of the reservoir are also discretized into a number of salt concentration states which act as the other two sets of state variables for the dynamic program.

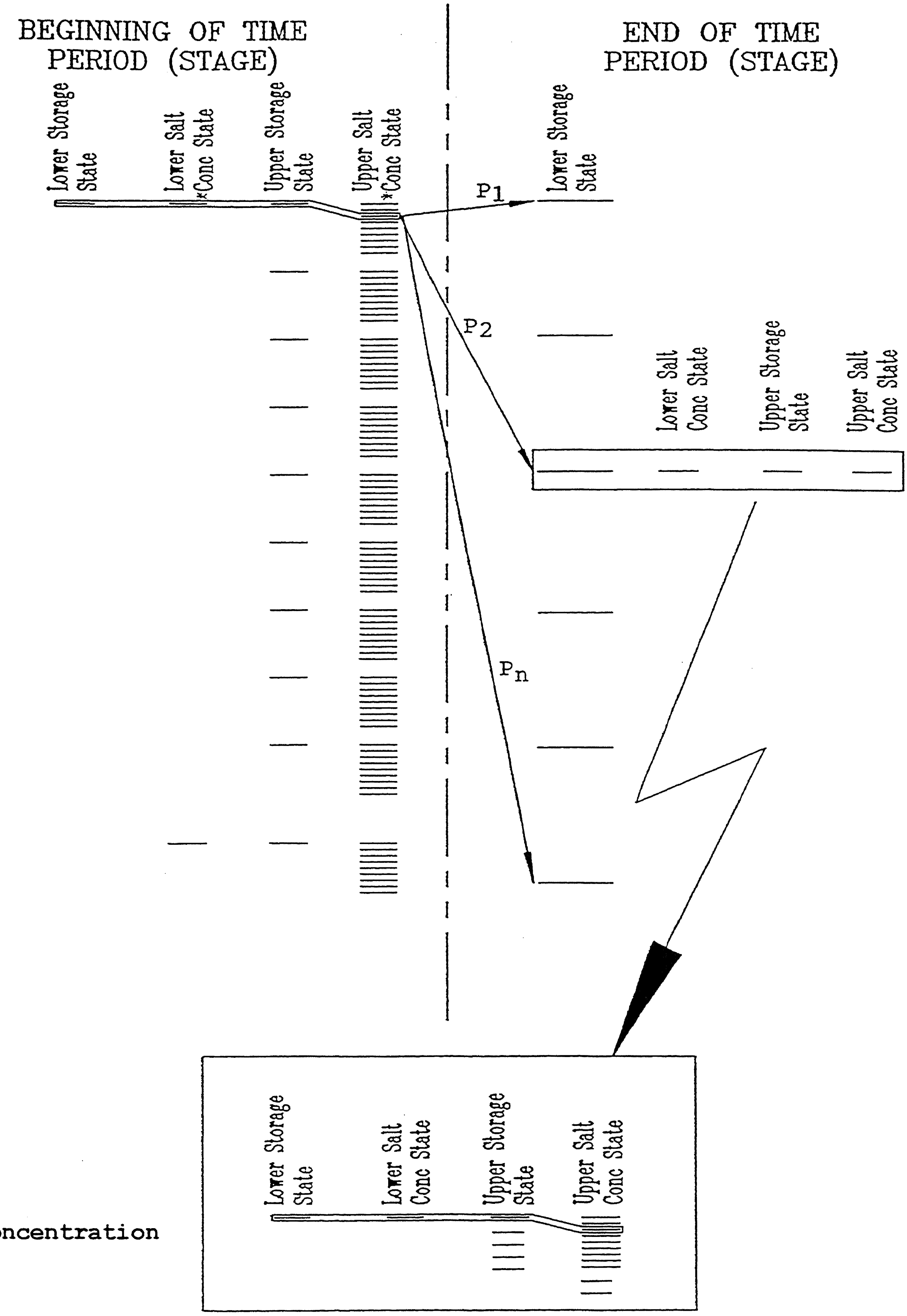
The decision to be made in the planning process for a particular time period for this case is what amount of water to release from the reservoir in that period. This release will be from the bottom layer. When this release is combined with the inflow to the lower layer, it will transform the storage and salt concentration in the lower layer at the beginning of the period to a new lower layer storage and salt concentration combination at the end of that period. The decision, or more precisely the optimal decision, for a given month is selected for each combination of level of storage and salt concentration in both the upper and lower layers of the reservoir at the beginning of a month, from the range of possible release decisions available in that month.

Although a withdrawal from the less saline top layer for salinity management purposes is unlikely, the storage in the top layer will change as the domestic and municipal demands are taken from this less saline layer. These withdrawals are relatively small compared to the bottom layer release for salinity control. Thus the storage in the top layer does not change very much in any given month or stage of the winter season. Furthermore the salt concentration in this upper layer does not change because there is no inflow of water or salt to the upper layer.

The return for a given release decision is then calculated by multiplying each sum of the immediate returns resulting from the release and the long range returns associated with the storage and salt concentration states occurring at the end of the stage as a result of the decision, by the probability of the inflows that caused those outcomes.

As with the single layer to single layer formulation the release decisions, and outcomes from these decisions for each stage are subjected to number of constraints, e.g., maximum and minimum values of release, maximum and minimum levels of total (sum of upper and lower layer) storage, and maximum allowable salt concentration in the reservoir. A more complete definition of the constraints used to identify the optimal policy is given later in the discussion of the chance constraints.

A graphical depiction of the planning operation problem in the winter stratified double layer reservoir is given in Figure 4.2. As shown in this figure, at the beginning and end of each stage or time period (month) there is a range of lower layer storage state values, each having a range of lower layer salinities, and upper layer storages and salinities associated with it



*Concentration

FIGURE 4.2 Double layer to double layer case

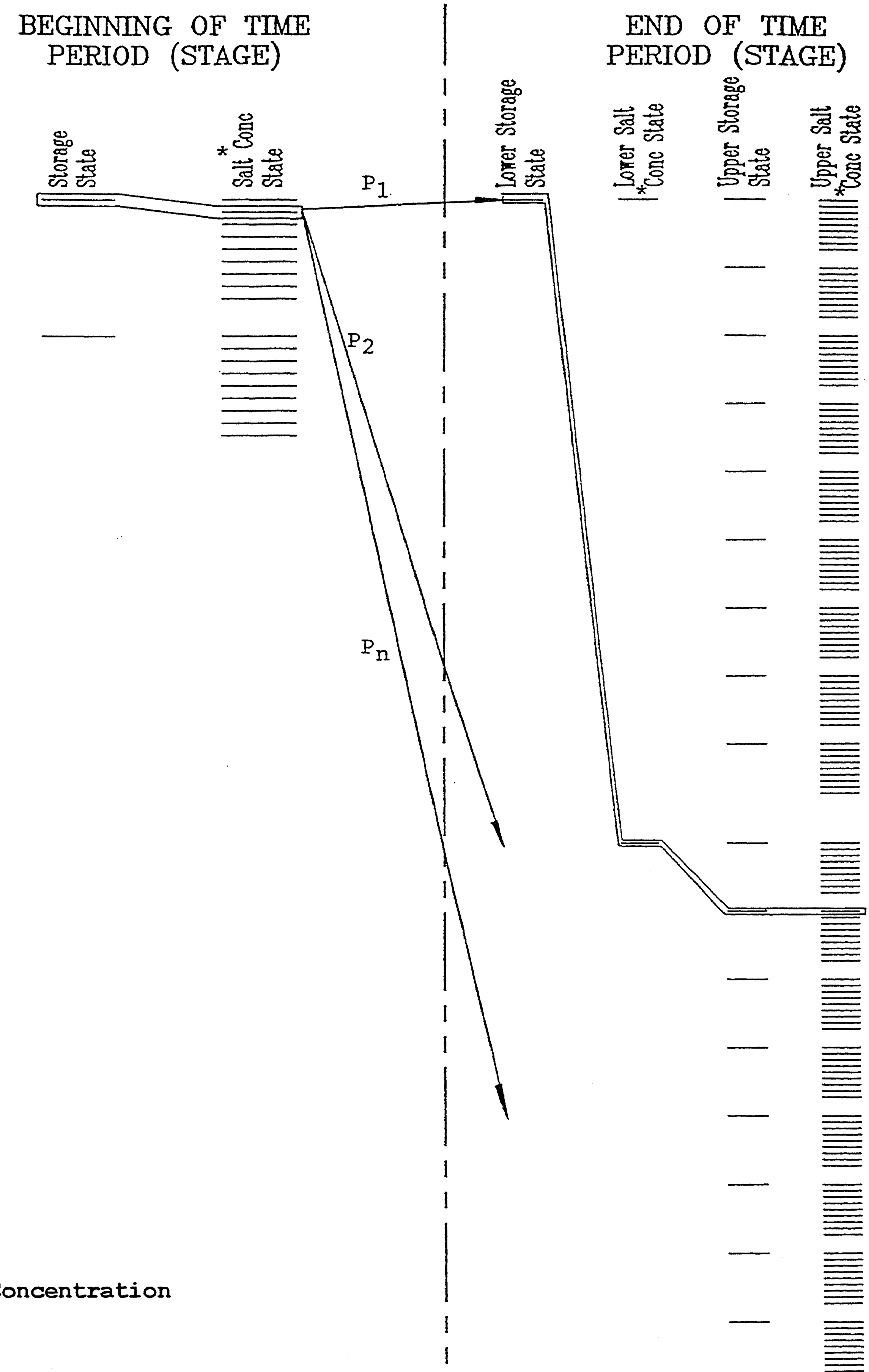
SINGLE LAYER TO DOUBLE LAYER COMPONENT :

At the beginning of the winter months the reservoir exists as a single layer, non-stratified, reservoir. In this condition, the reservoir model has two state variables. The total storage volume of the reservoir in this single layer condition is again discretized into a number of storage levels corresponding to storage states which act as the first set of state variables in the dynamic program. Similarly the salt concentration of the reservoir is discretized into a number of salt concentration states which act as the other set of state variables for the dynamic program.

As noted earlier the winter inflows are more saline, cooler and more dense than water already in the reservoir and therefore underflow the water in the reservoir to form a cold saline wedge in the bottom layer. The stage or time period in which the first winter inflow occurs is the stage in which the reservoir changes from a single layer condition to a double layer condition. Consequently with the first winter inflow, the reservoir changes from a single layer non-stratified reservoir to the stratified double layer winter reservoir condition. As such, the state variable situation at the beginning of the stage is that of a two state variable condition and at the end of the stage is that of a four state variable condition.

As in the double layer to double layer condition discussed earlier, the storage volume of the upper layer of the reservoir at the end of the stage is discretized into a number of upper layer storage states which act as state variables in the dynamic program. Similarly the storage volume of the lower layer of reservoir also acts as a state variable for the dynamic program. Salt concentrations in the upper layer and lower layer of the reservoir are the two other state variables for the dynamic program.

As described graphically in Figure 4.3 the transition from single to double layer reservoir can be modelled in the following manner. The storage and salt concentration of the single layer reservoir at the beginning of a particular time period (stage) become the storage volume and salt concentration for the upper layer of the stratified winter reservoir at the end of the time period (stage). The inflows of the water and salt in the time period contribute solely to the storage volume and salt concentration of the lower layer of the double layer reservoir. In this single layer to double layer case, the operating policy for the reservoir specifies the reservoir release in a particular period as a function of



*Concentration

FIGURE 4.3 Single layer to double layer case initial storage volume and initial salt concentration existing in a single layer reservoir at the beginning of that time period on the basis of the known or estimated probability distribution of inflow of water (and salt) in that period.

The decision to be made for a particular time period for this case is the amount of the volume of water to be released from the reservoir in that period. Note that, the true decision is again solely how much to release from the newly forming lower layer to reduce the salinity while maintaining sufficient water to meet the irrigation demands in the following summer. Release from the top layer (which is derived directly from the single layer condition existing at the beginning of the period) in this double layer condition is also again generally only the fixed domestic and environmental needs for the particular month.

The release decision results in a range of combinations of possible lower layer and upper layer storages and salt concentrations in the reservoir at the end of that time period. The possible lower layer storages and salt concentrations occur as a result of the range of possible water and salt inflows during that time period. Note that upper layer storage and salt concentration states at the stage are essentially defined by the single layer storage and salt concentration at the beginning of period because there is no inflow to that layer and only the relatively small mandatory domestic and municipal releases are withdrawn from the layer. The return for a given release decision is then calculated by multiplying each sum of the immediate returns resulting from the release and the long range returns associated with the storage and salt concentration states occurring at the end of the stage as a result of the release, by the probability of the inflows that caused those outcomes.

The decision, or more precisely the optimal decision, for a given month is selected for each combination of level of storage and salt concentration of the single layer reservoir at the beginning of a month, from the range of possible release decisions for that combination of storage and salt concentration in that month.

The decision and outcomes from that release decision for each stage are subjected to a number of constraints, e.g., minimum and maximum total (sum of upper and lower layer) level of storage, minimum and maximum level of release, and maximum allowable salt concentration in the reservoir. A more complete definition of the constraints used to identify the optimal policy is given in the later discussion of chance constraints.

DOUBLE LAYER TO SINGLE LAYER COMPONENT

In the beginning of the summer months the reservoir exists as double layer stratified reservoir. In this condition, the reservoir model has the four state variables of volume and salt concentration for each of the upper and lower layers of the reservoir. However, early in summer, the reservoir mixes throughout its depth and changes to a single non stratified reservoir. In this mixed condition, the reservoir model has only two state variables, namely, total storage volume of the reservoir, discretized into a number of storage levels corresponding to storage states, and salt concentration of the reservoir, also discretized into a number of salt concentration states.

A graphical depiction of the planning operation problem in the double layer to single layer reservoir transition as it relates to the dynamic programming formulation is shown in Figure 4.4. This figure shows how the states of upper and lower storage volume and salt concentration at the beginning of each time period (month) are integrated into the formulation and how the decision of amount of volume of water to release from the reservoir in that time period transforms the storages and salt concentrations of the upper and lower layers of the double layer reservoir at the beginning of the period to the storage and salt concentration of the single layer reservoir at the end of that period.

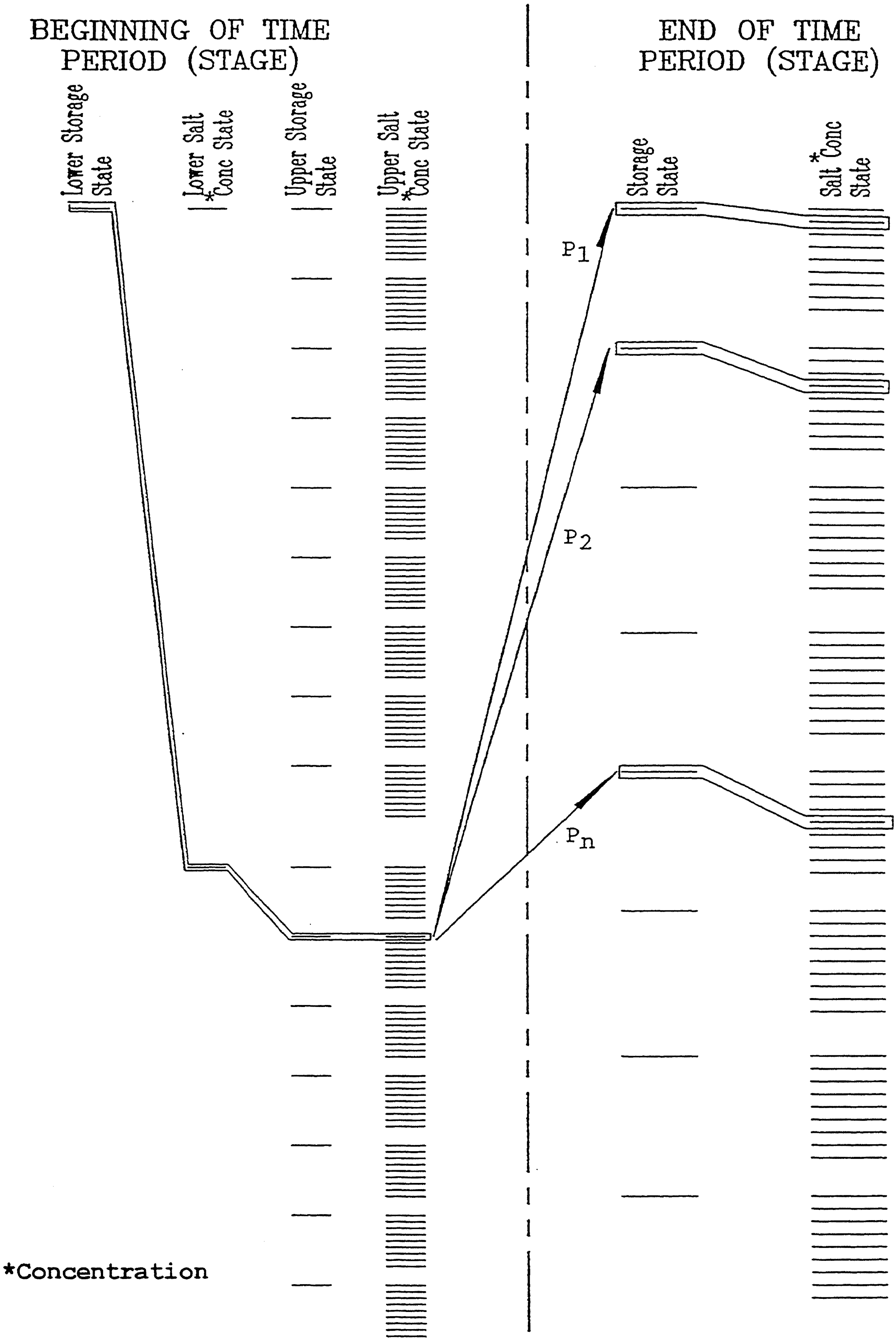


FIGURE 4.4 Double layer to single layer case

The return for a given release decision is then calculated by multiplying each sum of the immediate returns resulting from the release and the long range returns associated with the storage and salt concentration states occurring at the end of the stage as a result of the release, by the probability of the inflows that caused those outcomes. The decision, or more precisely the optimal decision, for a given month in this condition is selected for each of the potential existing levels of upper and lower storage and level of salt concentration at the beginning of the month, from the range of possible release decisions for that combination of storage and salt concentration in that month.

A more complete definition of the return function used to identify the optimal decision for each of these four situations is given later in this section.

4.3

RESERVOIR OPERATING MODEL

Since the model is a stochastic dynamic program, backward recursion, i.e., from the future backwards, is required in the solution process. Note that in terms of stages in this classical backward recursion dynamic program, time period t corresponds to stage n while time period t+1 corresponds to stage n-1 and time period t-1 to stage n+1. Thus terms n and t both refer to position within the recursive process. The use of both terms facilitates the tracing of the stage by stage movement of the dynamic program. The n term keeps the track of the actual computational position of the recursion while the t term keeps the track of the actual time period of the recursion and the stage by stage (month to month) variation of the transition probabilities. If the dynamic program is used only for the period of 1 year, then n=1 at t=12 and n=12 at t=1.

If the dynamic program is used for a period greater than one year as is necessary to get steady state results, t will continue to vary between 1 and 12 while n will trace the absolute position of the dynamic program through the N stages of analysis where N is the number of stages required to obtain steady state conditions.

4.3.1

RECURSIVE EQUATION AND OPTIMUM TOTAL RETURN:

The objective function of the model is to minimise the deviation of water supplied for irrigation in each time period from the target supply levels for irrigation in those time periods. Since the process is stochastic the formal mathematical objective of the system is minimisation of the expected deviations.

Let I_{it} be the ith discrete value of the range of random inflows in time period stage t. Let IS_{ct} be the c^{th} discrete value of the range of random inflows of salt in time period t.

In the single layer to single layer component of the reservoir model, let the discrete value of the reservoir storage volume and salt concentration states at the beginning of the time period t be denoted by S_{jt} and SC_{kt} respectively for interval j of the storage levels and a interval k of the salt concentration range. Let R_{jkt} be a decision associated with the single layer storage state j and salt concentration state k at the beginning of the time period t. Let the storage state and salt concentration states at the end of time period t, be denoted by S_{lt+1} and SC_{mt+1} respectively for intervals l and m of the storage and salt concentration state ranges respectively.

The immediate return derived as the deviation between actual release and demands at stage t, corresponding to a transition from single layer to single layer, for a particular decision R_{jkt} can be stated as

$$B_{jkt} = \left| R_{jkt} - T(t) \right| \tag{19}$$

where

B_{jkt} = immediate return resulting from a release R_{jkt}

R_{jkt} = release (decision D) for storage state j and salt concentration state k at the beginning of time period t.

T(t) = demand target for the time period month (t)

= irrigation demand plus the mandatory domestic and municipal releases in this period(month) t.

Note R_{jkt} must be greater than or equal to the municipal and environmental release in this time period.

The recursive equation at a given stage n or time period t for the single layer to single layer formulation can be written mathematically as

$$f_t^n(j,k) = \min_{D \varepsilon D_t}[B_{jkt} + \sum_{j=1}^{NS_{t+1=1}} \sum_{k=1}^{NSC_{t+1}} (P_{jklmt} * f_{t+1}^{n-1}(l,m))] \tag{20}$$

where

D = decision that causes release R_{jkt} in time period t

$\overline{D}_t$ = range of release decisions at stage t.

$f_{t+1}^{n-1}(l,m)$ = long term expected return at the beginning of time period t+1 associated with storage state 1 and salt concentration state m at the end of time period t

Ns_{t+1} = total number of storage states at the end of time period t, i.e. at beginning of time period t+1

NSC_{t+1} = total number of salt concentration states at the end of time period t, i.e., at the beginning of time period t+1

P_{jklmt} = probability of getting to storage state 1 and salt concentration state m at the end of time period t (beginning of time period t+1) given a storage state j and salt concentration state k at the beginning of time period t, and the decision option R_{jkt}.

In the double to double layer component of the reservoir model, let the discrete values of the lower layer reservoir storage volume and salt concentration states at the beginning of time period t be denoted by S_{jt} and SC_{kt} respectively for interval j of the storage levels and an interval k of salt concentration range. Let the discrete values of the upper layer reservoir storage volume and salt concentration states at the beginning of time period t be denoted by SU_{ut} and SCU_{vt} respectively for interval u of the storage levels and a interval v of salt concentration range. Let R_{jkuvt} be the release (decision D) associated with lower layer storage and salt concentration states j and k respectively, and upper layer storage and salt concentration states u and v respectively at the beginning of time period t.

In this double to double layer condition of the reservoir the objective of the model is again to minimise the expected present value of deviation between water demand and water actually supplied, given a lower layer storage level j, lower layer salt concentration level k, upper layer storage level u and upper layer salt concentration level v at the beginning of time period t, the range of possible inflows to the reservoir in time period t, and the range of possible releases. Demand targets for winter months are very small and correspond to the domestic, municipal and environmental demands. The top layer release is assumed equal to these domestic municipal and environmental demands for these months. Since the objective of the system is minimisation of the expected value of deviation between actual release and demand target. The immediate decision for a particular decision at this stage can be stated,

$$B_{jkuvt} = \left| R_{jkuvt} - T(t) \right| \tag{21}$$

where,

B_{jkuvt} = immediate return resulting from the lower layer release decision R_{jkuvt} in time period t

R_{jkuvt} = release (decision D) for lower layer storage state j, lower layer salt concentration state k, upper layer storage state u and upper layer salt concentration state v at the beginning of time period t

T(t) = target release for time period t. It is very small for these months, i.e., any release is the mandatory domestic municipal, and environmental requirement. Releases for the purpose of management of salinity in this period do not represent targets.

Recall also that the release from the upper layer is a known amount, i.e., it is not a decision, corresponding to the total mandatory domestic, municipal and environmental requirements.

The recursive equation at given stage n or time period t for the double layer to double layer formulation can be written mathematically as

$$f_t^n(j,k,u,v) = \min_{D\varepsilon \overline{D_t}} [B_{jkuvt} + \sum_{j=1}^{NS_{t+1}} \sum_{k=1}^{NSC_{t+1}} \sum_{u=1}^{NSU_{t+1}} \sum_{v=1}^{NSCU_{t+1}} (P_{jkuvlmyzt} * f_{t+1}^{n-1}(l,m,y,z))] \quad (22)$$

where,

$f_{t+1}^{n-1}(l,m,y,z)$ = long term expected return at the beginning of time period t+1 associated with lower layer storage level l, lower layer salt concentration level m, upper layer storage level y, and upper layer salt concentration level z at the end of time period t.

NSU_{t+1} = total number of upper layer storage states at the end of time period t, i.e., at the beginning of time period t+1

$NSCU_{t+1}$ = total number of the upper layer salt states at the end of time period t, i.e., at the beginning of time period t+1

$P_{jkuvlmyzt}$ = probability of getting to lower layer storage state l, lower layer salt concentration state m, upper layer storage state y, and upper layer salt concentration state z, at the end of stage (time period) t, given upper layer storage state j, lower layer salt concentration state k, upper layer storage state u, lower layer salt concentration state v at the beginning of stage (time period) t and the release decision R_{jkuvt}.

All other variables as described previously.

In the single to double layer condition of the reservoir, let the discrete values of the reservoir storage volume and salt concentration states of the single layer at the beginning of the time period t in which the transition from single to double condition occurs be denoted by S_{jt} and SC_{kt} respectively for interval j of the storage levels and interval k of salt concentration range. At the end of time period t, let the upper and lower layers of the storage states be denoted by SU_{vt} and S_{lt} for interval u of the upper layer and interval l of the lower layer storage states range. Similarly let the salt concentration for the upper and lower layers at the end of time period t be denoted by SCU_{vt} and SC_{mt} respectively for interval v of the upper layer and interval m of the lower layer salt concentration range.

Let R_{jkt} be the decision associated with the single layer storage state j and salt concentration state k at the beginning of time period t for this condition.

The demand target for these months is again very small with the top layer release being set equal to the total domestic, municipal and environmental demands. In this single layer to double layer condition of the reservoir the objective of the model remains the same, namely minimisation of the expected value of deviation between water demand supplied given lower layer storage and salt concentration levels j and k respectively, at the beginning of time period t, the range of possible inflows to the reservoir in time period t, and the range of possible releases from the lower layer. The immediate return for a particular decision at this stage can be stated,

$$B_{jkt} = \left| R_{jkt} - T(t) \right| \tag{23}$$

A mathematical description of the recursive equation for this situation is as follows

$$f_t^n(j,k) = \min_{D\varepsilon D_t}[B_{jkt} + \sum_{j=1}^{NS_{t+1}} \sum_{k=1}^{NSC_{t+1}} \sum_{u=1}^{NSU_{t+1}} \sum_{v=1}^{NSCU_{t+1}} (P_{jklmyzt} * f_{t+1}^{n-1}(1,m,y,z))] \tag{24}$$

where $P_{jklmyzt}$ = probability of getting to lower layer storage state l, lower layer salt concentration state m, upper layer storage state y, upper layer salt concentration state z at the end of stage (time period) t, given storage state j, salt concentration state k at the beginning at stage (time period) t and release decision R_{jkt}.

All other terms are as described previously.

In the double to single layer component of the reservoir model, let the discrete values of the reservoir storage volume and concentration states at the beginning of the time period (stage) t in which transition from double layer to single layer occurs, be denoted by S_{jt} and SC_{kt} respectively for interval j of the storage level and an interval k of salt concentration range of the lower layer. Similarly let the discrete values of the reservoir upper layer storage volume and salt concentration states be denoted by the S_{ut} and SC_{vt} respectively for interval u of the storage levels and interval v of the salt concentration levels. Define R_{jkuvt} as the decision associated with storage states j and u and salt concentration states k and v of the lower layer and upper layer respectively at the beginning of time period t.

In the double to single layer condition of the reservoir, the objective of the model is to minimise the expected value of deviation between water demand and water actually supplied given lower layer storage level j, lower layer salt concentration level k, upper layer storage level u and upper salt concentration level v at the beginning of time period t, the range of possible inflows to the reservoir in time period t, and the range of possible releases (decisions). The demand target for this month is assumed to be very small and equal to the total domestic, municipal and environmental demands. Since the objective of the system is minimisation of the expected deviation between actual release and demand, the immediate return for the beginning of the planning period t, for a particular decision of the stage, can be stated,

$$B_{jkuvt} = \left| R_{jkuvt} - T(t) \right| \tag{25}$$

with all variables as described previously.

A mathematical description of the recursive equation for this situation is as follows.

$$f_t^n(j,k,u,v) = \min_{D\varepsilon \bar{D}_t} [B_{jkuvt} + \sum_{j=1} \sum_{k=1} (P_{jkuvlmt} * f_{t+1}^{n-1}(l,m))] \tag{26}$$

where $P_{jkuvlmt}$ = probability of getting to storage state l, salt concentration state m, at the end of stage (time period) t given lower layer storage state j, lower layer salt concentration state k, upper layer storage state u, upper layer salt concentration state v, at the beginning of stage (time period) t and release decision R_{jkuvt}

with all other variables as described previously.

Sequential application of the four recursive equations described above in appropriate succession for a number of annual cycles, results in the situation where the operating policy begins to repeat itself on a yearly basis. The repeating policy is termed the steady state policy. This steady state policy is repeated provided the inflows and net benefit function in each time period do not change from year to year. The difference between the total expected return for any given combination of storage and salt concentrations in any time period of a year and the same combination of storage and salt concentrations in the same time period in the following year then becomes constant. This constant value is known as the annual expected 'gain' of the system and for the single layer reservoir is given by

$$f_t^{n+12}(l,m) - f_t^{n}(l,m) \tag{27}$$

and for double layer reservoir is given by

$$f_t^{n+12}(l,m,y,z) - f_t^{n}(l,m,y,z) \tag{28}$$

4.4

TRANSITION PROBABILITIES:

Case 1:

Probability of inflow of salt is totally dependent on the probability of inflow of water.

In the stochastic dynamic programming approach proposed above, in the single to single layer condition of the reservoir, the transition from an initial state combination, i.e., initial combination of storage level j and salt concentration level k, in one time period to a new state combination, i.e., final combination of storage level l and salt concentration level m, in the next time period, depends on the inflow of water and its associated salt load. In this case the probability of the salt load is assumed to be equal the probability of inflow of water with which it was associated. The probability of transition from initial state combination to final state combination is therefore the probability of occurrence of the inflow that causes the transition between the initial and final storage states.

The transition probability in the single to single layer component can therefore be expressed mathematically as

$$P_{jklmt} = PI_{it} \tag{29}$$

where Pi_{it} = probability of the inflow I_{it} in time period t that causes the transition from initial storage state j to final storage state l given release decision R_{jkt}.

indicating that the probability of getting to storage state l and salt concentration state m at the end of time period t (beginning of time period t+1) given a storage state j and salt concentration state k at the beginning of time period t, for a release R_{jkt} is same as the probability PI_{it} of the inflow

I_{it} that causes the transition from initial storage state j to final storage state l.

The probability terms in the recursive equation for each of the other combinations of the dynamic program (conditions of the reservoir) for this case can therefore be developed in the following fashion.

In the double to double layer component the transition from an initial state combination, i.e., initial combination of lower layer storage level j, lower layer salt concentration level k, upper layer storage level u, and upper layer salt concentration level v, in one time period to a new state combination, i.e., final combination of lower layer storage level l, lower salt concentration level m, upper layer storage level y and upper layer salt concentration state z, in the next time period given release R_{jkuvt} can be expressed mathematically as

$$P_{jkuvlmyzt} = PI_{it} \tag{30}$$

indicating that the probability of getting to lower layer storage state l, lower layer salt concentration state m, upper layer storage state u and upper layer salt concentration state v at the end of time period t given an initial lower layer storage state j and salt concentration state k, and upper layer storage state u and salt concentration level v, at the beginning of time period t, for a release R_{jkuvt} is same as the probability of the inflow I_{it} that causes the transition from initial lower layer storage state j to final lower layer storage state k, in time period t. Recall that the transition from initial upper layer storage level to final upper layer storage level is function of the mandatory domestic and environmental releases. Therefore since all inflow water in this component goes to the lower layer there is no probabilistic component to the upper layer transition.

Similarly in the double to single layer component the transition from a state combination, i.e., initial combination of lower layer storage level j, lower layer salt concentration level k, upper layer storage level u, and upper layer salt concentration level v, in one time period to a new state combination, i.e., final combination of storage level l, salt concentration level m, in the next time period for a release decision R_{jkuvt} can be expressed mathematically as

$$P_{jkuvlmt} = PI_{it} \tag{31}$$

indicating that the probability of getting to a final combination of storage state l and salt concentration state m at the end of time period t given an initial combination of lower layer storage state j and upper layer storage state u, lower layer salt concentration k and upper layer salt concentration state v for a release R_{jkuvt} is the same as the probability of the inflow I_{it} that causes the transition from an initial total storage made up of upper and lower layer storage states j and u to a final total storage at the end of the time period as represented by storage state l.

Again in the single to double layer component the transition from a state combination, i.e., initial combination of storage level j, salt concentration level k, in one time period to a new state combination, i.e., final combination of lower layer storage level l, lower salt concentration level m, upper layer storage level y and upper layer salt concentration state z, in the next time period for a release R_{jkt} can be expressed mathematically as

$$P_{jklmyzt} = PI_{it} \tag{32}$$

indicating that the probability of getting to a final lower layer storage state l and upper layer storage state y from an initial storage state j and salt concentration level v at the beginning of the time period for release R_{jkt} is equal to the probability of the inflow I_{it} that causes the transition from the storage at the beginning of the time period represented by storage level j to a total storage at the end of the time period constituted by the sum of the lower and upper layer storages l and y respectively.

Case 2:

Inflow of salt is completely independent of the inflow of water.

In this case the transition probability term for the single to single layer condition of the reservoir can be written

$$P_{jklmt} = PI_{it} * PS_{ct} \qquad (33)$$

where,

PI_{it} , PS_{ct} = probabilities of water and salt load inflows respectively that for the particular release decision cause the transition from initial storage state j to final storage state l and from initial salt concentration state k to final salt concentration state m respectively.

Similarly in the single to double layer condition of the reservoir, the transition probability can be written

$$P_{jklmyzt} = PI_{it} * PS_{ct} \tag{34}$$

PI_{it}, PS_{ct} = probabilities of water and salt load inflows respectively that for the particular release decision cause the transition from initial storage state j to final upper lower storage state l and upper lower storage state y and from initial salt concentration state k to final lower layer salt concentration l and upper layer salt concentration state z respectively.

In the double to double layer condition of the reservoir the mathematical description of the transition probability can be written

$$P_{jkuvlmyzt} = PI_{it} * PS_{ct} \tag{35}$$

PI_{it}, PS_{ct} = probabilities of water and salt load inflows respectively that for the particular release decision cause the transition from initial lower layer storage state j and upper layer storage state u to final lower layer storage state l and upper layer storage state y and from initial lower layer salt concentration state k and upper layer salt concentration state v to final lower layer salt concentration state m and upper layer salt concentration z respectively.

In the double to single layer condition of the reservoir the mathematical description of the transition probability can be written

$$P_{jkuvlmt} = PI_{it} * PS_{ct} \qquad (36)$$

PI_{it} , PS_{ct}= probability of water and salt load inflow respectively that for the particular release decision cause the transition from initial lower layer storage state j and upper layer storage state u to final storage state l and from initial lower layer salt concentration state k and upper layer salt concentration state v in final salt concentration state m.

Case 3:

Probability of inflow of salt is partially dependent on the probability of inflow of water.

In this case the inflow of salt in a given time period is assumed to be partially dependent on the volume of inflow water.

The approach taken to specify the transition probability in this case is to derive a relationship between the water and salt inflows in each time period using the Bivariate Normal distribution.

$$P(it,ct) = \frac{\exp - \frac{1}{2(1-C_{sw}^2)}[(\frac{I_{it}-\mu_w}{\sigma_w})^2 - 2C_{sw}(\frac{I_{it}-\mu_w}{\sigma_w})(\frac{IS_{ct}-\mu_s}{\sigma_s}) + (\frac{IS_{ct}-\mu_s}{\sigma_s})^2]}{2\pi\sigma_w\sigma_s\sqrt{1-C_{sw}^2}} \tag{37}$$

σ_s	=	standard deviation of salt inflow
σ_w	=	standard deviation of water inflow
μ_s	=	mean of salt inflow
μ_w	=	mean of water inflow
C_{sw}	=	correlation coefficient of salt and water inflow

P(it,ct) = joint probability of water inflow I_{it} and salt inflow IS_{ct} in time period t.

The transition probability in this case for single to single layer condition can be written mathematically as follows

$$P_{jklmt} = P(it,ct) \tag{38}$$

where

$P(it,ct)=$ probability of getting salt load IS_{ct} and inflow of water I_{it} in time period t, where salt load IS_{ct} and water inflow I_{it} cause the transition from initial storage state j and salt concentration state k to final storage state l and salt concentration state m in time period t.

[All other variables as defined previously].

The transition probabilities in this case for the double to double layer condition can be written mathematically as

$$P_{jkuvlmyzt} = P(it,ct) \tag{39}$$

where,

$P(it,ct)=$ probability of getting salt load IS_{ct} and inflow of water I_{it} in time period t, where salt load IS_{ct} and water inflow I_{it} causes the transition from initial lower layer storage state j, salt concentration state k, upper layer storage state u, salt concentration state v to final lower layer storage state l, salt concentration state m, and upper layer storage state y, salt concentration state z in time period t.

The transition probability for the single to double layer condition can be written mathematically as

$$P_{jklmyzt} = P(it,ct) \tag{40}$$

where,

$P(it,ct)$ = probability of getting salt load IS_{ct} and inflow of water I_{it} in time period t and, where salt load IS_{ct} and water inflow I_{it} cause the transition from initial storage state j and salt concentration state k to final lower layer storage state l, salt concentration state m, and upper layer storage state y, salt concentration state z in time period t.

The transition probability for the double to single layer condition can be written mathematically as

$$P_{jkuvlmt} = P(it, ct) \tag{41}$$

where,

$P(it,ct)$ = probability of getting salt load IS_{ct} and inflow of water I_{it} in time period t, where salt load IS_{ct} and water inflow I_{it} cause the transition from initial storage state j and salt concentration state k to final lower layer storage state l, salt concentration state m, in time period t.

4.5

CHANCE CONSTRAINTS:

Recall that the primary objective of the proposed model is to manage the salinity in the reservoir by maintaining acceptable levels of salt concentration and storage volume in the reservoir itself. By maintaining salinity levels in the reservoir at a relatively low level, it is then possible to control indirectly the salt concentration in the release from the reservoir. Given that optimal objective function minimises the deviation between the actual releases and the demand, the control over salinity levels can be achieved by the application of a firm deterministic constraint on the level of salt concentration in the reservoir. However, given the stochastic nature of the problem and the likelihood that infrequent violation of the salt standard can be tolerated, a more appropriate type of constraint is the chance constraint. For these reasons, chance constraints have been employed in this approach.

These chance constraints effectively restrict the number of times salt concentration can exceed the maximum allowable level or, more precisely, they restrict the probability that the salt concentration will exceed that maximum value. Although chance constraints can be, and in this model, have been employed for the whole summer period when irrigation withdrawals are occurring, they are most effective only at the beginning of summer months (when transition from double layer to single layer takes place) because during the summer months there are no major inflows to the reservoir, and the salinity levels are essentially constant. There is no conceptual difficulty in chance constraining salt in the other conditions of the reservoir namely, double to double layer and single to double layer. All that is required is to combine the two layers in the reservoir at the end of the period and check the resulting total salt concentration. The chance constraints for these two conditions are therefore also given for completeness.

Maximum, rather than average, level of salt concentration in the reservoir water is used in the formulation because the maximum level of salt in irrigation has more immediate impact on crop production than average level of salt concentration. However there is also no conceptual difficulty with chance constraining the mean if it is believed that this parameter is the most important factor.

The constraints themselves can be developed mathematically as follows. Consider the single to single layer component of the reservoir operation occurring over the summer months. Define the salt concentration level at the end of the time period t after the system has been adjusted for the inflow and release as described previously to be SC_{mt}. Further define $AMAXSC_t$ to be the maximum acceptable level of salt concentration in the reservoir at the end of time period t. If this maximum allowable level of salt concentration should be violated less than x of the time, the appropriate chance constraint for a decision D *for an initial storage level j and salt concentration level k* can be written

$$\Pr(SC_{mt} \leq AMAXSC_t) \geq x \tag{42}$$

where,

$$\Pr(SC_{mt} \leq AMAXSC_t) = \sum_{d \varepsilon RD_t} P_{jklmt} \tag{43}$$

where

d = set of outcomes of release decision RD_t in time period t that, for an initial storage level j and salt concentration level k, result in a salt concentration less than or equal to $AMAXSC_t$

$AMAXSC_t$ = limit on the salt concentration in reservoir in time period t.

Equation 4.42 indicates that, for a decision RD_t in time period t, x of the time the level of salt concentration in the reservoir should be less than allowable salt concentration level of $AMAXSC_t$. This restriction means, there is less than a

(1-x) probability that, for a given decision, the salt concentration level will exceed the allowable salt concentration level in time period t. If the probability of salt concentration in the reservoir being higher than $AMAXSC_t$ resulting from a given decision D, is greater than (1-x) then that decision is not an allowable alternative.

In the double to single layer condition of the reservoir occurring at the end of the winter, let the salt concentration at the end of time period again be SC_{mt}. The mathematical description of the chance constraint for this condition for an initial lower layer storage level j, salt concentration level k, and upper layer storage level u, salt concentration level v can be written as follows

$$Pr(SC_{mt} \leq AMAXSC_t) \geq x \tag{44}$$

where

$$Pr(SC_{rt} \leq AMAXSC_t) = \sum_{d\epsilon RD_t} P_{jkuvlmt} \tag{45}$$

where

$AMAXSC_t$ = limit on salt concentration in the single layer condition of the reservoir in time period t

d = set of outcomes of release decision RD_t, in time period t for an initial lower layer storage j and salt concentration k and upper layer storage u and salt concentration v that result in a salt concentration less than or equal to $AMAXSC_t$

In the double to double layer component of the reservoir operating model, let the salt concentration in the total combined reservoir volume at the end of time period be SC_{rt}. The description of the chance constraint for this condition for an initial lower layer storage level l, salt concentration level k and upper layer storage level u, salt concentration level v can be written mathematically as follows

$$PR(SC_{rt} \leq AMAXSC_t) \geq x \tag{46}$$

$$Pr(SC_{rt} \leq AMAXSC_t) = \sum_{d \in RD_t} P_{jkuvlmyzt} \tag{47}$$

where

$AMAXSC_t$ = limit on salt concentration of the total combined volume of the reservoir in time period t

d = set of outcomes of release decision RD_t in time period t, for initial lower layer storage j and salt concentration k and upper layer storage u and salt concentration v that result in salt concentration in the total combined reservoir less than or equal to $AMAXSC_t$.

In the single to double layer component of the reservoir operating model, let the salt concentration in the total combined volume of the reservoir at the end of time period be SC_{rt}. The mathematical description of chance constraint for this condition for an initial storage level j and salt concentration level k can be written mathematically as follows

$$Pr(SC_{rt} \leq AMAXSC_t) \geq x \tag{48}$$

where

$$Pr(SC_{rt} \leq AMAXSC_t) = \sum_{d \in RD_t} P_{jklmyzt} \tag{49}$$

where

$AMAXSC_t$ = limit on salt concentration of the total combined volume of the reservoir in time period t

d = set of outcomes of release decision RD_t in time period t, that, for an initial storage state j and salt concentration state k, that result in salt concentration in the total combined reservoir less than or equal to $AMAXSC_t$

CHAPTER - 5

APPLICATION OF THE MODEL

The last case described in the previous chapter, namely the formulation in which inflows of salt are considered to be partially dependent on the inflow of water, was applied to the problem of managing the salinity in the Wellington Reservoir through management of the release policy as also described in that chapter. This model was chosen because it more closely reflects the true relationship between inflows of water and salt. As described earlier in Chapter 2, inflow of salt is not necessarily completely dependent on the inflow of water, i.e., a small inflow of water in June may carry a higher salt load than a higher inflow of water occurring later in the season after some initial inflows have already occurred.

The model was used to develop operating policies for a range of values of maximum allowable salt in the reservoir and for a range of salt level reliabilities or more precisely, a range of acceptable probabilities of the maximum salt level being exceeded. The consideration of these combinations of maximum allowable salt concentration and probability of exceeding that maximum allowable salt concentration value enable the multi - objective nature of the problem of managing supply, namely, meeting irrigation targets for water supply and reducing the salinity in the irrigation water, to be investigated. This multi - objective nature can be addressed by examining the variation in objective function values (deviation from water supply targets) with changes in the values of allowable salt concentration and probability of exceeding that value. The combinations of allowable salt concentration and probabilities of exceeding that value used in the analysis are summarised in Table 5.1.

Table 5.1

Description of Cases (Combinations of Maximum Allowable Salt Level and Probability of Being Less than that Level) Examined

Maximum Allowable Salinity Level in the Reservoir	Required Probability of Salt being less than maximum allowable level of salinity (Reliability Level)		
	90%	80%	50%
500 mg/l	CASE A11	CASE A12	CASE A13
525 mg/l	CASE A21	CASE A22	CASE A23
550 mg/l	CASE A31	CASE A32	CASE A33

In preparing the problem for solution by the model, the storages and salt concentrations in each layer of the stratified reservoir and in the single layer of the non stratified reservoir were discretized into nine levels. This choice of nine discrete values for the state variables was based upon the findings of the Goulter and Tai (1985) who noted that, as the number of discrete states used to represent the storage increases from three to nine, the value of the average annual benefits determined by the dynamic program rapidly approaches the value that would be obtained in the prototype. However, with further increase in the number of the states used to represent the storage past nine, the incremental 'improvement' in the estimate of the optimal return decreases significantly. It should also be noted that the choice of nine storage states was based not only on the accuracy of the approach, but, as noted in Goulter and Tai (1985), also on the computational requirements needed for obtaining a steady state operating policy and for solving the sets of simultaneous equations to obtain the various probability distributions of storage and release.

The decision variables of release from the upper and lower layers of the reservoir in the stratified situation and from the single layer of the non stratified reservoir case at the appropriate stages (time periods) were also discretized into nine intervals. Nine discrete values of inflow of water and inflow of salt are also used for each stage (time period).

The probability distributions of inflow of water and salt was derived from the seven year historical record from May 1975 to April 1982. The minimum storage values are those used by Green (1985) in his simulation study and are based on the provision of supply in the face of extreme drought in the following year. Targets for irrigation supply in each stage (time period) are shown in Table 5.2. The maximum storage is the capacity of the Welllington Reservoir, namely, 186 GL. The total annual town water requirement of 10 GL used is significantly higher than the current value of 5.5 GL. The higher value of 10 million cubic meters was used to allow for future expansion of the system as assumed by Hookey and Loh (1985).

An earlier application of the reservoir dynamics simulation model DYRESM to the Wellington Reservoir to develop and examine strategies to scour saline water over the period May 1975 to April 1976 in same manner as that being examined in thesis showed that strong saline stratification generally occurred in the winter months of June - September inclusive (Imberger, 1981). These months were therefore chosen as the

Table 5.2 DYRESM Studies Release Policy

(Source: Imberger and Hebbert, 1980)

MONTH	STORAGE (GL) AT THE BEGINNING OF MONTH	INFLOW (GL)	RELEASE (GL)	TARGET (GL)	DEVI-ATION (GL)
MAY	64.00	9.99	1.00	N.I.	N.I.
JUNE	72.99	39.66	1.00	N.I.	N.I.
JULY	111.65	44.38	26.00	N.I.	N.I.
AUG.	130.03	18.02	19.00	N.I.	N.I.
SEPT.	129.05	8.25	1.00	N.I.	N.I.
OCT.	136.30	2.13	1.00	N.I.	N.I.
NOV.	137.43	0.70	12.50	12.50	0.00
DEC.	125.63	0.69	8.00	8.00	0.00
JAN.	118.32	1.20	8.00	8.00	0.00
FEB.	111.52	0.91	9.00	9.00	0.00
MARCH	103.43	1.14	9.00	9.00	0.00
APRIL	95.57	0.92	8.00	6.00	2.00

N.I.= No Irrigation

winter months. The month of June is selected for the stage at which transition from single layer summer reservoir to double layer winter reservoir occurs. The May through September months are assumed as the winter months in which consideration of selective withdrawal from the lower layer of the stratified reservoir is appropriate. The month of October is selected for the stage at which transition from double layer to single layer non stratified reservoir occurs. The months of October through April are then assumed as summer months in which irrigation release requirements are high and the reservoir is essentially in a single layer, non stratified, condition.

The values of initial storage and salt concentration used in the reservoir operating model to compare the results against those developed in the simulation studies using the DYRESM model were those used in DYRESM model study, namely 378 mg/l and 64 GL respectively. These values were used for all combinations of maximum allowable salt level and probability of exceeding that level used in comparing operating policies and for evaluating the performance of the reservoir under these policies relative to the behaviour of the reservoir in the DYRESM model studies.

The quantities of water which can be scoured must be consistent with the demands on the reservoir. The determination of these quantities is a complex statistical problem depending in part on the prediction of future volumes of inflow and current storage volumes. Previous long term monthly simulations have, however, indicated that there is considerable scope for the development of operating rules which minimise spillage and maximise the available water for the scour (Loh and Hewer, 1977). The dynamic program formulated in this thesis, thus provides the opportunities of developing release policies which address the objective of meeting water supply needs while simultaneously minimising spillage, and meeting constraints of minimum and maximum level of reservoir storage and maximum allowable level of salt concentration.

As noted earlier the main objective of the model is to manage the salinity in the release to irrigation by managing the salinity levels in the reservoir. The only controls available over the behaviour of the reservoir to meet the objective are the release of water from the existing off takes. The Wellington Reservoir has two fixed level off takes; a mid-level off take located 15 meters above the base of the wall, and a bottom level off take approximately 1 meter above the base. The policies discussed below are based on the scouring of saline water from the bottom of the reservoir through the bottom off take. Upper layer release takes place from the mid-level off take or the spillway under flood conditions, whereas lower layer release takes place from the lower level off takes.

The performance of the model was evaluated in the following manner. The steady state operating policies developed by the dynamic programming model were evaluated by passing a historical data set of inflows of water and salt for a specific period through the optimal policy developed for each combination of maximum allowable salt concentration level and probability of exceeding that maximum level. The data used to evaluate the performance of the stochastic dynamic program are the same as those data used to derive the probability distribution used in this model itself. His process violates the basic principle of model development, calibration and verification. However, in this case there are very limited data and it is very difficult to get meaningful results by eliminating data from any step.

Actual evaluation of the operating policies was performed by comparing 1) the salinity in the reservoir and thereby the average salinity in the release in each time period 2) the storage in the reservoir in each time period and 3) the release from the reservoir in each time period, derived from the DYRESM studies for the period May 1975 to April 1976 with those developed by running inflow for the same period through the various steady state operating policies developed by the stochastic dynamic program for the range of combinations of maximum allowable salt concentration and probability of exceeding those values.

The comparisons among the dynamic programming derived operating policies and also between the dynamic programming based policies and those derived from the DYRESM simulation studies are described below. Table 5.3 describes release salinities for DYRESM simulation studies.

CASE A11, CASE A21 , CASE A31

The first case investigated was that of a 500 mg/l maximum allowable salt concentration constraint value. In Case A11 the reliability level was set at 90%, i.e., 90% of the time salt concentration level is less than maximum allowable salt concentration. In other words there is 10% probability of violating maximum allowable salt concentration level. Outputs of this case are illustrated in Tables 5.4 and 5.5 which give the values of release volume and average reservoir salinity respectively in the winter months.

For subsequent runs the maximum allowable salt concentrations were increased to 525 mg/l and 550 mg/l corresponding to Cases A21, and A31 respectively. The higher allowable salt concentrations in the reservoir in Cases A21 and A31 means less salt has to be removed during the winter months, thereby reducing the amount of lower layer saline water which has to be released in the winter to reduce the total salt concentration. Tables 5.6 - 5.9 summarise the results of the Cases A21 and A31.

Table 5.3 Reservoir Inflow and Release Salinities for the DYRESM Studies.

MONTH	RESERVOIR SALINITY AT THE BEGINNING OF MONTH (mg/l)	INFLOW SALINITY (mg/l)	RELEASE SALINITY (mg/l)
MAY	378.00	1300.00	502.48
JUNE	502.48	750.00	589.62
JULY	589.62	574.00	585.18
AUG.	585.18	623.00	589.78
SEPT.	589.78	589.00	589.73
OCT.	589.73	568.00	589.40
NOV.	589.40	576.00	589.33
DEC.	589.33	849.00	590.75
JAN.	590.75	689.00	591.74
FEB.	591.74	912.00	594.33
MARCH	594.33	917.00	597.85
APRIL	597.85	511.00	597.03

Table 5.4 Case A11 Release Policy

MONTH	STORAGE AT THE BEGINNING OF MONTH (GL)	INFLOW (GL)	RELEASE (GL)	TARGET (GL)	DEVIA-TION (GL)
MAY	64.00	9.99	1.0	N.I.	N.I.
JUNE	72.99	39.66	23.24	N.I.	N.I.
JULY	89.41	44.38	27.5	N.I.	N.I.
AUG.	106.29	18.02	23.62	N.I.	N.I.
SEPT.	100.69	8.25	11.4	N.I.	N.I.
OCT.	97.54	2.13	6.85	N.I.	N.I.
NOV.	92.82	0.70	12.50	12.50	0.00
DEC.	81.02	0.69	8.00	8.00	0.00
JAN.	73.71	1.20	8.00	8.00	0.00
FEB.	66.91	0.91	3.82	9.00	5.18
MARCH	64.00	1.14	1.14	9.00	7.86
APRIL	64.00	0.92	0.92	6.00	5.08

Table 5.5 Case A11 Average Reservoir Salinity

MONTH	AVERAGE RESERVOIR SALINITY AT THE BEGINNING OF MONTH (mg/l)	INFLOW SALINITY (mg/l)	RELEASE SALINITY (mg/l)
MAY	378.00	1300.00	502.00
JUNE	502.00	750.00	750.00
JULY	750.00	574.00	623.61
AUG.	623.61	623.00	623.40
SEPT.	623.40	589.00	616.11
OCT.	616.11	568.00	612.77
NOV.	531.69	576.00	531.96
DEC.	531.96	849.00	534.63
JAN.	534.63	689.00	537.11
FEB.	537.11	912.00	542.14
MARCH	542.14	917.00	548.70
APRIL	548.70	511.00	548.16

Table 5.6 Case A21 Release Policy

MONTH	STORAGE AT THE BEGINNING OF MONTH (GL)	INFLOW (GL)	RELEASE (GL)	TARGET (GL)	DEVIATIONS (GL)
MAY	64.00	9.99	1.00	N.I.	N.I.
JUNE	72.99	39.66	22.35	N.I.	N.I.
JULY	90.3	44.38	27.5	N.I.	N.I.
AUG	107.18	18.02	23.62	N.I.	N.I.
SEPT.	101.58	8.25	11.4	N.I.	N.I.
OCT.	98.43	2.13	2.93	N.I.	N.I.
NOV.	97.63	0.70	12.5	12.50	0.00
DEC.	85.83	0.69	8.00	8.00	0.00
JAN.	78.52	1.20	8.00	8.00	0.00
FEB.	71.72	0.91	8.63	9.00	0.37
MARCH	64.00	1.14	1.14	9.00	7.86
APRIL	64.00	0.92	0.92	6.00	5.08

Table 5.7 Case A21 Average Reservoir Salinity

MONTH	AVERAGE RESERVOIR SALINITY AT THE BEGINNING OF MONTH (mg/l)	INFLOW SALINITY (mg/l)	RELEASE SALINITY (mg/l)
MAY	378.00	1300.00	502.00
JUNE	502.00	750.00	750.00
JULY	750.00	574.00	625.40
AUG.	625.40	623.00	624.60
SEPT.	624.60	589.00	617.23
OCT.	617.23	568.00	613.91
NOV.	535.97	576.00	536.25
DEC.	536.25	849.00	538.75
JAN.	537.45	689.00	541.01
FEB.	541.01	912.00	545.66
MARCH	545.66	917.00	552.15
APRIL	552.15	511.00	551.57

Table 5.8 Case A31 Release Policy

MONTH	STORAGE AT THE BEGINNING (GL)	INFLOW (GL)	RELEASE (GL)	TARGET (GL)	DEVI-ATIONS (GL)
MAY	64.00	9.99	1.00	N.I.	N.I.
JUNE	72.99	39.66	18.16	N.I.	N.I.
JULY	94.49	44.38	14.88	N.I.	N.I.
AUG	123.99	18.02	21.17	N.I.	N.I.
SEPT.	120.84	8.25	8.75	N.I.	N.I.
OCT.	120.34	2.13	2.93	N.I.	N.I.
NOV.	119.54	0.70	12.50	12.50	0.00
DEC.	107.74	0.69	8.00	8.00	0.00
JAN.	100.43	1.20	8.00	8.00	0.00
FEB.	93.63	0.91	9.00	9.00	0.00
MARCH	85.54	1.14	9.00	9.00	0.00
APRIL	77.68	0.92	6.00	6.00	0.00

Table 5.9 Case A31 Average Reservoir Salinity

MONTH	AVERAGE RESERVOIR SALINITY AT THE BEGINNING OF MONTH mg/l)	INFLOW SALINITY (mg/l)	RELEASE SALINITY (mg/l)
MAY	378.00	1300.00	502.00
JUNE	502.00	750.00	750.00
JULY	750.00	574.00	633.21
AUG.	633.21	623.00	630.62
SEPT.	630.62	589.00	624.81
OCT.	624.81	568.00	553.98
NOV.	553.98	576.00	554.10
DEC.	554.10	849.00	555.98
JAN.	555.98	689.00	557.55
FEB.	557.55	912.00	560.96
MARCH	560.96	917.00	566.28
APRIL	566.28	511.00	565.63

Comparison of the Results for the Cases A11, A21 and A31 with DYRESM Studies Results

Figure 5.1 shows the comparison of release volumes for the Cases A11, A21 and A31 with DYRESM release volumes. At the beginning of summer months, average reservoir salinity for Cases A11, A21 and A31 is 531.69 mg/l, 535.97 mg/l and 553.98 mg/l respectively. In case of DYRESM average release salinity at the beginning of the summer months is 589.40 mg/l. Although there are high inflows of salt to the reservoir, the average salinity in the reservoir during the winter months in Cases A11, A21 and A31 is decreasing. This decreasing salinity in the reservoir over the winter months is due to the scour policy applied during the winter months.

Figure 5.1 also shows higher values of release for Case A11 relative to DYRESM over the winter months. These higher releases occur because the dynamic programming algorithm utilises the full range of available storage capacities. Figure 5.2 shows lower values of reservoir salinity for Case A11 relative to DYRESM. Figure 5.1 also shows that, in comparison to the scour policy developed by DYRESM, from the beginning of June the model recommends a policy which results in an increasing difference in release volume, i.e., higher release values in Cases A11, A21 and A31. This difference in releases decreases in July and August but increases again for the month of September. As observed in Figure 5.1, the higher scours during the winter months for these three cases relative to the DYRESM studies in turn give lower values of average reservoir salinity at the beginning of summer months for these three cases in comparison with those from the DYRESM studies.

Figure 5.1 also indicates that in the DYRESM simulation case the volume of scour is large only in the months of July and August with very low scour volumes occurring after August. Total scour volumes during the winter months in Cases A11, A21, and A31 are 87.61 GL, 82.8 GL, and 60.89 GL respectively which are 103.74%, 92.55 %, and 41.60% higher respectively than the DYRESM derived value of 43 GL. The total storage values at the beginning of summer months for the three cases, as shown in Tables 5.4, 5.6, and 5.8, are very low compared to the DYRSEM total storage values shown in Table 5.1. Thus it might be asserted that, despite achieving the objective of salinity reduction in the reservoir, the operating policy of case A11 is not really practical because the other objective of meeting summer irrigation demand (minimisation of deviation between irrigation release target and actual release) is not well achieved, i.e., there are high values of deviation between the release targets and actual release values in summer months.

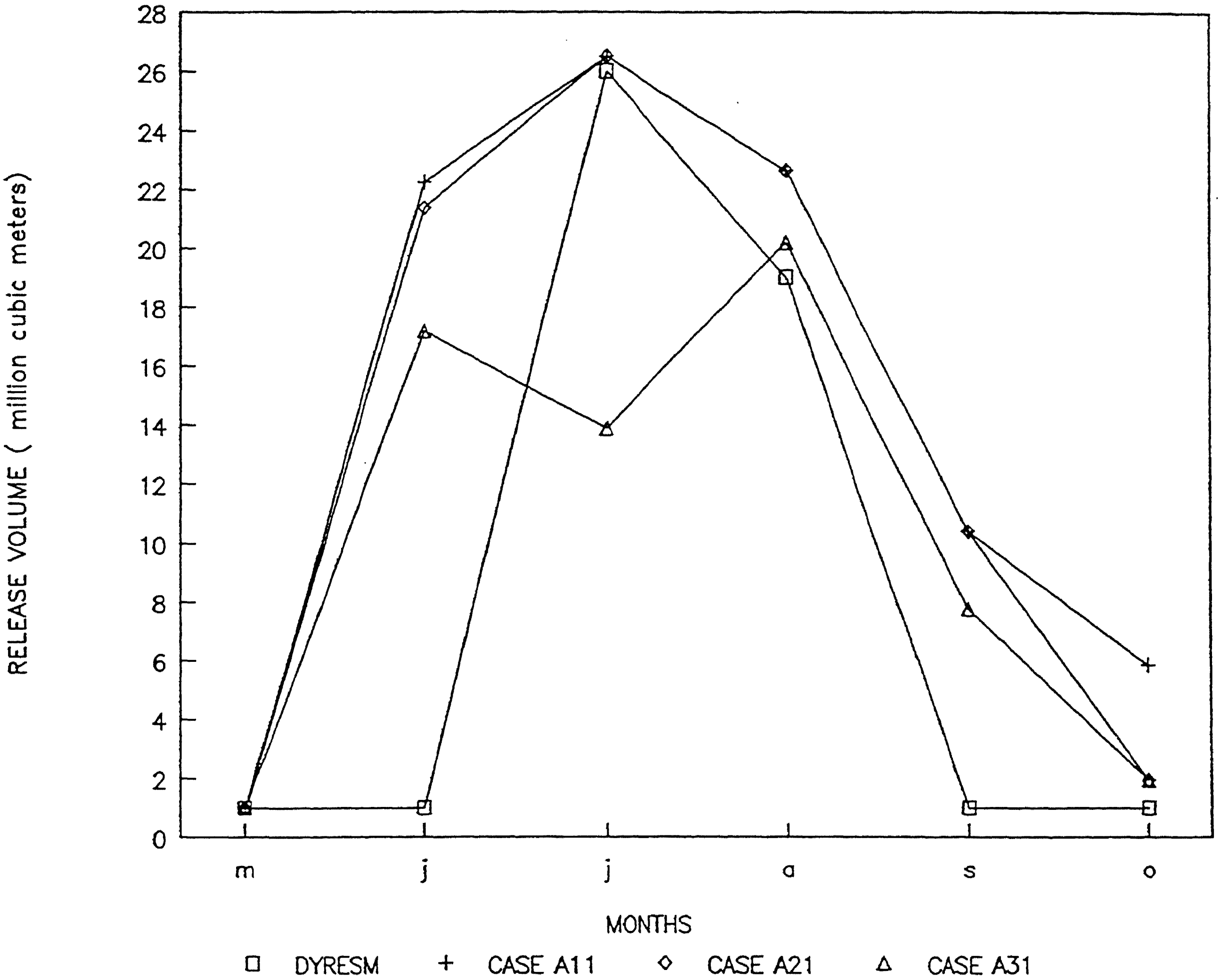


FIGURE 5.1

Comparison of scour release policies during winter months for

Cases A11, A21 and A31

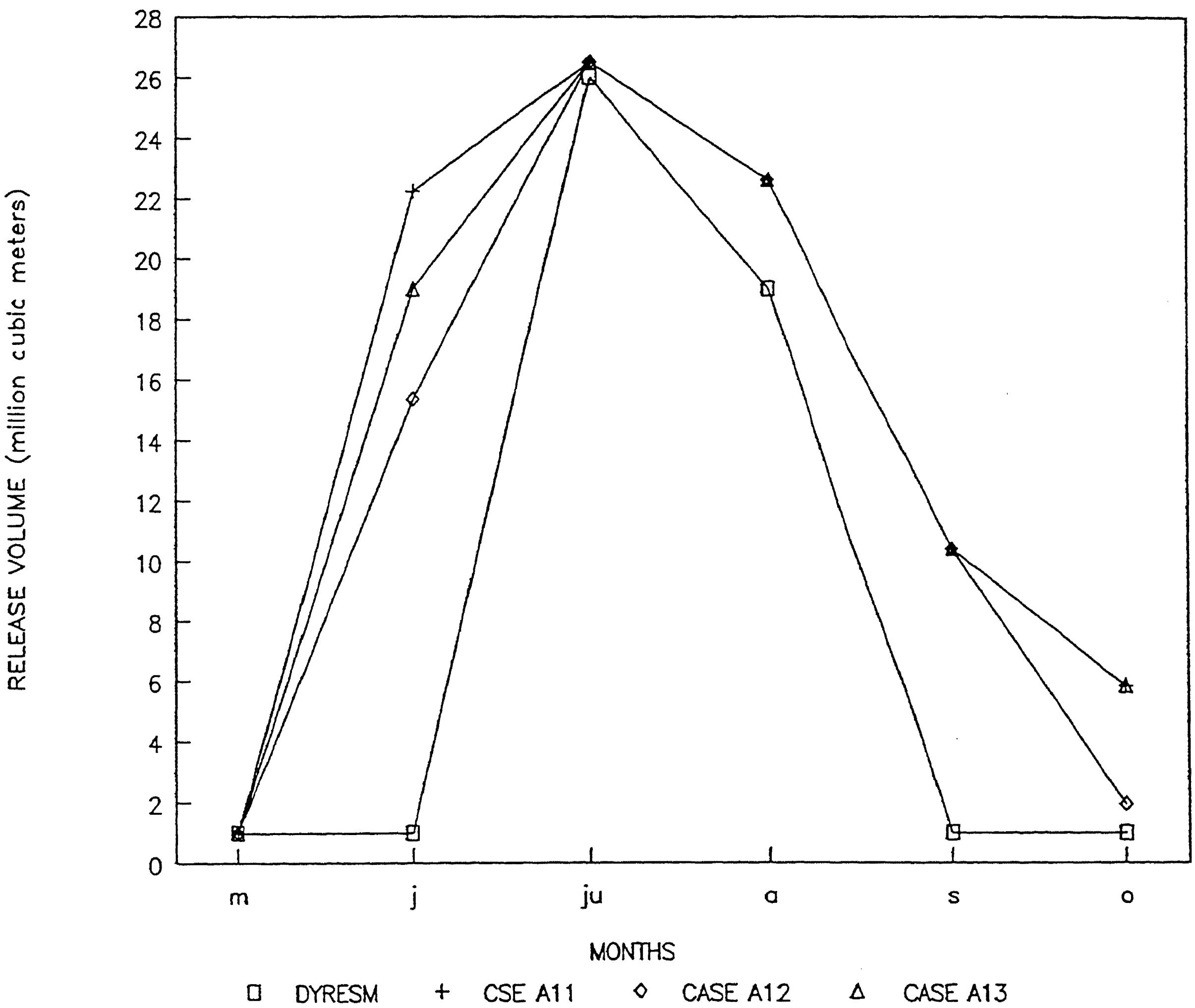


FIGURE 5.2

Comparison of scour release policies during winter months for

Cases A11, A12 and A13

It may therefore be concluded from this comparison that the Case A11 release policy only satisfies the first objective of maintaining salinity in the reservoir at no higher than 531.69 mg/l but is not able to simultaneously meet the other objective of reasonably minimising the deviation between irrigation targets and releases. The DYRESM release policy on the other hand goes further towards meeting the objective of minimising deviation between irrigation targets and demands but does not achieve the same reductions in the salinity levels in the reservoir and therefore, by direct implication, in the releases to irrigation.

In comparison to DYRESM, the Case A21 release policy achieves a significant reduction in average reservoir salinity at the beginning of summer months (535.97 mg/l) and also goes a long way towards meeting the objective of minimisation of deviation between the demands and releases, by essentially meeting irrigation demands in the summer months.

Case A31 scour policy achieves lower average reservoir salinity (553.98 mg/l) in comparison to DYRESM (589.40 mg/l) at the beginning of summer months at a reliability level of 90%. Total scour volume during the winter months for Case A31 is 41.6 % greater than the DYRESM scour volume, although total storage at the beginning of summer month in Case A31 is sufficient to obtain the zero deficit between irrigation release and release target at the end of irrigation season. This deficit is comparable to the zero deficit associated with the DYRESM studies. Case A31 achieved a lower allowable average salinity level than DYRESM because 41.6% more water is scoured during the winter months to remove the excessive salt in this case than in the DYRESM case.

Comparison Among Cases A11,A21 and A31

Figures 5.1 and 5.2 also give a comparison of release policy and average reservoir salinity respectively among the three cases. Figure 5.1 shows Case A21 to have higher values of average reservoir salinity than Case A11. The scour policy for Case A21 (Case A21 release policy) was in fact worse than the Case A11 scour policy (Case A11 release policy) in terms of average irrigation salinity and in terms of total salt removed. It can, however, be argued that the Case A21 release policy is still preferable to that of Case A11 because it also resulted in a significantly lower value of deviation between release and release targets, with a corresponding rise in the total storage. The increase in total storage also contributes in a small way to a general dilution of salt in the reservoir. Case A31 shows a reasonably acceptable level of average reservoir salinity and altogether also shows smaller values of deviation between irrigation demand and actual supply than either Case A11 or A21. Figure 5.1 also indicates that the difference in total scour values between Case A31 and Case A21 is quite small although there is a substantial difference in their average release salinities.

CASES A12, A22, A32 AND CASES A13, A23, A33

In these cases the effect of relaxing the probabilities in the chance constraints (in Equation 4.39) of violating the maximum allowable salt concentrations was examined. In Cases A12, A22, A32 and in Cases A13, A23, A33 the reliability level (probability of exceeding the various maximum allowable salt concentrations) was set at 80% and 50% respectively. Results of these cases are summarised in Tables 5.10 - 5.21.

Table 5.10 Case A12 Release Policy

MONTH	STORAGE AT THE BEGINNING OF MONTH (GL)	INFLOW (GL)	RELEASE (GL)	TARGET (GL)	DEVI-ATIONS (GL)
MAY	64.00	9.99	1.00	N.I.	N.I.
JUNE	72.99	39.66	19.99	N.I.	N.I.
JULY	92.66	44.38	27.50	N.I.	N.I.
AUG	109.54	18.02	23.62	N.I.	N.I.
SEPT.	103.94	8.25	11.40	N.I.	N.I.
OCT.	100.79	2.13	6.85	N.I.	N.I.
NOV.	96.07	0.70	12.50	12.50	0.00
DEC.	84.27	0.69	8.00	8.00	0.00
JAN.	76.96	1.20	8.00	8.00	0.00
FEB.	70.16	0.91	7.07	9.00	1.93
MARCH	64.00	1.14	1.14	9.00	7.86
APRIL	64.00	0.92	0.92	6.00	5.08

Table 5.11 Case A12 Average Reservoir Salinity

MONTH	AVERAGE RESERVOIR SALINITY AT THE BEGINNING OF MONTH (mg/l)	INFLOW SALINITY (mg/l)	RELEASE SALINITY (mg/l)
MAY	378.00	1300.00	502.00
JUNE	502.00	750.00	750.00
JULY	750.00	574.00	629.92
AUG.	629.92	623.00	627.72
SEPT.	627.72	589.00	620.13
OCT.	620.13	568.00	616.85
NOV.	535.57	576.00	535.86
DEC.	535.86	849.00	538.40
JAN.	538.40	689.00	540.77
FEB.	540.77	912.00	545.53
MARCH	545.53	917.00	552.03
APRIL	552.03	511.00	551.45

Table 5.12 Case A22 Release Policy

MONTH	STORAGE AT THE BEGINNING OF MONTH (GL)	INFLOW (GL)	RELEASE (GL)	TARGET (GL)	DEVI-ATIONS (GL)
MAY	64.00	9.99	1.00	N.I.	N.I.
JUNE	72.99	39.66	20.67	N.I.	N.I.
JULY	91.98	44.38	27.50	N.I.	N.I.
AUG	108.86	18.02	23.62	N.I.	N.I.
SEPT.	103.26	8.25	7.98	N.I.	N.I.
OCT.	103.53	2.13	2.63	N.I.	N.I.
NOV.	103.03	0.70	12.50	12.50	12.50
DEC.	91.23	0.693	8.00	8.00	0.00
JAN.	83.92	1.20	8.00	8.00	0.00
FEB.	77.12	0.91	9.00	9.00	0.00
MARCH	69.03	1.14	6.17	9.00	2.83
APRIL	64.00	0.92	0.92	6.00	5.08

Table 5.13 Case A22 Average Reservoir Salinity

MONTH	AVERAGE RESERVOIR SALINITY AT THE BEGINNING OF MONTH (mg/l)	INFLOW SALINITY (mg/l)	AVERAGE RELEASE SALINITY (mg/l)
MAY	378.00	1300.00	502.00
JUNE	502.00	750.00	750.00
JULY	750.00	574.00	628.68
AUG.	628.68	623.00	626.83
SEPT.	626.83	589.00	619.31
OCT.	619.31	568.00	616.33
NOV.	540.88	576.00	541.11
DEC.	541.11	849.00	543.42
JAN.	543.42	689.00	545.47
FEB.	545.47	912.00	549.74
MARCH	549.74	917.00	555.71
APRIL	555.71	511.00	555.08

Table 5.14 Case A32 Release Policy

MONTH	STORAGE AT THE BEGINNING OF MONTH (GL)	INFLOW (GL)	RELEASE (GL)	TARGET (GL)	DEVI-ATIONS (GL)
MAY	64.00	9.99	1.00	N.I.	N.I.
JUNE	72.99	39.66	13.61	N.I.	N.I.
JULY	99.04	44.38	10.60	N.I.	N.I.
AUG.	103.82	18.02	18.55	N.I.	N.I.
SEPT.	132.29	8.25	7.98	N.I.	N.I.
OCT.	132.56	2.13	2.63	N.I.	N.I.
NOV.	132.06	0.70	12.50	12.50	0.00
DEC.	120.26	0.69	8.00	8.00	0.00
JAN.	112.95	1.20	8.00	8.00	0.00
FEB.	106.15	0.91	9.00	9.00	0.00
MARCH	98.06	1.14	9.00	9.00	0.00
APRIL	90.20	0.92	6.00	6.00	0.00

Table 5.15 Case A32 Average Reservoir Salinity

MONTH	AVERAGE RESERVOIR SALINITY AT THE BEGINNING OF MONTH (mg/l)	INFLOW SALINITY (mg/l)	RELEASE SALINITY (mg/l)
MAY	378.00	1300.00	502.00
JUNE	502.00	750.00	750.00
JULY	750.00	574.00	640.65
AUG.	640.65	623.00	636.66
SEPT.	636.66	589.00	631.08
OCT.	631.08	568.00	629.04
NOV.	563.63	576.00	563.70
DEC.	563.70	849.00	565.32
JAN.	565.32	689.00	566.62
FEB.	566.62	912.00	569.56
MARCH.	569.56	917.00	573.55
APRIL	573.55	511.00	572.92

Table 5.16 Case A13 Release Policy

MONTH	STORAGE AT THE BEGINNING OF MONTH (GL)	INFLOW (GL)	RELEASE (GL)	TARGET (GL)	DEVIATIONS (GL)
MAY	64.00	9.99	1.00	N.I.	N.I.
JUNE	72.99	39.66	16.36	N.I.	N.I.
JULY	96.29	44.38	27.50	N.I.	N.I.
AUG.	113.17	18.02	23.62	N.I.	N.I.
SEPT.	107.57	8.25	11.40	N.I.	N.I.
OCT.	104.42	2.13	2.45	N.I.	N.I.
NOV.	104.10	0.70	12.50	12.50	0.00
DEC.	92.30	0.69	8.00	8.00	0.00
JAN.	84.99	1.20	8.00	8.00	0.00
FEB.	78.19	0.91	9.00	9.00	0.00
MARCH	70.10	1.14	7.24	9.00	1.76
APRIL	64.00	0.92	0.92	6.00	5.08

Table 5.17 Case A13 Average Reservoir Salinity

MONTH	AVERAGE RESERVOIR SALINITY AT THE BEGINNING OF MONTH (mg/l)	INFLOW SALINITY (mg/l)	RELEASE SALINITY (mg/l)
MAY	378.00	1300.00	502.00
JUNE	502.00	750.00	750.00
JULY	750.00	574.00	636.27
AUG.	636.27	623.00	632.29
SEPT.	632.29	589.00	624.50
OCT.	624.50	568.00	621.30
NOV.	540.26	576.00	540.49
DEC.	540.49	849.00	542.78
JAN.	542.80	689.00	544.82
FEB.	544.82	912.00	549.04
MARCH	549.04	917.00	554.93
APRIL	554.93	511.00	554.30

Table 5.18 Case A23 Release Policy

MONTH	STORAGE AT THE BEGINNING OF MONTH (GL)	INFLOW (GL)	RELEASE (GL)	TARGET (GL)	DEVI- ATIONS (GL)
MAY	64.00	9.99	1.00	N.I.	N.I.
JUNE	72.99	39.66	16.36	N.I.	N.I.
JULY	96.29	44.38	4.50	N.I.	N.I.
AUG.	136.17	18.02	12.18	N.I.	N.I.
SEPT.	142.01	8.25	5.70	N.I.	N.I.
OCT.	144.56	2.13	2.45	N.I.	N.I.
NOV.	144.24	0.70	12.50	12.50	0.00
DEC.	132.44	0.69	8.00	8.00	0.00
JAN.	125.13	1.20	8.00	8.00	0.00
FEB.	118.33	0.91	9.00	9.00	0.00
MARCH	110.24	1.14	9.00	9.00	0.00
APRIL	102.38	0.92	8.00	6.00	0.00

Table 5.19 Case A23 Average Reservoir Salinity

MONTH	AVERAGE RESERVOIR SALINITY AT THE BEGINNING OF MONTH (mg/l)	INFLOW SALINITY (mg/l)	RELEASE SALINITY (mg/l)
MAY	378.00	1300.00	502.00
JUNE	502.00	750.00	750.00
JULY	750.00	574.00	636.27
AUG.	636.27	623.00	633.39
SEPT.	633.39	589.00	628.83
OCT.	628.83	568.00	627.16
NOV.	568.16	576.00	568.17
DEC.	568.17	849.00	569.62
JAN.	569.62	689.00	570.76
FEB.	570.76	912.00	573.36
MARCH	573.36	917.00	576.88
APRIL	576.88	511.00	576.29

Table 5.20 Case A33 Release Policy

MONTH	STORAGE AT THE BEGINNING OF MONTH (GL)	INFLOW (GL)	RELEASE (GL)	TARGET (GL)	DEVIATIONS (GL)
MAY	64.00	9.99	1.00	N.I.	N.I.
JUNE	72.99	39.66	6.33	N.I.	N.I.
JULY	106.32	44.38	4.50	N.I.	N.I.
AUG.	146.2	18.02	12.18	N.I.	N.I.
SEPT.	152.04	8.25	5.70	N.I.	N.I.
OCT.	154.59	2.13	2.45	N.I.	N.I.
NOV.	154.27	0.70	12.50	12.5	0.00
DEC.	142.47	0.69	8.00	8.00	0.00
JAN.	135.16	1.20	8.00	8.00	0.00
FEB.	128.36	0.91	9.00	9.00	0.00
MARCH	120.27	1.14	9.00	9.00	0.00
APRIL	112.41	0.92	8.00	6.00	0.00

Table 5.21 Case A33 Average Reservoir Salinity

MONTH	AVERAGE RESERVOIR SALINITY AT THE BEGINNING OF MONTH (mg/l)	INFLOW SALINITY (mg/l)	RELEASE SALINITY (mg/l)
MAY	378.00	1300.00	502.00
JUNE	502.00	750.00	750.00
JULY	750.00	574.00	650.76
AUG.	650.00	623.00	645.39
SEPT.	645.00	589.00	640.23
OCT.	639.00	568.00	638.48
NOV.	578.33	576.00	578.32
DEC.	578.32	849.00	579.62
JAN.	579.62	689.00	580.58
FEB.	580.58	912.00	582.92
MARCH	582.92	917.00	586.05
APRIL	586.05	511.00	585.44

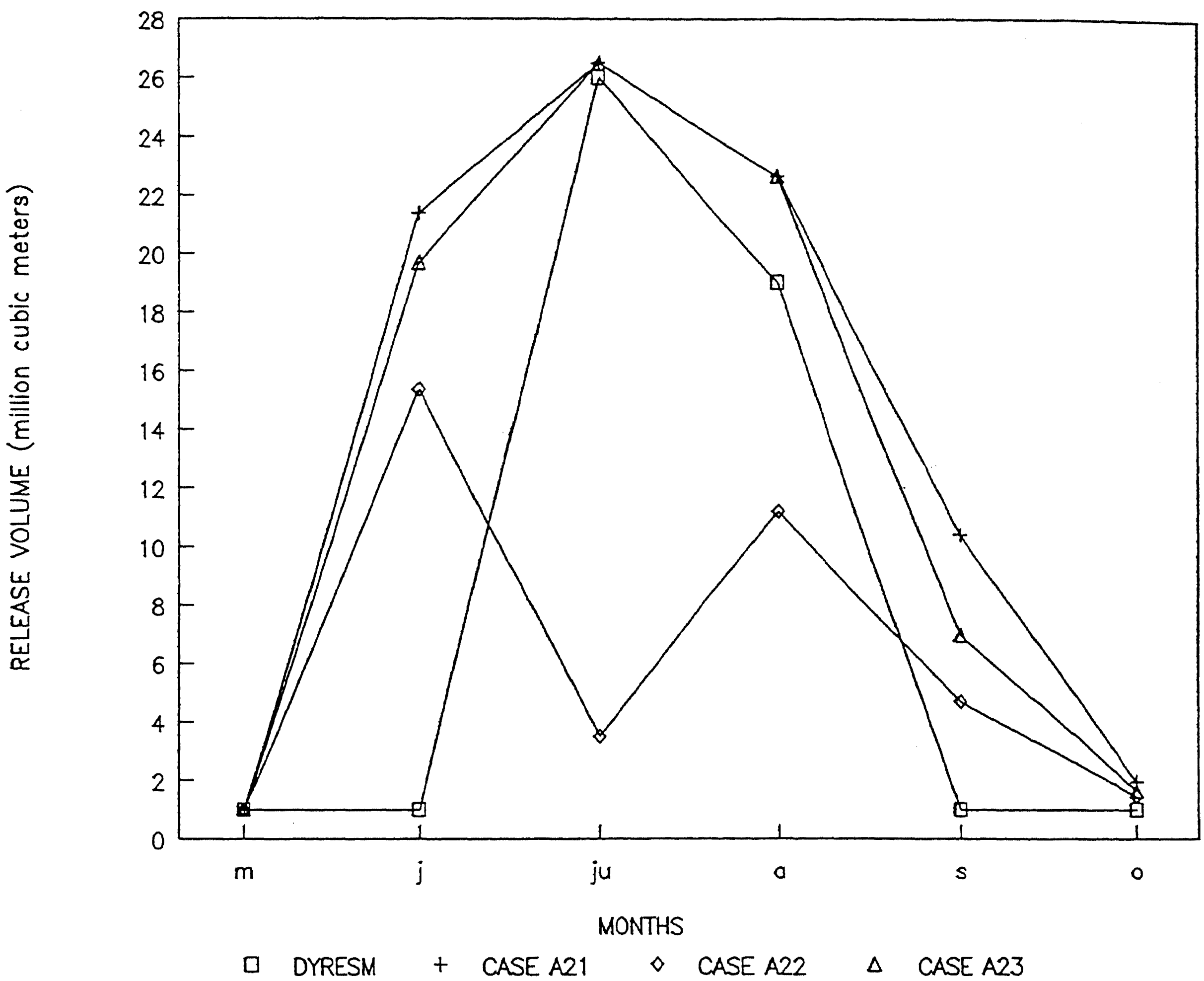


FIGURE 5.3

Comparison of scour release policies during winter months for Cases A21, A22 and A23

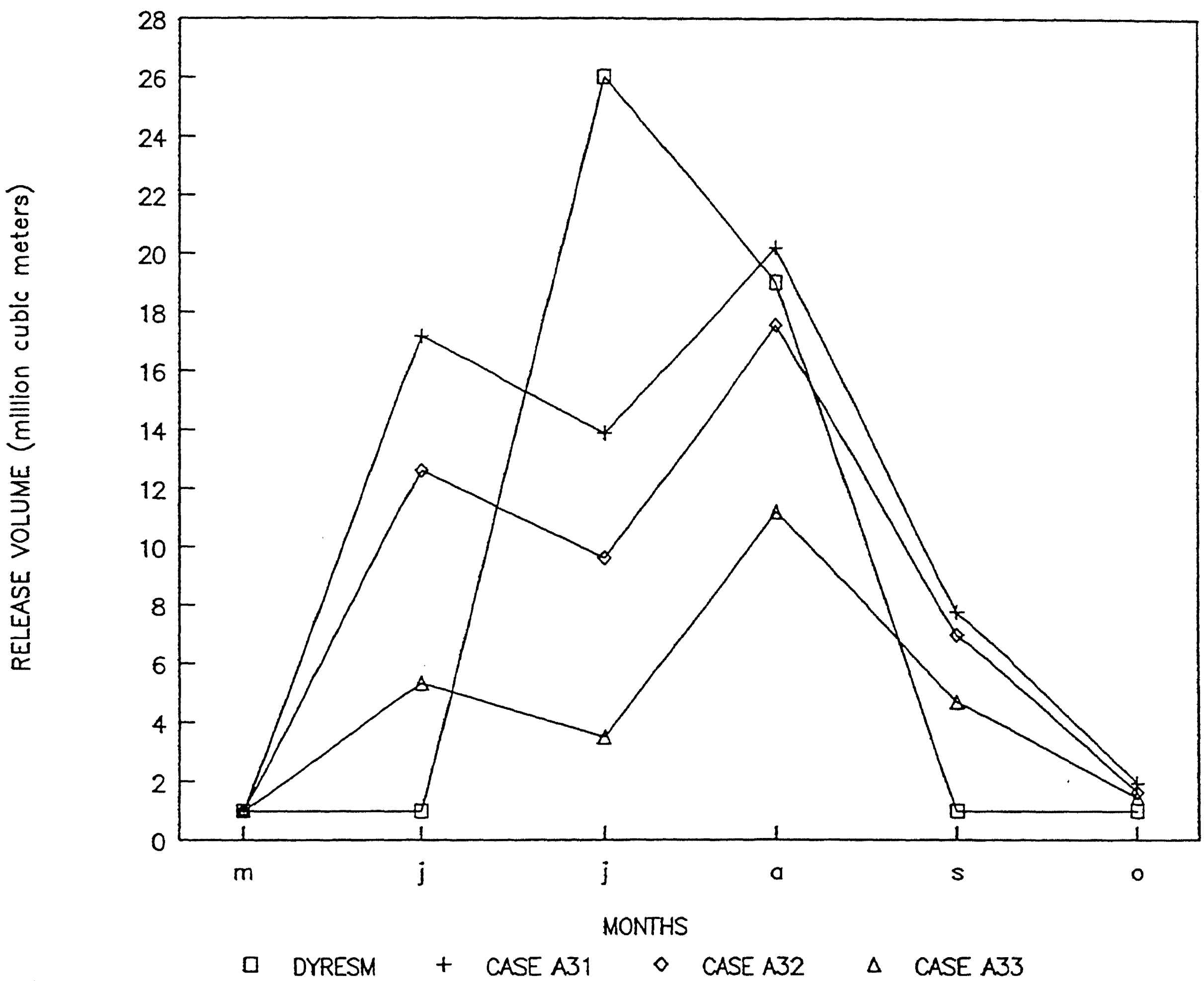


FIGURE 5.4

Comparison of scour release policies during winter months for Cases A31, A32 and A33

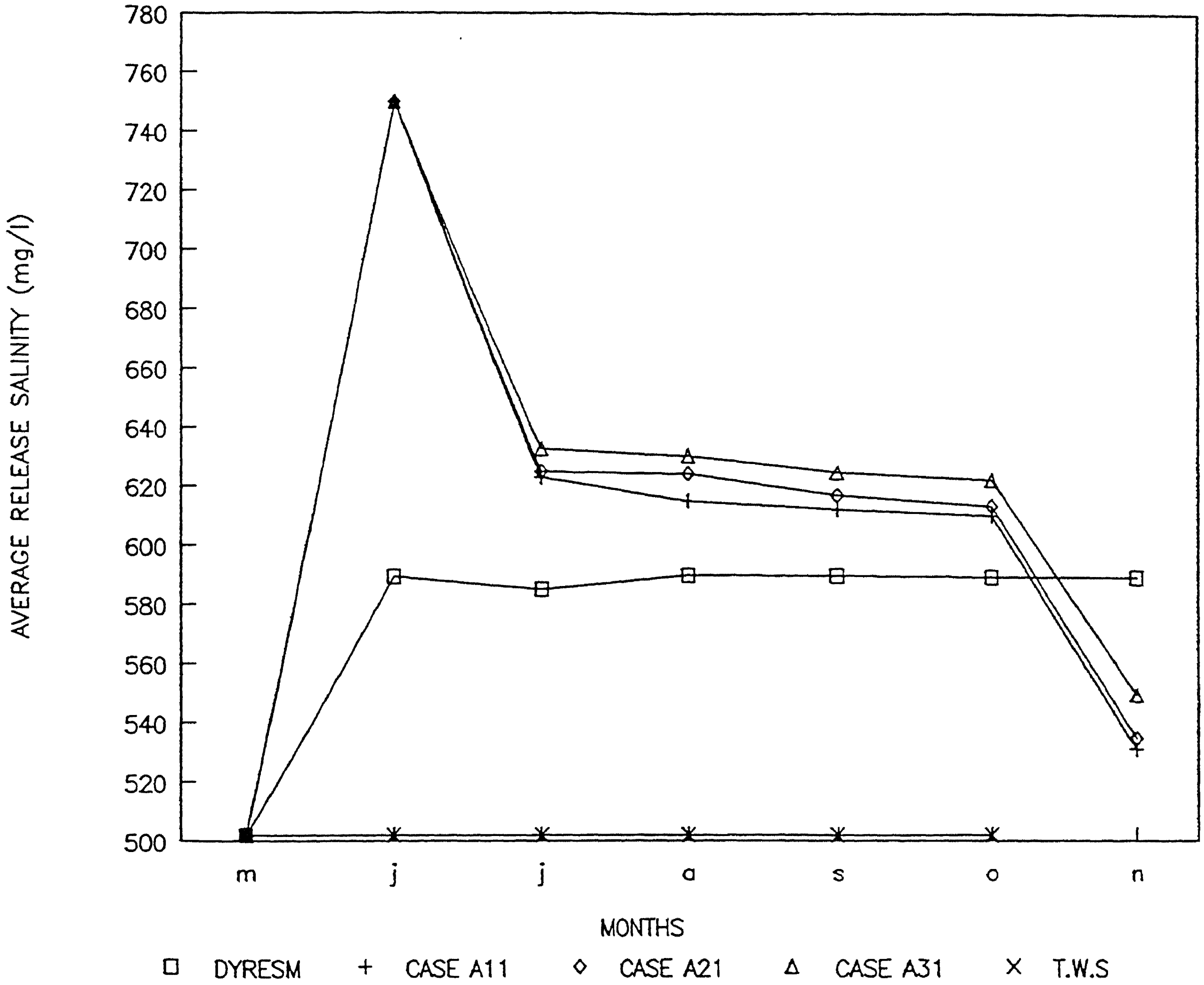


FIGURE 5.5

Comparison of release salinities during winter and at the beginning of the summer months for Cases A11, A21 and A31

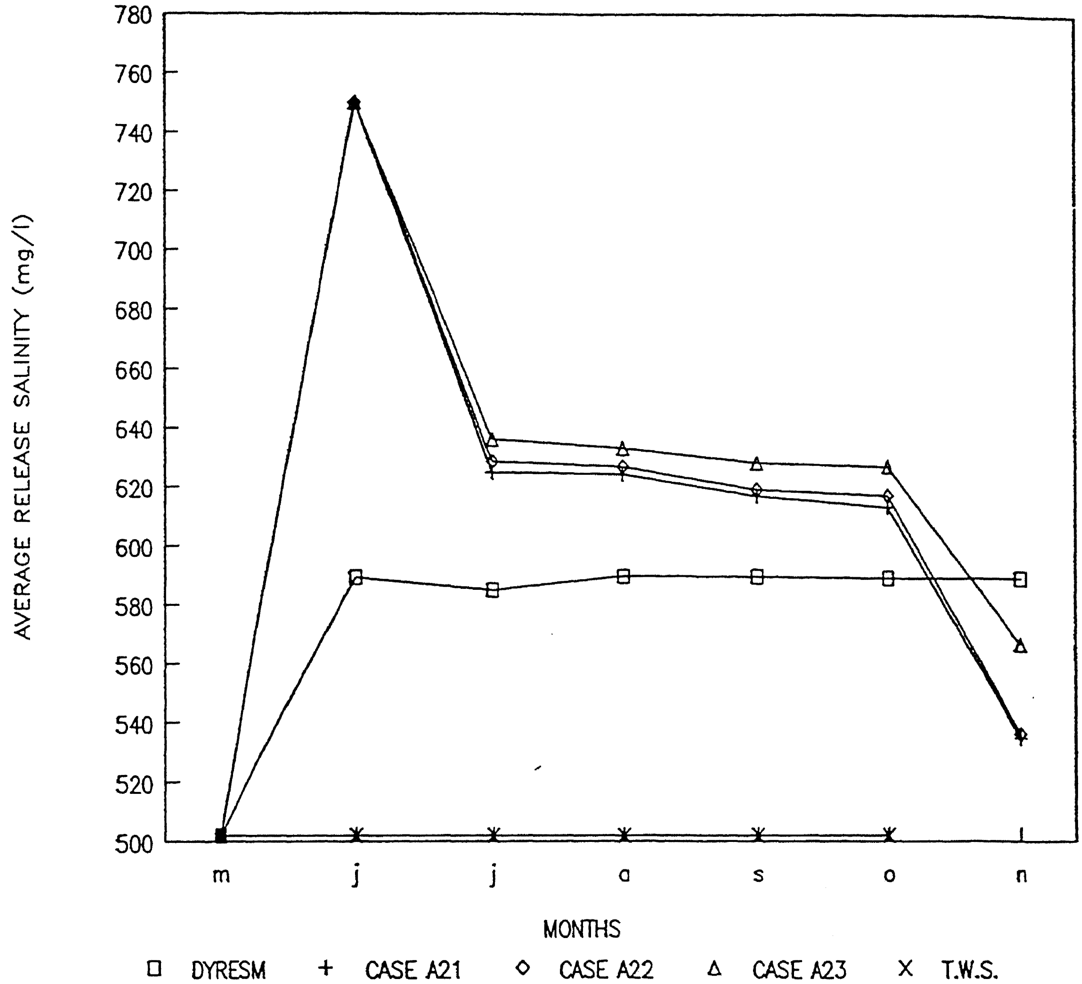


FIGURE 5.6

Comparison of release salinities during winter and at the beginning of the summer months for Cases A21, A22 and A23

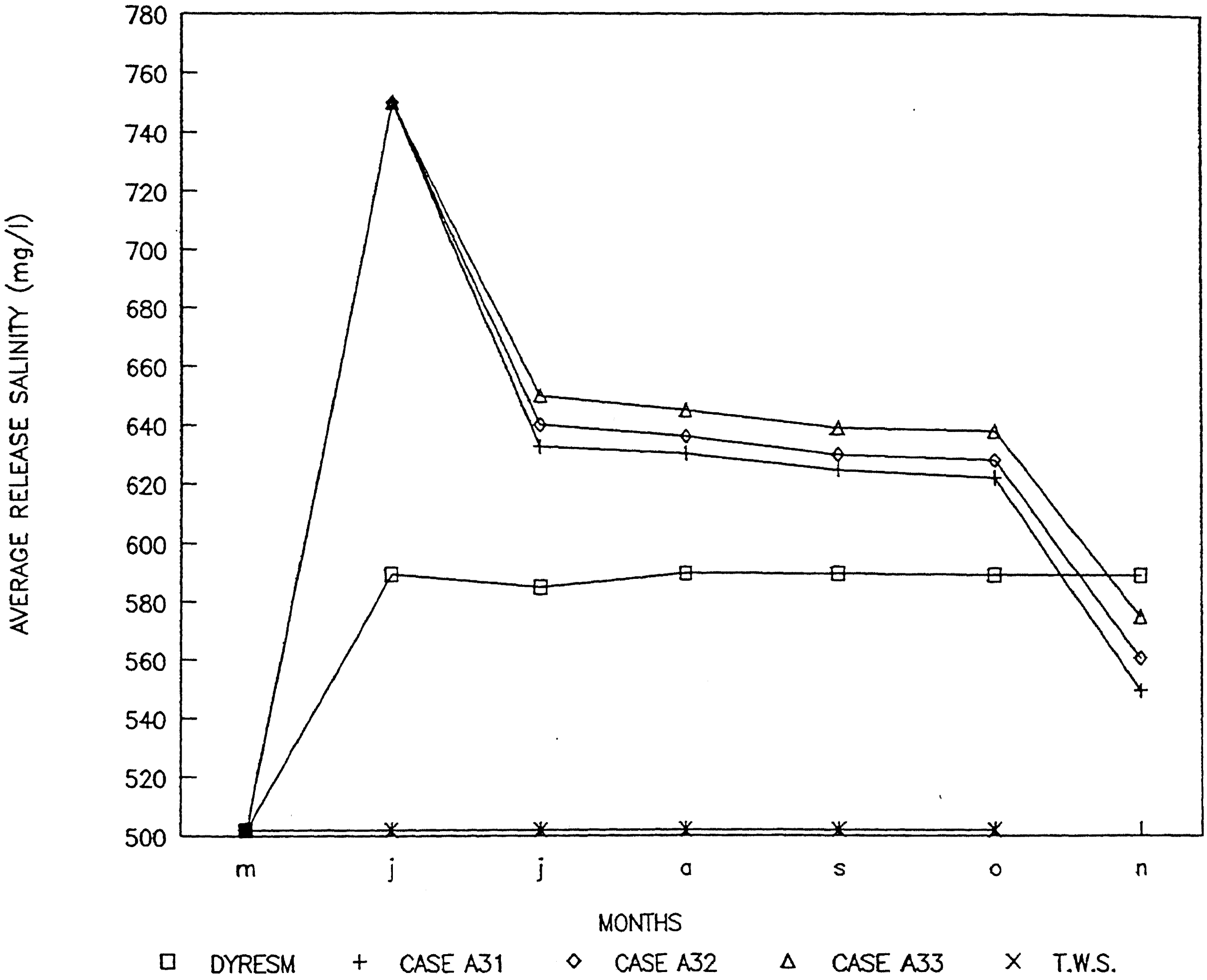


FIGURE 5.7

Comparison of release salinities during winter and at the beginning of the summer months for Cases A31, A32 and A33

Figures 5.3 and 5.4 show the release volumes for 500 mg/l, 525 mg/l and 550 mg/l allowable salinity levels respectively at each of the 90%, 80% and 50% levels of reliability. Figures 5.5, 5.6 and 5.7 compare average reservoir salinity levels respectively at each of the 90%, 80% and 50% levels of reliability.

These figures show the expected results that, as the level of reliability decreases, higher average reservoir salinities are tolerated. As a result, in comparison to Case A31, average reservoir salinities in Cases A32 and A33 tend to increase and the objective function of managing the salinity is achieved at the lower reliability level of salt concentration but for comparatively lower scour volumes. These lower scour volumes are due to the fact that since more salt is allowed in the reservoir, less salt is to be removed. Less water is therefore required for scour during winter months. This process results in higher storage values at the beginning of summer months. Higher values of total storage at the beginning of the summer in turn assist in meeting the irrigation demand targets during the summer, thereby minimising the deviation between the irrigation targets and release. In fact the irrigation supply can be achieved with zero deficit.

These results show, the expected result that as the level of reliability for maximum allowable average salinity decreases less scour volume is required to achieve the allowable salt levels with the result that more water (and salt) remains in the reservoir to meet the irrigation demands thereby reducing the deviations between those irrigation demands and the actual water supplied. This condition also results in higher values of average reservoir salinity because the water that remains is both greater in volume and high in salt concentration.

The results of all cases indicate that it is desirable to remove the first inflow which lodges in the base of the reservoir. As noted earlier, the first significant inflows of water, which normally occur in June, carry high inflows of salt to the reservoir. Thus comparatively less scour is required early in the winter to remove more salt because average reservoir salinity level in the bottom layer is high at that time and less water is required to remove this salt. A similar situation exists, but on a reduced scale, due to the reduced salinities in the inflows, for subsequent winter inflows.

CHAPTER - 6

SUMMARY AND CONCLUSIONS:

A stochastic dynamic programming based model for salinity management of the Wellington Reservoir system has been developed. The model is formulated in a multi-objective framework in which two objectives, namely minimising the average reservoir salinity at the beginning of the irrigation season and meeting irrigation demands by minimising the absolute difference between the actual release and irrigation targets are addressed.

The problem for which the approach is specifically developed is characterised by the presence of a strongly stratified, essentially two layer condition, in a reservoir used to supply irrigation water. The two layer condition essentially occurs over the winter months when cold and heavy saline flows enter the reservoir and flow to the bottom of the reservoir. The two layer condition continues until mixing of the reservoir occurs in early summer. While the reservoir is stratified it is possible to flush the saline water out of the reservoir by low level intakes. This flushing reduces overall salinity levels in the reservoir when mixing occurs in the summer, and thereby reduces the salinity of the irrigation water withdrawn from the reservoir over the summer. However, removing the saline bottom layer also reduces the volume of water available for irrigation.

The problem facing operation of the reservoir is how to optimise the performance of the reservoir to meet irrigation demands, while minimising salt concentration in the irrigation water. A stochastic dynamic programming model is formulated to address the problem. The stochastic component is used to recognise the uncertainty in the inflows. Chance-constraints are also employed in the model to recognise possible acceptability of exceeding maximum allowable salt levels on an infrequent basis.

The formal mathematical objective of the model is minimisation of the expected deviation between targets for irrigation and releases to irrigation during the summer. Modelling of the stratified and non-stratified reservoir and transition between stratified to non-stratified, and non-stratified to stratified states is included in the model.

The chance-constraints are used within the formulation to control the level of salt in the reservoir at the beginning of the irrigation season after mixing of the stratified reservoir has occurred. (Since there are no major inflows to the reservoir during the summer months, salinity levels remain essentially constant during each irrigation season.)

The operating policy developed by the stochastic dynamic program uses a policy of scouring saline water inflows from storage while attempting to ensure that sufficient water remains in the reservoir to meet irrigation targets in summer.

The results of application of the model to the Wellington Reservoir in Western Australia where such stratification conditions occur suggest that, as the level of reliability for maximum allowable average salinity decreases, less scour volume is required to obtain the allowable salt levels, with the result that more water (and salt) remains in the reservoir to meet the irrigation demands, thereby reducing the deviations between those irrigation demands and the actual water supplied. This condition also results in higher values of average reservoir salinity because the water that remains is not only greater in volume and but is also high in salt content.

Similar results occur when the maximum salt concentration allowable in the reservoir is increased. As the value of maximum allowable salt in the reservoir increases, a greater amount of salt in the reservoir is tolerated. Thus less salt remains to be scoured and consequently, less water is required for scouring, leaving behind more water (with higher salinity) in the summer to meet the irrigation targets. This condition also results in higher values of average reservoir salinity, because water that remains after the winter is both greater in volume and high in salt concentration.

Comparison of results from the stochastic dynamic programming (SDP) operating policies and DYRESM simulation studies used to evaluate scouring policy for the same reservoir indicate that the DYRESM uses lower amounts of water for scour during winter months, resulting in higher salinities in the reservoir at the beginning of the summer irrigation period. On the other hand, at the beginning of the irrigation season, higher volumes of water were available in the DYRESM studies in comparison to the SDP cases to meet the irrigation targets during summer months. Although the SDP cases used higher amounts of water to reduce the salinity of the reservoir during winter months, enough water was still left to meet the irrigation demands in summer for a number of combinations of maximum allowable salt concentration and probability of exceeding that maximum allowable salt concentration. In other words, in the SDP cases it is possible to meet the irrigation targets while improving the salinity of the reservoir.

Recommendations for Future Work

During the formulation of the model, it was assumed that transition (mixing) of the reservoir from a single layer to double layer condition occurs at a fixed time at the beginning of winter season and that transition from a double layer to single layer reservoir condition similarly occurs at a fixed time at the end of the winter months. In fact, the period in which these transitions occurs is uncertain. Extension of the work in this thesis should include consideration of the uncertainty in the period in which mixing of the reservoir takes place.

Recent work on the salinity problem in the Wellington Reservoir has examined the possibility of developing another dam upstream of the Wellington Reservoir and operating the two reservoirs conjunctively to improve the salinity problems (Hookey and Loh, 1985). This condition is not examined in this thesis and is another area to which future research using models of the type developed in this thesis could be directed.

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APPENDIX A

Salt and Inflow Records Used in the Study

YEAR	MONTH	INFLOW OF WATER (m^3)	INFLOW OF SALT (kg)
1974	APRIL	9213	6941
	MAY	8024	33916
	JUNE	30274	41226
	JULY	68807	35992
	AUGUST	1722734	99494
	SEPTEMBER	182165	8644
	OCTOBER	21592	3219
	NOVEMBER	15729	867
	DECEMBER	1831	9949
1975	JANUARY	578	285
	FEBRUARY	159	72
	MARCH	679	399
	APRIL	698	348
	MAY	9994	13003
	JUNE	39662	29746
	JULY	44379	25473
	AUGUST	18024	11228
	SEPTEMBER	8254	4861
	OCTOBER	2130	1209
	NOVEMBER	705	406

	DECEMBER	693	588
1976	JANUARY	1201	827
	FEBRUARY	914	833
	MARCH	1143	1045
	APRIL	927	473
	MAY	1021	1044
	JUNE	7861	15749
	JULY	41558	38104
	AUGUST	8989	7445
	SEPTEMBER	13926	13487
	OCTOBER	3110	2706
	NOVEMBER	839	781
	DECEMBER	400	411
1977	JANUARY	113	135
	FEBRUARY	46	60
	MARCH	69	99
	APRIL	153	183
	MAY	1453	1287
	JUNE	8918	14850
	JULY	56843	43400
	AUGUST	15795	10705
	SEPTEMBER	16494	16513
	OCTOBER	20624	13426
	NOVEMBER	1036	516

	DECEMBER	105	427
1978	JANUARY	116	146
	FEBRUARY	56	82
	MARCH	331	457
	APRIL	329	215
	MAY	1616	1663
	JUNE	11435	16251
	JULY	7123	9162
	AUGUST	6123	4261
	SEPTEMBER	4284	6426
	OCTOBER	3418	4353
	NOVEMBER	1422	1735
	DECEMBER	338	426
1979	JANUARY	245	165
	FEBRUARY	83	60
	MARCH	74	53
	APRIL	486	604
	MAY	3791	7553
	JUNE	17003	24074
	JULY	33516	31995
	AUGUST	30114	14876
	SEPTEMBER	12883	9934
	OCTOBER	4066	3718

	NOVEMBER	673	473
	DECEMBER	656	510
1980	JANUARY	110	188
	FEBRUARY	78	148
	MARCH	125	226
	APRIL	275	326
	MAY	9943	13163
	JUNE	28754	29813
	JULY	80406	43482
	AUGUST	25797	15872
	SEPTEMBER	12938	7249
	OCTOBER	6639	5918
	NOVEMBER	1523	1002
	DECEMBER	2026	1374
1981	JANUARY	279	273
	FEBRUARY	69	86
	MARCH	98	124
	APRIL	452	310