Reservoir Management Under Consideration of Stratification and Hydraulic Phenomena

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Reservoir Management Under Consideration of Stratification and Hydraulic Phenomena

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To my parents

STATEMENTS

1. Integration of water quality elements into water resources management is undoubtedly important.

   This thesis

2. The concentration of salinity in the water supplied from a reservoir can be improved by controlling the releases. These improvements can be considerably enhanced by manipulating the inflows.

   This thesis

3. Reservoirs undergo stratification and mixing cycles within a year. However, the assumption of completely mixing of water throughout the year in such a reservoir is a valid simplification that could be effectively used while developing operating policies for it.

   This thesis

4. Learning is more than listening; it is smelling, seeing, feeling and touching as well.

5. The transfer of knowledge and appropriate technology is the fundamental form of development aid and the water sector should obtain a particularly high priority in national and international development policy and such transfer should be made in a holistic manner to include novel, non-conventional and cost-effective technologies.

   The Committee on the Transfer of Knowledge and Technology to the Intergovernmental Council of UNESCO, Paris, 1992.

6. If you have a big problem, try to reduce it to a small problem. If you have a small problem, try to reduce it to no problem.

7. At the global scale, technology for water resources management is developed very much more rapidly than the global community is able to disseminate it and apply it.

8. Just as agricultural activities have numerous impacts of water quality, similarly water quality considerations have important implications for agricultural activities.

9. Every social group, no matter what its size, must establish patterns of authority and delegate power, status, and responsibilities to its members.

10. A problem that is well formulated is half resolved.

11. Good life is inspired by love and guided by knowledge.

12. The world grows smaller and smaller, more and more interdependent ... today more than ever before life must be characterized by a sense of Universal Responsibility, not only nation to nation and human to human, but also human to other forms of life.

His Holiness the Dalai Lama

K.D.W. Nandalal
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Abstract

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Reservoirs are the most important components in a water resources system. They are used to store water to extend its temporal availability. The physical, chemical and biological characteristics of water change when impounded in reservoirs. This implies the possibility of using reservoirs for the control of the quality of water besides merely satisfying the quantity requirement. This study presents several techniques formulated to manage a reservoir when both quantity and quality of water are of interest. In this study salinity is selected to characterize the water quality status. The approaches are demonstrated using data from the Jarreh Reservoir on the Shapur river in Iran.

Water in a reservoir is stratified for most of a year due to difference in density caused by temperature, dissolved and suspended solids. Therefore, in a stratified reservoir the quality of water that is interrelated to density varies with depth. Consequently, this feature could be used in the process of reservoir operational policy determination to improve the quality of water supply. The aim of this research is to analyze different approaches regarding the incorporation of this phenomenon into reservoir operational policies and to propose those which require the least increase in mathematical and computational complexity.

Initially, two techniques that rely on the natural process of stratification occurring in a reservoir are presented. The first methodology proceeds stepwise in time alternating optimization and simulation of reservoir operation at each time step. A one-dimensional reservoir dynamics simulation model is employed to simulate the stratification of the reservoir. A constrained nonlinear optimization model is used to identify optimum releases. In the optimization step the reservoir is assumed to be equivalent to the parallel configuration of several smaller hypothetical reservoirs, the number of which being equal to the number of outlets. There is no communication among these hypothetical reservoirs. The applicability of the technique is tested for three hydrologically different years and for a continuous period of five years. Incorporation of inflow stochasticity into the methodology is devised through the integration of an optimization model based on Stochastic Dynamic Programming technique.

Next, an iterative technique, in which an optimization model and a reservoir stratification simulation model operate interactively, is presented. One iteration cycle comprises the run of the optimization model and the simulation model: i) Reservoir operation is optimized over the entire time period (year); ii) Simulation of stratification is applied over the entire time period. The optimization model is based on Incremental Dynamic Programming technique. In the optimization model, the hypothetical reservoir concept used in the above model is adopted. However, communication between any two adjoining hypothetical reservoirs is allowed in the model. The one-dimensional reservoir dynamics simulation

model simulates the stratification of the reservoir. The applicability of the technique is examined for three hydrologically different years.

Reservoirs could also be modelled by assuming that complete mixing of water is occurring throughout its entire volume during a year. It is a simplification as compared with the real behaviour of stratification occurring in reservoirs. Two models are developed based on this assumption to improve the quality of water supply. In one model only the releases are controlled. In the other, both inflows and releases are controlled. Optimization is based on Incremental Dynamic Programming technique. The results from both models show improvements in the quality of water supplied from the reservoir. However, the improvements obtained by manipulating both inflows and releases are more profound.

Improving the quality of water supplied from a reservoir by diverting poor quality inflows and satisfying downstream quantity demands are two conflicting objectives. This problem is studied under the multiobjective analysis framework. The reservoir is assumed to be completely mixed throughout its volume during the whole annual cycle. The results show that a cautious balance between the quantity of water supplied for downstream and the volume of inflows diverted would lead to marked reduction in the supply salinity.

The study reveals that the quality of reservoir releases could be improved by withdrawals from different elevations in a stratified reservoir. However, the benefits obtained in this way are marginal for the case study reservoir. Similar improvements are observed under the assumption that the reservoir is completely mixed throughout a year. On the other hand, by manipulating the inflows to the Jarreh reservoir these improvements could be enhanced significantly. That is, by-passing of poor quality inflows seems to be a very promising management alternative for improving the quality of water supplied from the reservoir. The assumption of reservoir's complete mixing is warranted for the stratified reservoir by the obtained results. Hence, a relatively simple and straightforward methodology based on the non-stratification assumption proves to be suitable in managing a density stratified reservoir.

Samenvatting

Nandalal, K.D.W. (1995), Reservoir Management Under Consideration of Stratification and Hydraulic Phenomena, proefschrift, Landbouwuniversiteit Wageningen, Wageningen, Nederland, (xviii) + 173 pp., 94 figuren, 33 tabellen.

Reservoirs zijn de belangrijkste onderdelen in een waterhuishoudingssysteem. Ze worden gebruikt om water op te slaan teneinde de beschikbaarheid ervan in de tijd te verlengen. De fysische, chemische en biologische eigenschappen van water veranderen wanneer het wordt opgeslagen in reservoirs. Dit impliceert de mogelijkheid om reservoirs te gebruiken voor de beheersing van de waterkwaliteit naast de beheersing van de waterkwantiteit. Deze studie presenteert verscheidene technieken die zijn geformuleerd om een reservoir te beheren wanneer zowel kwantiteit als kwaliteit van het water van belang zijn. In deze studie wordt het zoutgehalte gebruikt om de waterkwaliteit te karakteriseren. De benaderingen worden gedemonstreerd met gebruikmaking van data van het Jarreh Reservoir aan de Shapur-rivier in Iran.

Gedurende het grootste deel van het jaar is water in een reservoir gestratificeerd als gevolg van verschil in dichtheid veroorzaakt door temperatuur, opgeloste en gesuspendeerde vaste stoffen. Daarom varieert in een gestratificeerd reservoir de kwaliteit van water, dat is gerelateerd aan de dichtheid, met de diepte. Dit verschijnsel kan worden gebruikt om met behulp van reservoir beheersmaatregelen de kwaliteit van de water afgifte te verbeteren. Het doel van dit onderzoek is om verschillende benaderingen met betrekking tot de opname van dit verschijnsel in reservoir beheersmaatregelen te analyseren en om die voor te stellen welke de kleinste toename in mathematische en rekenkundige complexiteit vereisen.

In eerste instantie worden twee technieken gepresenteerd die steunen op het natuurlijke proces van stratificatie zoals dat plaatsvindt in een reservoir. De eerste methodologie schrijdt stapsgewijs in de tijd voort, waarbij de optimalisatie en simulatie van reservoirbeheer op iedere tijdstap elkaar afwisselen. Een eendimensionaal simulatiemodel voor reservoir-dynamica wordt gebruikt om de stratificatie van het reservoir te simuleren. Een Constrained Nonlinear Optimization Model wordt gebruikt om optimale uitstromen te identificeren. In de optimalisatiestap wordt aangenomen dat het reservoir gelijkwaardig is aan een parallelle configuratie van verscheidene kleinere hypothetische reservoirs, waarvan het aantal gelijk is aan het aantal uitstroomopeningen. Er is geen communicatie tussen deze hypothetische reservoirs. De toepasbaarheid van de techniek wordt getest voor drie hydrologisch verschillende jaren en voor een continue periode van vijf jaar. Incorporatie van instroom-stochasticiteit in de methodologie wordt bereikt door de integratie van een optimalisatiemodel gebaseerd op de Stochastisch Dynamische Programmeringstechniek.

Vervolgens wordt een iteratieve techniek gepresenteerd waarin een optimalisatiemodel en een simulatiemodel voor reservoir-stratificatie op een interactieve manier werken. Eén iteratiecyclus bevat de loop van het optimalisatie- en het simulatiemodel: i) Reservoir

beheer wordt geoptimaliseerd over de gehele periode (jaar); ii) Simulatie van stratificatie wordt toegepast over de gehele periode. Het optimalisatiemodel is gebaseerd op de Incrementeel Dynamische Programmeringstechniek. In het optimalisatiemodel wordt het hypothetische reservoir concept zoals gebruikt in bovenstaand model gehanteerd. Echter, communicatie tussen elke twee aangrenzende hypothetische reservoirs is toegestaan in het model. Het eendimensionale simulatiemodel voor reservoir-dynamica simuleert de stratificatie van het reservoir. De toepasbaarheid van de techniek wordt onderzocht voor drie hydrologisch verschillende jaren.

Reservoirs zouden ook kunnen worden gemodelleerd door aan te nemen dat gedurende het jaar complete menging van water door het gehele volume plaatsvindt. Dat is een vereenvoudiging vergeleken met het echte stratificatiegedrag dat plaatsvindt in reservoirs. Gebaseerd op deze aanname worden twee modellen ontwikkeld om de kwaliteit van de water afgifte te verbeteren. In één model worden slechts de uitstromen gestuurd. In het andere model worden zowel in- als uitstroom gestuurd. Optimalisatie wordt gebaseerd op de Incrementeel Dynamische Programmeringstechniek. De resultaten van beide modellen vertonen verbeteringen in de kwaliteit van water verkregen van het reservoir. De verbeteringen verkregen door zowel in- als uitstromen te manipuleren zijn echter duidelijker.

Verbetering van de kwaliteit van water verkregen van een reservoir door het omleiden van de instroom van water van lage kwaliteit en het voldoen aan de kwantiteitseisen stroomafwaarts zijn twee conflicterende doelstellingen. Dit probleem wordt bestudeerd met behulp van technieken voor de analyse van problemen met meervoudige doelstelling. Het reservoir wordt verondersteld gedurende de gehele jaarlijkse cyclus volledig te zijn gemengd door het hele volume. De resultaten tonen dat een voorzichtige balans tussen de hoeveelheid water geleverd voor de gebruikers benedenstrooms en het volume van de omgeleide instromen zou leiden tot een opmerkelijke reductie in het zoutgehalte van de afgifte.

De studie onthult dat de kwaliteit van reservoir-uitstromen zouden kunnen worden verbeterd door onttrekkingen van verschillende diepten in een gestratificeerd reservoir. Echter, de op deze manier verkregen voordelen zijn marginaal voor het onderzochte reservoir. Vergelijkbare verbeteringen zijn waargenomen onder de aanname dat het reservoir compleet gemengd is gedurende het jaar. Aan de andere kant konden door de instromen naar het Jarreh-reservoir te manipuleren deze verbeteringen aanzienlijk versterkt worden. Dat betekent, dat het omleiden van instromen van slechte kwaliteit een veel belovend beheersalternatief lijkt om de kwaliteit van water verkregen van het reservoir te verbeteren. De aanname van complete menging van het reservoir wordt bevestigd voor het gestratificeerde reservoir door de verkregen resultaten. Dientengevolge bewijst een relatief simpele en rechtstreekse methodologie gebaseerd op de aanname van non-stratificatie geschikt te zijn om een dichtheidsgestratificeerd reservoir te beheren.

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About the Author

Kosgallana Duwage Wasantha Nandalal was born at Ratnapura in Sri Lanka on January 23rd, 1958. In August 1981, he received the degree in Civil Engineering from the University of Peradeniya in Sri Lanka. Then he joined the Central Engineering Consultancy Bureau (CECB) of Sri Lanka as a Civil Engineer.

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His PhD study at Wageningen Agricultural University (WAU) was started in March 1991. In September 1991 he returned to Sri Lanka and joined the University of Peradeniya as a lecturer in Civil Engineering. He continued his research while engaged in the teaching activities at the University of Peradeniya. He returned to Wageningen in October 1993 to complete his PhD thesis.

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List of Abbreviations

BOD	-	Biochemical Oxygen Demand
DDDP	-	Discrete Differential Dynamic Programming
DM	-	Decision Maker
DO	-	Dissolved Oxygen
DP	-	Dynamic Programming
IDP	-	Incremental Dynamic Programming
LP	-	Linear Programming
MCM	-	Million Cubic Meters
MO	-	Multi Objective
m	-	meters
mm	-	millimetres
m MSL	-	metres above mean sea level
NLP	-	Nonlinear Programming
O.F.	-	Objective Function
ppm	-	parts per million
SDP	-	Stochastic Dynamic Programming
Sq.km	-	Square kilometres
TDS	-	Total Dissolved Solids

1 Introduction

Water is a finite resource, essential for agriculture, industry and human existence itself. Without water of adequate quantity and quality, sustainable development is not possible. To ensure the availability of water when and where it is needed, and to safeguard its quality in an era of rapid demographic and economic expansion, water resources management will be needed even in humid regions having an abundant supply of water. In arid regions, water resources management is indispensable if we wish to ensure an adequate supply for the most important uses, and maintain the flow and quality of the water source for future generations.

Individuals responsible for water management policies have overlooked the fact that water quantity and quality are different aspects of the same resource, intrinsically linked. Quality cannot be managed independent of quantity. The perception of water as a freely available public good must be abandoned. Its limited supply and competitive economic value must be recognized. Rational use and quality conscious management are the most powerful tools in managing the water quality problems. Therefore, integration of water quality elements into water resources management is essential. Quantity of water, without any reference to its quality, can easily be a meaningless term for general planning and management purposes.

The right quantity and quality of water are not generally available wherever required and whenever needed throughout the year. Often there is either too much of water (floods) or too little (droughts). Therefore, proper water management is essential to control the ravages of floods and droughts. Reservoirs are expected to fulfil this basic task of changing the availability of water in space and time. The usage of the reservoirs is multipurpose. Reservoirs not only release desired quantities of water for domestic, industrial and agricultural uses, but also generate hydroelectric power, provide storage for excess floodwater, facilitate development of inland waterways, and enhance fisheries and recreational potential. It is important to realize, however, that availability of water should not only mean the quantity of water available for different purposes, but also its quality. Advantageously, reservoirs are capable in improving the quality of the water supplied for various purposes besides satisfying the quantity requirement. Thus, reservoir management practices considering both quantity and quality aspects are undoubtedly become important.

1.1 Reservoirs for Quality Control

When a flowing river is dammed and becomes an impoundment, two major changes occur. Both have a marked effect on water quality. First, creating an impoundment greatly increases the time required for water to travel the distance from the headwaters to the discharge at the dam. Second, thermal or density and therefore, chemical stratification may take place. Both the increased detention time and thermal stratification in an impoundment change the characteristics of the water discharged at a given geographical location from what they had been when the stream was free flowing. Some effects of impoundments improve water quality; others deteriorate it (Churchill, 1957; Symons *et al.*, 1967a). This implies the possibility for using the reservoirs for the control of quality of water besides merely satisfying the quantity requirement.

1.1.1 Stratification in Reservoirs

Many lakes and reservoirs become stratified during particular times of the year, so that temperature gradients with depth effectively prevent mixing. In particular in the summer, lakes often exhibit two zones; an upper region of almost uniformly warm, circulating and fairly turbulent water called the epilimnion, and a deep, cold and relatively undisturbed region called the hypolimnion. Each of these two is fairly well mixed while their different densities prevent complete mixing between the two. The transition zone of rapid decrease in temperature separating the epilimnion from the hypolimnion is called the metalimnion. The plane of maximum rate of decrease in temperature is termed the thermocline (Hutchinson, 1957).

The features of thermal stratification of a reservoir, such as timing of turnover and the onset of stratification, the vertical dimensions of the layers, and the temperature of the layers, are the manifestation of a number of reservoir specific characteristics and the influence of various environmental forcing functions. These features of thermal stratification in a particular lake or reservoir are related to the basin morphometry and geography, attendant meteorological conditions (Ford and Stefan, 1980), hydrology, reservoir operations, and the extent of light penetration (Stefan and Ford, 1975; Harleman, 1982). However, weather is more important than morphometry in driving thermal stratification in reservoirs (Ford and Stefan, 1980; Owens *et al.*, 1986).

There are many possible solutions for overcoming the adverse water quality conditions caused by impoundment stratification. The use of reservoir outlet structures incorporating multilevel selective withdrawal intakes is a primary method for the control of reservoir release quality (Austin *et al.*, 1969; Brooks and Koh, 1969; Clay and Fruh, 1971; Dortch and Holland, 1984). These structures permit release of water from various vertical strata in the reservoir, thereby allowing greater water quality control through blending or direct release. In fact this approach takes advantage of the natural characteristics of the strong stratification found in reservoirs. Another method would be to artificially mix the water of various levels within the reservoir to improve its overall quality. This process is called destratification, either complete or partial (Irwin *et al.*, 1966; Symons *et al.*, 1967a; Symons *et al.*, 1967b). Destratification achieved by various means such as mechanical pumping, diffused air pumping, etc., results in a reservoir of approximately uniform density, temperature and perhaps chemistry. Finally, inflows may be controlled in various ways to produce varying amounts of mixing and stratification. For example, warm water discharges may be diverted away before entering the reservoir, skimmed over the surface of the reservoir, or well mixed by a diffusion structure.

Stratified reservoirs usually show a characteristic yearly temperature cycle. At the end of winter the reservoir is isothermal and well mixed. As spring progresses, surface waters are warmed by solar and atmospheric radiation. In addition, river waters will be warmer than the initial reservoir temperature and enter near the surface. These two effects combine to develop warm layers at the surface that increase in thickness with time. These warm surface layers gradually form the epilimnion, and the colder deep waters form the hypolimnion. During the autumn period, the reservoir surface water cools and sinks, resulting in convective mixing of the surface layers. This establishes an isothermal layer at the surface whose depth increases with time. As the inflowing river water cools to a temperature lower than that of the reservoir surface, it no longer enters at the surface but dives to find a level corresponding to its own density. This level is also depend upon the amount of mixing that occurs between the inflow and reservoir water. As the fall and winter seasons progress, the reservoir overturn continues until it is again in an isothermal state. Diurnal temperature variations also may establish a small mixed layer at the surface during the spring and summer months.

1.1.2 Modelling of Stratification in Reservoirs

The desire to manage the quality of the water stored in lakes and reservoirs has led to the development of numerical models for the simulation of the internal dynamics of them. The actual parameters constituting "quality" vary from reservoir to reservoir and range from conservative traces such as temperature or salinity to reacting or growing chemical and biological constituents. Lakes or reservoirs that do not show significant thermal stratification during the yearly cycle could be modelled assuming complete mixing is occurring throughout its volume during the whole year (O'Connor and Mueller, 1970).

However, for reservoirs in which the foregoing conditions do not apply, more complex models have to be developed to predict thermal gradients, density stratification, and the impact that various designs and operating rules may have on these and other physical, chemical and biological quality characteristics of the impoundment water. Much of the development in modelling reservoir dynamics has occurred under the assumption of one-dimensionality, where vertical motions are inhibited and transverse and longitudinal variations are quickly evened out. Even with this great simplification, it is difficult to model the interaction of a number of complex processes occurring in a reservoir. Over the last several decades, many models of varying complexity and success have been produced (Huber *et al.*, 1972; Markofsky and Harleman, 1973; Stefan and Ford, 1975; Imberger *et al.*, 1978). There has also been, to a lesser extent, some development of two- and three-dimensional stratification models (Marjanovic and Orlob, 1987; Young and Lin, 1987); the increasing complexity and computational requirements have severely limited this development. The relative ease with which such models can be manipulated is of great use, if not essential, for a better understanding of the physical processes occurring in reservoirs.

1.1.3 Reservoir Operation with Quality Consideration

There are occasions when the quality of water supplied from a reservoir is of interest besides the quantity. Reservoir dynamics simulation models predict the quality of water in and withdrawn from a reservoir. Hence, these models could be used to investigate various management strategies (based on inflow and withdrawal manipulations) for a reservoir with respect to the quality of water. The scouring of water of poor quality to waste from a reservoir (using a multilevel outlet structure) and the diversion of (by-passing) poor quality inflows before entering a reservoir are two such operation strategies that could be used to improve the quality of supply water (Fischer *et al.*, 1979; Imberger and Hebbert, 1980; Imberger, 1981; Shiati, 1991).

Reservoir dynamics simulation models could be incorporated into an optimization framework, thereby allowing better decisions to be made as to the operation of multi-use reservoirs. The water resources literature presents numerous models based on operation simulation and optimization techniques, for the optimal operation of reservoirs. However, there have been relatively few studies in which water quality in reservoirs had been considered. Even among them the natural process of stratification in the reservoir has been considered only in very few studies (Kaplan, 1981; Fontane *et al.*, 1981). In others water quality in the reservoir has been modelled assuming complete mixing of water is occurring in the reservoir (Foruria *et al.*, 1985; Dandy and Crawley, 1992).

1.2 Statement of the Problem

The systems analytical (operations research based) techniques to derive reservoir operation rules are largely hampered by the fact that they do not account for fundamental (physical) phenomena occurring in the reservoir pool. Instead, the state of the reservoir system is simply described by the single variable, water volume. This approach does not allow the direct involvement of quality criteria. On the other hand lake stratification, secondary currents, eutrophication, sedimentation etc. are inserting a considerable impact upon the reservoir performance. Therefore, attempts to close the gap between modelling these phenomena in (sophisticated) simulation procedure and using optimization techniques to derive operational policy relying on a simple (continuity) equation of the water balance are vital when the quality of water is of concern.

1.3 Objectives of the Study

The increased emphasis on water quality accents the need for formulation of methodologies for operating reservoirs for control of water quality. This study aims at coupling reservoir dynamics with optimization techniques in the derivation of optimum operation policies for a reservoir when the quality of the water supplied is of interest besides satisfying the quantity requirement.

The assumption of complete mixing of water in a reservoir throughout its entire volume during a year is a simplification compared to the real behaviour of reservoirs that undergo mixing and stratification cycles. This study further aims at investigating the ability to model reservoirs based on the complete mixing assumption and studying how adequately this simplification represents the real behaviour.

The Jarreh reservoir in South-West Iran is used to examine the applicability of the methodologies suggested.

1.4 Scope of the Study

With respect to the above outlined objective, several methodologies are formulated for the derivation of optimum operation policies for a reservoir. This section contains a brief description of these different approaches.

1.4.1 Stepwise Optimization-Simulation Model

A methodology combining an optimization model and a simulation model was developed to derive operational policies for a reservoir. The reservoir is to be operated for the improvement of the quality of the water supplied besides satisfying the quantity requirements. A one-dimensional reservoir simulation model "DYRESM" is employed to simulate the stratification in the reservoir. A constrained nonlinear optimization model "ADS" is used to identify optimum releases and scour volumes from the reservoir. The optimization-simulation approach proceeds stepwise in time.

The above method operates on a period-by-period basis and does not directly include anticipation of future conditions. Therefore, a model based on stochastic dynamic programming technique is incorporated to the above methodology to impart uncertainty to the approach.

1.4.2 Iterative Optimization-Simulation Model

A methodology combining an optimization model and a simulation model operating in an iterative fashion is developed for the derivation of operating policies for the reservoir. Both quality and quantity considerations are of interest in the operation of the reservoir. The model "DYRESM" simulates the reservoir dynamics. The optimization model is developed based on incremental dynamic programming technique.

1.4.3 Completely Mixed Reservoir Models

Reservoirs could be modelled assuming complete mixing of water is occurring in it throughout the year. This is a simplification compared to the real behaviour of a reservoir that undergoes mixing and stratification cycles during a year. In this study two optimization models are developed based on the incremental dynamic programming technique. One model uses only releases while the other model uses both inflows and releases in the improvement of the quality of the water supplied from the reservoir.

1.4.4 Multiobjective Considerations in Satisfying Quantity and Quality Requirements

Quality of water supplied could be improved by diverting away the poor quality inflows before entering the reservoir. By diverting more water, more improvements in the quality of the water supplied from the reservoir could be obtained. But the diversion of more water from inflows might affect the downstream quantity demand. Therefore, the objectives of satisfying downstream quantity demand and improving quality of water are two conflicting objectives. This problem is studied under the multiobjective analysis framework. A generating technique, "Weighting Method" is used to generate the nondominated solution for the problem. The reservoir is modelled assuming complete mixing occurring in the reservoir throughout the year.

Table 1.1 illustrates the different models and the techniques used in the study.

Table 1.1 Techniques and Models Used in the Study

Chapter	Model	Techniques/Models used	Description
4	Stepwise Optimization-Simulation Model	DYRESM : One-dimensional reservoir dynamics simulation model ADS : A Nonlinear Algorithm applicable for constrained problems; based on "Method of Feasible Directions"	Approach relies on stratification in the reservoir. Proceeds stepwise in time (monthly steps). Following assumptions are made during the optimization phase: (a) Reservoir is equivalent to several smaller hypothetical reservoirs and there is no communication among them; (b) quality remains unchanged during time step.
	SDP Incorporated Optimization-Simulation Model	Above two models (DYRESM and ADS) and Stochastic Dynamic Programming technique	The above procedure (with above assumptions) is adopted constraining the total of the release and scour volumes to discharges obtained from a SDP model. The SDP model considers quantity requirement only. Monthly time steps are considered.
5	Iterative Optimization-Simulation Model	DYRESM : One-dimensional reservoir dynamics simulation model Incremental Dynamic Programming technique	Approach relies on stratification in the reservoir. In contrast to the above methods, a longer period (e.g., one year or even more, with monthly steps) is considered in one optimization-simulation cycle. Following assumptions are made during the optimization phase: (a) Reservoir is equivalent to several smaller hypothetical reservoirs and communication between adjacent reservoirs are possible; (b) quality remains unchanged during time step.
6	Completely Mixed Reservoir Model 1 (Controlling only Discharges)	Incremental Dynamic Programming technique	The simplification of completely mixing of water in the reservoir during the whole annual cycle is adopted. Quality in the reservoir changes during the time steps. Only releases are controlled.
	Completely Mixed Reservoir Model 2 (Controlling both Inflows and Discharges)	Incremental Dynamic Programming technique	The simplification of completely mixing of water in the reservoir during the whole annual cycle is used. All above models consider manipulation of reservoir releases only. This model considers by-passing low quality (saline) water option, too.
7	Multiobjective Considerations in Satisfying Quantity and Quality Requirements	"Weighting Method" to generate the nondominated solution and Incremental Dynamic Programming technique	By-passing may affect downstream demand supply. This problem is studied under multiobjective framework. The simplification of completely mixing of water in the reservoir throughout the year is used. Optimization Model 2 in Chapter 6 is used with a few modifications.

2 Literature Review

2.1 Systems Approach to Reservoir Management

During last few decades the field of water resources systems analysis has experienced a considerable growth. In one of its main areas, namely reservoir management and operation, mathematical models based on simulation and optimization techniques have been used extensively.

A simulation model is a representation of a system used to predict the behaviour of the system under a given set of conditions. Alternative executions of a simulation model are made to analyze the performance of the system under varying conditions, such as for alternative operating policies. An optimization model is a mathematical formulation in which a formal algorithm is used to compute a set of decision-variable values that minimize or maximize an objective function subject to constraints. Whereas simulation models are limited to predicting system performance for a user-specified set of variable values, optimization models automatically search for an 'optimum' solution.

Although optimization and simulation are two alternative modelling approaches with different characteristics, the distinction is somewhat obscured by the fact that most models, to various degrees contain elements of both approaches. All optimization models also 'simulate' the system. Optimization algorithms are embedded within many major reservoir-system-simulation models to perform certain computations. An optimization procedure may involve iterative execution of a simulation model, with the iteration being automated to various degrees. Various strategies are employed for using simulation and optimization models in combination. For example, a study may involve preliminary screening of many alternatives using an optimization model followed by a more detailed evaluation of selected plans using a simulation model.

2.1.1 Simulation Models

Simulation models have been routinely applied for many years by water resources development agencies and other entities responsible for planning, construction and management of reservoir projects.

Sigvaldason (1976) developed a mathematical simulation model for assessing alternative policies of operation for a reservoir system (45 reservoirs). Every reservoir was subdivided into five storage zones, which were variable in a temporal sense. A time-based rule curve was prescribed to represent ideal reservoir operation. Ranges were prescribed for channel flows, which were dependent on water-based needs. Penalty coefficients were assigned to those variables that represented deviations from ideal conditions. Different operational policies were simulated by altering relative values of these coefficients. The development and use of the model were simplified by representing the entire reservoir system in a 'capacitated network' form and deriving optimum solution for individual time periods with the 'out-of-kilter' algorithm.

Loucks *et al.* (1989,1990) developed Interactive River System Simulation Programme (IRIS) that simulates a water supply and conveyance system of any normal configuration. It also has limited hydroelectric power simulation features. The distinctive feature of the programme is its extensive use of interactive computer graphics for information transfer between machine and user.

Generally simulation models permit very detailed and realistic representation of the complex physical, economic and social characteristics of a reservoir system. The concept inherent in the simulation approach is easier to understand and communicate than other modelling concepts. They are some advantages simulation models have over other types of reservoir analysis.

2.1.2 Optimization Models

Yeh (1985) presented a comprehensive indepth state-of-the-art review of reservoir operation models, with a strong emphasis on optimization techniques. Most of the applications of the optimization techniques to reservoir system analysis involve linear programming (LP) and/or dynamic programming (DP). Various other nonlinear programming (NLP) methods, particularly search algorithms have also been used.

Optimization models are formulated in terms of determining values for a set of decision variables that will maximize or minimize an objective function subjected to constraints. The objective function and constraints are represented by mathematical expressions as a function of the decision variables. For a reservoir operation problem, the decision variables are typically release rates and end-of-period storage volumes. Constraints typically include storage capacities and other physical characteristics of the reservoir stream system, diversion or streamflow requirements for various purposes.

LP has been one of the most widely used techniques in water resources management. It is concerned with solving problems in which all relations among the variables are linear, both in constraints and in the objective function to be optimized. But very often objective functions as well as some of the constraints are nonlinear. By various linearization techniques such as piecewise linearization, first order Taylor Series expansion and iterative schemes this problem has been successfully overcome. The essential advantages of LP include (a) its ability to accommodate relatively high dimensionality with comparative ease, (b) universal optima are obtained, (c) no initial policy is needed, and (d) standard computer codes are readily available. Loucks *et al.* (1981) presented several LP reservoir problem formulations for deterministic problems based on maximizing reservoir yield.

Shane and Gilbert (1982), and Gilbert and Shane (1982) described a model called HYDROSIM used to simulate the 42-reservoir Tennessee Valley Authority (TVA) system based on an established set of operating priorities. A series of operating constraints were formulated to represent the various objectives. The model sequentially minimizes the violation of the constraints in their order of priority. The HYDROSIM model uses LP to compute reservoir storages, releases, and hydroelectric power generation for each week of a 52-week period beginning at the present, based on alternative sequences of historical streamflows. A search procedure was used to handle a nonlinear hydropower cost function.

Palmer and Holmes (1988) described the Seattle Water Department integrated drought-management expert system. A LP model was incorporated in this decision support system to determine optimal operating policies for the reservoirs in the system and system yield. The LP model was based on the two objectives of maximizing yield and minimizing the economic loss associated with deficit from a specified target.

Randall *et al.* (1990) developed a LP model to study the operation, during drought, of a metropolitan water system consisting of multiple reservoirs, ground water, treatment plants and distribution facilities. Four objectives were incorporated in the modelling study: (a) maximizing net revenues, which were the differences between revenues for selling water and electric pumping costs; (b) maximizing reliability, expressed as the minimum of the ratios of consumption to demand for each water use district; (c) maximize reservoir storage at the end of the optimization horizon; and (d) maximize the minimum flow in the streams. Alternative versions of the model were formulated with one objective being optimized as the objective function, with the other objectives being incorporated as constraints at user-specified levels. Trade-off curves were developed to show the trade-off between the four alternative objectives.

Nonlinear Programming (NLP) is not popular in water resources systems analysis compared with the other methods. NLP is usually slow and takes up large amounts of computer storage and time. The mathematics involved is more complicated and cannot easily accommodate the stochastic nature of the system. NLP techniques include search techniques, quadratic programming, geometric programming, and separable programming. Literature on water resources analysis does not contain much on the use of NLP techniques in the operation of reservoir systems.

Chu and Yeh (1978) derived a modified gradient projection technique for an hourly operation model, which they applied to the Shata reservoir in Northern California. The objective was to maximize the sum of hourly power generation over a period of one day. It was subjected to constraints of hourly power schedules, daily flow requirement for water supply and other purposes, and the limitation of the facilities. The objective function was nonlinear concave. The constraints were nonlinear concave and linear.

Simonovic and Marino (1980) applied gradient projection method with a two-dimensional Fibonacci search to solve a reliability problem for single reservoir management. They considered both random inflow and demand in their continuity equation. In their objective function both benefit and risk were considered for a discrete determination of reliability concerning flood and drought.

Dynamic Programming is an efficient mathematical technique for making a sequence of interrelated decisions. It is based on the Bellmann's principle of optimality (Bellmann, 1957) that implies a sequential decision process in which a problem involving several variables is broken down into a sequence of simpler problems, each having a single variable. DP is very well suited to reservoir problems. The DP technique is not restricted to any particular problem structure. It can handle nonlinear objective functions and nonlinear constraints. For most reservoir problems, if DP is applied to determine reservoir releases, the state variable is the storage, the decision variable is the release, and the stage is represented by the time period. Applications of DP to reservoir problems have been many. A number of changes have been applied to the basic concept of DP to make the technique more efficient to certain reservoir problems: differential dynamic programming, constrained differential dynamic programming, reliability constrained dynamic programming, and stochastic dynamic programming. Yakowitz (1982) discussed in detail the role and suitability of dynamic programming in reservoir operation.

Chung and Helweg (1985) combined DP with HEC-3 (multipurpose, multireservoir system simulation model developed by the Hydrologic Engineering Centre of the Corps of Engineers, USA) in an analysis of operating policies for the Lake Oroville and the San Luis reservoir, which are components of the California State Water Project. HEC-3 was used to determine the amount of excess water still available for export after all system commitments were met. A DP model was then used to decide how the reservoirs should be operated to maximize the net benefits of exporting the excess water. The DP decision variables were the reservoir releases in each period, and the objective function was an expression of revenues from selling the water. Since approximations were necessary in formulation of the DP model, HEC-3 was used to check and refine the release schedules determined with the DP model.

Allen and Bridgeman (1986) applied DP to three case studies involving hydroelectric power scheduling: (a) optimal instantaneous scheduling of hydropower units with different generating characteristics to maximize over all plant efficiency; (b) optimal hourly scheduling of hydropower generation between two hydrologically linked power plants to maximize overall daily/weekly system efficiency; and (c) optimal monthly scheduling of hydropower generation to minimize the purchase cost of imported power supply subject to a time-of-day rate structure.

2.1.3 Multiobjective Analysis

Besides the application of LP, DP and NLP techniques, the reservoir problems are also addressed by the multiobjective (MO) analysis. Application of MO approach has many advantages over conventional single objective techniques: (a) noncommensurable objectives can be incorporated in the analysis; (b) trade-off functions are available explicitly so that the reservoir decision makers can formulate more effective decisions; and (c) more realistic problems can be addressed eliminating the requirement of a single objective function. The applicability of MO analysis in reservoir management is wide.

The literature on multiobjective decision making models is substantial. Cohon and Marks (1975) and Goicoechea *et al.* (1979) reviewed the application of multiobjective decision making models to water resources problems. Bogardi and Nachtnebel (1994) presented the application of Multicriteria Decision Analysis in Integrated Water Resources Management comprehensively.

Harboe (1992) presented a possible classification of the numerous amount of multiobjective (or multicriteria) decision making methods presented in literature (Goicoechea *et al.*, 1982; Cohon, 1978) based on the timing of the decision maker's articulation of preferences. The classification is as follows.

(a) Methods that require a-priori establishment of weights by the decision maker. Eg.
   1. ELECTRE I, II (and III)
   2. Compromise (and Consensus) Programming
   3. Goal Programming
   4. Multicriteria Q-Analysis
   5. Multiattribute Utility
   6. Tchebycheff Approach

(b) Methods that require a-posteriori establishment of weights and are used only to find Pareto optimal solutions. Eg.
   7. Weighting Method
   8. Constraint Method
   9. Multiobjective Simplex Method

(c) Methods that use an interactive procedure in which weights are varied by the decision maker during the application until the results are acceptable. Eg.
   10. STEM-Method
   11. Surrogate-Worth-Trade-off-Method
   12. SEMOPS
   13. SIGMOP
   14. Protrade

However, these methods can be classified in other forms also. Further, Harboe (1992) presented six applications of multiobjective decision making techniques for finding optimal or satisfying operating rules for reservoir systems. The techniques applied, include the constraint method, compromise programming, goal programming, Tchebycheff approach, consensus and ELECTRE I and II.

Cohon and Marks (1975) discussed the applicability of the constraint method and the weighting method in the generation of noninferior solutions in a multiobjective problem. In these methods the trade-off values among objectives are explicitly considered, and all noninferior alternatives are found. The major weakness is computational efficiency when there are several objectives. Thus utility of these two methods may be confined principally to problems having two or three objectives. In the present study, to generate noninferior solution set the weighting method and constraint method are used.

Whitlatch *et al.* (1988) used the weighting method (formulation is based on dynamic programming technique) to analyze a multiobjective problem. They examined the management of the Hoover reservoir and its associated pumped-water intertie with Alum Creek reservoir in water supply system of Columbus, Ohio. Optimal monthly operating policies were derived in a multiobjective environment involving trade-offs of pumping and water supply shortage costs, target draft rates and reliability levels.

Yeh and Becker (1982) reported the development of a practical procedure for the analysis of a multipurpose, multi-facility reservoir system to guide real time decisions concerning the optimal operation of a system. Application was made to the California Central Valley Project (CVP). The constraint method was used to develop the trade-offs while a specially modified linear programming and dynamic programming algorithm was used for optimization.

Mohan and Raipure (1992) developed a linear multiobjective programming model and used the constraint technique to derive optimal releases from a large-scale multireservoir system consisting of five reservoirs in India. Maximization of irrigation releases and maximization of hydropower production have been considered as the twin objectives in the model. The optimization was subjected to constraints on physical limitations, environmental restrictions and storage continuity.

2.2 Dynamic Programming in Water Resources Systems Analysis

State-of-the-art reviews with extensive lists of references on dynamic programming and its applications are found in the work by Yakowitz (1982) for several water resources problems and Yeh (1985) for optimal reservoir operation. Models developed for solving reservoir operation problems can be classified by how they characterize the streamflow process. One group of models called deterministic models uses specific sequence of streamflow - either historical or synthetically generated - in deriving operating rules. The other group of models called stochastic models uses a statistical description of the streamflow process instead of a specific streamflow sequence.

2.2.1 Deterministic Dynamic Programming in Reservoir Operation

Hall and Buras (1961) were the first to apply dynamic programming technique in water resources systems analysis. They used DP to solve a problem of capacity allocation among several reservoir sites. A loss function was used to measure the cost and benefit of capacity allocation to different sites.

Larson (1968) introduced the concept of Incremental Dynamic Programming (IDP), putting DP into an iterative context. IDP uses the incremental concept for the state variables. Only a limited state space is considered for a given iteration run. The method starts with a feasible initial solution that can be visualized as a trajectory along the subsequent stages. Traditional DP is then applied in the neighbourhood of this trajectory. At the end of each iteration step an improved trajectory is obtained, which is used as the trial trajectory for the next iteration step.

Computer time and memory requirements are vastly reduced by considering only a limited state space. However, the major setback of using this technique is its possibility to end up at a local optimum (Turgeon, 1982). That can be avoided by starting with large increments to define the imaginary corridor around the actual trajectory and reducing them gradually as the iteration proceeds. Another way to avoid getting trapped at a local optimum is to repeat the iteration with different initial conditions. Finally both approaches, i.e., varying increments and different starting solutions can be coupled (Nandalal, 1986).

Heidari *et al.* (1971) systematized the use of incremental dynamic programming and referred to as Discrete Differential Dynamic Programming (DDDP). Nopmongkol and Askew (1976) analyzed the difference between IDP and DDDP and concluded that DDDP is the generalization of IDP.

Murray and Yakowitz (1979) developed a successive approximation dynamic programming technique using differential dynamic programming principles, constraining a sequential decision variable as applicable to multireservoir control problems in some cases. This approach is known as the Constrained Differential Dynamic Programming (CDDP) algorithm.

Karamouz and Houcks (1987) formulated two dynamic programming models, one deterministic and one stochastic, to generate operating rules for a single reservoir. The deterministic model comprised of a deterministic dynamic programme, regression analysis and simulation. The stochastic model is a stochastic dynamic programme. It describes streamflow with discrete lag-one Markov process. It was concluded that the deterministic model generated rules were effective in the operation of medium to very large reservoirs. The stochastic dynamic programming generated rules were more effective for the operation of small reservoirs.

2.2.2 Stochastic Dynamic Programming in Reservoir Operation

Stochastic dynamic programming is very common in reservoir operation. Since uncertainty is the inherent characteristic of water resources systems, it is often inadequate to opt for deterministic decision models, both for planning and operational stages.

Stochastic nature of the inflows can be handled by two approaches; an implicit or an explicit approach. In the implicit approach, a time series model is used to generate a number of synthetic inflow sequences. The system is optimized for each streamflow sequence and the operating rules are found by multiple regression. During the optimization the synthetic data series are considered as deterministic ones.

Implicit approach optimizes the system operation under a large number of streamflow sequences, at the expense of computer time. It is therefore employed only for long range planning purposes. The explicit approach considers the probability distribution of the inflows rather than specific flow sequences. This approach generates an operation policy comprising storage targets or release decisions for every possible reservoir storage and inflow states in each month, rather than a mere single schedule of reservoir releases.

Butcher (1971) used explicit stochastic dynamic programming to determine the optimal operation policy for a multipurpose reservoir. The optimal policy is expressed in terms of the state of the reservoir indicated by the storage volume and the streamflow in the preceding month.

Loucks *et al.* (1981) presented a stochastic dynamic programming model with application to a single reservoir. That model comprised two periods within a year, each having only two possible discrete inflows and two initial storages.

Stedinger *et al.* (1984) developed a stochastic dynamic programming model that employs the best forecast of the current period's inflow to define the reservoir release policy and to calculate the expected benefit from future operations. Use of the best inflow forecast as a hydrologic state variable, instead of the preceding period's inflow resulted in substantial improvements in simulated reservoir operations with derived stationary reservoir operation policies.

Goulter and Tai (1985) used SDP to model a small hydroelectric system. The variation in the number of stage iterations and the computer time required to reach steady state conditions with changes in the number of storage states has been investigated in this study.

Laabs and Harboe (1988) presented three models based on DP including a deterministic model, an independent probability model and a Markov model for finding Pareto-optimal operation rules for a multiobjective reservoir problem. In the independent probability model, the inflow probabilities of each time step are considered. Inflow transitional probabilities are considered in the Markov model. The Markov model included several objective functions and weights for each objective as needed in a compromise programming analysis of multiobjective decision making. A number of Pareto-optimal operation rules were generated. The final selection of the optimal policy can be done only after simulations with these operation rules have been performed and a multiobjective selection criterion is applied to the results.

Bogardi *et al.* (1988) cited that stochastic dynamic programming relying on discretized storage and inflow state spaces offers an effective way to derive long term optimal operational policies for reservoirs while considering the uncertainties of the inflows. They investigated the impact of varying number of storage and inflow classes upon the operational performance of both single and multi-unit reservoir systems. Different objective functions, constraints and hydrological regimes were considered.

For the analysis of a complex water resources system Kularathna (1992) used reservoir operation optimization models developed based on stochastic dynamic programming technique and incremental dynamic programming technique.

2.3 Reservoirs for the Control of Water Quality

Reservoirs are built to store water to increase its availability by preventing waste during the periods of high runoff. As these storage impoundments became many and were called on to serve more uses and users, the quality of water stored in and released from were under strict scrutiny to determine its suitability for various uses. Therefore, the fully understanding of the advantages and disadvantages of storage impoundments with regard to water quantity and water quality became very important at the planning of water resources development works.

Churchill (1957) examined and presented some changes in the physical, bacteriological, sanitary-chemical and mineral quality of impounded waters in Tennessee Valley that have been observed over a period of approximately 20 years. He showed that although most of the changes result in a generally improved water quality, certain qualities and downstream water uses may be adversely affected. His study revealed that the water released through low-level outlets from deep storage impoundments during summer months is considerably cooler than that flowing in the unregulated stream. Also the released water is less turbid, usually has less colour and odours caused by algae are practically non-existent. He further showed that the bacterial concentrations are normally less than 10% of that in the inflow. Dissolved oxygen concentrations in the outflow during the summer months are normally far below saturation. The B.O.D. of the released water is also low. A reservoir located downstream from significant deposits of iron ore or manganese ore may release through deep outlets water having relatively high concentrations of these minerals in soluble, un-oxidized form.

Churchill and Nicholas (1967) reported a comprehensive water quality field survey made on Tennessee Valley Authority (TVA) reservoirs to study the effect of impoundments on water quality. The study was focused on water qualities, temperature and dissolved oxygen (DO). They observed variation of temperature and DO in the reservoir (with depth due to stratification) during the year.

2.3.1 Reservoir Modelling

The need to manage the quality of the water stored in lakes and reservoirs led to the development of numerical models capable of predicting variations of one or more properties.

Orlob (1992) traced the historical development of water-quality modelling of natural surface-water systems since 1960's. He states that even though the advances in mathematical modelling have enhanced the decision making process, there still are questions concerning the proper role of such tools and how they can be most effectively used in water-quality decision making. His paper includes a brief review of a few of the more widely used models those have been applied to surface-water systems (river systems, lakes and reservoirs, estuaries and coastal systems). This review serves to point out the present state of model development and also the need for implementing those as useful tools in water-quality management.

Raphael (1962) presented a procedure for predicting the temperature of various water bodies from weather records, inflow and outflow characteristics, and the surface area and volume of the body of water. The method suggested was applicable to shallow lakes, flowing streams, and detention reservoirs in which the thermocline is absent and the water is so stirred by wind or current that temperatures are uniform.

Dake and Harleman (1969) developed theories for the time dependent vertical temperature distribution in a deep lake during the yearly cycle of solar heating and cooling. The developed theory was shown to be in good agreement with field observations of temperature distribution in lake Tahoe. A laboratory investigation was undertaken for the dual purpose of providing data for verification of the theory and to investigate the technique of thermal simulation under laboratory conditions. They concluded claiming the possibility to simulate the development of thermal stratification under laboratory conditions.

A mathematical model to simulate thermal behaviour of deep impoundments was formulated by Orlob and Selna (1970). In the model the water mass in the reservoir was sliced into horizontal layers of uniform thickness. They showed that the transfer of energy into deep stratified impoundments is accomplished by four primary mechanisms: advection, direct solar insolation, convective mixing associated with cooling at the surface and 'effective diffusion' identified with momentum transfer within the water body. The initial verification simulation of the model on the Fontana Reservoir in the TVA system was also presented.

Chen (1970) described an ecologic model based on fundamental principles of biology, chemistry and physics. He showed that the basic ecologic processes including photosynthesis, respiration, zooplankton grazing, fish predation, sedimentation, nutrient recycling, and others can be represented by mathematical functions. These functions can be assembled and operated to simulate simultaneously physical, chemical and biological behaviour of an ecosystem. Preliminary tests of the ecologic model showed the reasonableness of the technique. It is concluded that model development and application will aid greatly in development of a more fundamental understanding of eutrophication processes and their control.

O'Connor and Mueller (1970) presented a mathematical analysis of the concentration of chlorides in the Great Lakes, USA. This analysis was based on the assumption that each lake is a completely mixed body of water. They noted a reasonable agreement between the calculated values of the concentration of chlorides (assuming complete mixing) and field observations. It was also shown that the characteristics of each lake determine its response to changes in discharge and control procedures with concern to quality.

Huber *et al.* (1972) presented the development of a mathematical model to predict the vertical temperature distribution in stratified reservoirs. The model was based upon the assumption of horizontal isotherms throughout all phases of the annual cycle. It includes the effects of heat sources and sinks at boundaries, internal absorption of solar radiation and distribution of heat within the reservoir by advection and diffusion. The wind effect is neglected. The model was applied to the prediction of temperature in a laboratory and a field reservoir.

Markofsky and Harleman (1973) presented the development of a water quality mathematical model that is coupled with a thermal stratification prediction model for a reservoir. The quality considered in this study is dissolved oxygen (DO). The water quality model was initially verified by comparing the results with measurements made under controlled laboratory conditions. They also studied the application of the model to the Fontana Reservoir in the Tennessee Valley Authority (TVA) system.

Stefan and Ford (1975) presented the formulation of a one-dimensional reservoir model using a total energy integration approach. They showed that the prediction of daily water temperature distributions in temperate lakes under the effect of variable meteorologic conditions throughout a season is possible using total energy concept. Heat energy input (or output) into a lake includes shortwave (solar) radiation, longwave (atmospheric) radiation, back radiation, evaporation and convection. Mechanical input is by wind. Although energy inputs and losses are computed separately in succession, the method of analysis recognizes and incorporates the mutual interdependence between different forms of energy inputs. Heat energy and mechanical energy are applied successively. The application of the model to two sample lakes is also presented.

Loh and Hewer (1977) developed a two-layer reservoir model with monthly time steps to evaluate the benefit of winter scour policies in reducing long term salinities. The model has two discrete layers, which represent salinities in the upper and lower portion of the reservoir. During winter months streamflow is usually more dense than the water in the reservoir. Therefore, it is placed into the bottom layer, while during summer months it is usually less dense and is placed into the top layer. At the end of summer cooling at the surface completely mixes the reservoir and is accounted for by combining the two layers. Results from the model indicated that reservoir salinities could be reduced if scouring is carried out during the periods of saline winter inflow for years of non critical storage.

Jirka *et al.* (1978) presented the physical and mathematical background of temperature prediction models and their verification with field and experimental data. They further discussed the various heat transport phenomena in natural reservoirs and in cooling impoundments. In this study, impoundments were classified into four major types; (a) natural deep lakes and reservoirs with seasonally induced vertical stratification, (b) deep stratified cooling lakes, (c) shallow vertically mixed cooling ponds with longitudinal dispersion effects and (d) shallow vertically mixed cooling ponds with internal circulation patterns. Their verification with field and laboratory data was given for each type.

Octavio *et al.* (1980) presented a flexible computer model that was based on the physical and mathematical basis of the report mentioned in the above reference. This one-dimensional model "MITEMP: M.I.T. Transient Temperature Prediction Model for Natural Reservoirs and Cooling Impoundments" is applicable to different commonly occurring lakes and reservoirs of different geometries.

Imberger *et al.* (1978) described a model that uses a Lagrangian system of horizontal layers in which the thickness of the layers responds to expansion and contraction caused by inflow and outflow. Layers above the affected layers move vertically and change thickness to accommodate a total volume change. Mixed layer deepening is modelled by an integrated energy model, which incorporates the processes of convective overturn from surface cooling, wind stirring, and shear stress at the base of the mixed layer resulting from internal seiches. Mixing in the hypolimnion is modelled by an eddy diffusivity parameterization. The parameterizations do not change in application of the model to different lakes. The model constructed from the basic dynamical considerations, appears to simulate well the extreme behaviour encountered in the test year.

Patterson *et al.* (1984) showed the applicability of the one-dimensional dynamic reservoir simulation model DYRESM for two lakes, the Wellington reservoir in Western Australia and the Kootenay lake in British Colombia, which widely differ in geometry and size. Both lakes were shown to be satisfying one-dimensional criteria by estimating the non dimensional numbers, Wedderburn number, internal Rossby radius of deformation and internal Froud number. But the dynamics of epilimnion of the small Wellington lake were dominated by stirring from surface wind and cooling whereas shear at the pynocline (the plane separating the two layers of different density) was also significant in the larger Kootenay lake. Shiati (1991) applied the model DYRESM for the Jarreh reservoir in Southern Iran.

Harleman (1982) gave brief history of the development of physical and mathematical techniques for predicting the hydrothermal structure of lakes and reservoirs. He stated that the laboratory models have played a key role in the development and testing of early mathematical models based on the vertical diffusion concept. He demonstrated the sensitivity of these models to variations in turbulent diffusivity, internal heat absorption and vertical advection due to inflows and outflows.

Marjanovic and Orlob (1987) developed a two-dimensional finite element hydrodynamic model which is capable of describing accurately the spatial and temporal distribution of hydrodynamics (velocity fields, pressure and density) and water quality (temperature and salinity) characteristics of flow within a reservoir, which is stratified due to the combined effect of temperature and salinity. Using this model, they showed the importance of salinity on density stratification. The increased salinity was observed to be intensifying temperature gradients, that is to increase the differences in the temperature of successive water layers in a reservoir.

Young and Lin (1987) modelled reservoir dynamics using finite elements. They simulated a transient two-dimensional hypothetical irregular reservoir for different wind and thermal loadings. By changing the appropriate initial and boundary conditions it was shown that the major characteristics of the reservoir dynamics could be simulated by the finite element analysis.

Michioku and Kadoyu (1992) performed an analytical work to examine the effects of lake depth and meteorological factors upon thermal regimes in lakes. The stratified temperature field was analytically described by means of a one-dimensional mixed-layer model. The computed seasonal development of temperature field and surface heat exchanges were in satisfactory agreement with field data. Based on the model, two dimensionless governing parameters, dimensionless amplitude of an equilibrium temperature and dimensionless depth of the water body were obtained. With those, a parametric analysis was performed. Based on the analysis they showed that lakes could be classified into three categories; (a) stratified lakes, (b) moderately mixed lakes and (c) well mixed lakes.

2.3.2 Operation of Reservoirs for Quality Control

Symons *el al.* (1967a) reported changes in water quality parameters in an impoundment due to increased detention time and thermal stratification. They further demonstrated the influence of mechanical mixing on impoundment water quality by comparing the quality parameters in a stratified impoundment with those in an artificially destratified impoundments. In their study the water quality characteristics investigated were grouped into three categories as;

(a) physical characteristics; temperature and total suspended solid concentration,
(b) dissolved oxygen and related parameters; DO, manganese and sulphide concentration,
(c) nutrients and related biological population; nitrogen and phosphorous concentrations, total algal population and blue-green algal population.

Finally they concluded that artificial destratification of impoundments by pumping water from the bottom and discharging it at the surface as an effective engineering method of improving water quality of impounded water bodies.

Austin *et al.* (1969) described the design and performance of multilevel outlet works of four reservoirs. They showed that the requirement for number, location, capacity and operating arrangement of the intakes for multilevel outlets for selective withdrawal varies widely among different reservoirs and should be determined to fit the particular set of conditions at hand for effectiveness and economy. Based on the observations made at two reservoirs, they further stated that the multilevel outlets alone may not be the complete solution to water quality stratification problems in some reservoirs. Supplemental means such as copper sulphate treatment for algae and destratification to some degree by air injection may be justified for those reservoirs.

Wunderlich and Elder (1969) developed a method based on the principles of thermohydrodynamics of reservoirs, to illustrate how factors such as reservoir geometry, intake elevation and operation, inflow quantity and its temperature as well as climate will influence reservoir water temperature (spatial and temporal distribution), a dominating water quality parameter. This method was applied to two reservoirs on the Tennessee river to study the influence of intake elevation and reservoir operation on reservoir and discharge water temperature. It was shown that dependent upon the combination of these factors the same sole reservoir could produce variety of temperature patterns ranging from the release of warm surface water to cold winter water all the year.

Brooks and Koh (1969) presented a review of analysis and experiments for withdrawal layer flows from linearly stratified fluids. This covered steady two-dimensional withdrawal flows, steady three-dimensional withdrawal flows and unsteady flows. They investigated selective withdrawal in discrete-layer systems briefly. An extension to turbulent flows has also been proposed. They stated that as a technique for water quality management, selective withdrawal is somewhat overrated for continuously stratified flows. The temperature of water withdrawn at an outlet may be that of the water column at that level but nonetheless the discharge is a blend of water from the entire withdrawal layer thickness, which should vary within a very large range. The withdrawal will be most selective when withdrawal layer thickness is small or when the unit discharge is relatively small and the stratification is very strong.

Nece *et al.* (1970) prepared a register of selective withdrawal works in U.S. reservoirs. This report presented information on 90 projects including the agencies from whom more specific information might be obtained on particular projects, which can be of assistance in the planning of selective withdrawal works. Selective withdrawal intake type (free standing vertical towers, inclined structures and structures on the face of the dam), purpose of the project, dam height and type, reservoir capacity, selective withdrawal range, withdrawal gate type, size and number and reference intake elevations are some data listed in this register. This report records that selective withdrawal from predetermined reservoir elevations for improving and controlling downstream water quality has been an objective in design and operation of many reservoirs.

Clay and Fruh (1971) investigated the usefulness of the selectivity of withdrawal from reservoirs in the management of reservoir release quality. Their results indicated that water layers of varying thickness could be withdrawn more selectively at lower rates than at higher rates of flow. The dimensions, width and height, of the withdrawal port were among the variables found to affect the stratified flow profile. The wider port of narrower height (line sink) caused a much thinner withdrawal layer, which would allow considerably more selectively in discharging desirable or undesirable water.

Imberger (1981) used the dynamic reservoir simulation model DYRESM to investigate the response of the Wellington reservoir to changes of streamflow salinity and outflow strategies. He studied the impact of the increases and decreases of inflow salinities have on the average reservoir salinity. The study indicates that the scouring a reservoir as beneficial only if it is carried out at the appropriate time and if not might have detrimental effects. By-passing water of high salinity concentration was shown to be the most effective method in reducing salinity. But this is at the expense of a reduction in water for irrigation.

Gaillard (1984) developed a one-dimensional vertical model, which simulates water quality in reservoirs and used for the study of the influence of outlet location on both reservoir and outflow water quality. Three different outlet locations were considered on the Grangent reservoir in France, as well as various conditions in inflow water quality, reservoir size and reservoir operation. The thermal structure of the reservoir was observed to be dependent of the outlet location while outflow temperature was less affected. This was related to the fact that in this reservoir the volume of water contained in the bottom of the reservoir is very small compared with the total capacity and the average throughflow. The capacity of the reservoir for stocking cold water is therefore limited and the outflow temperature is mainly governed by the inflow temperature and the meteorological conditions. It was also shown that when the retention time that is defined as the ratio of the reservoir capacity to the average throughflow during the stratification period is large, a relatively significant temperature gradient develops in the reservoir. That can be used for the efficient outflow temperature management through selective withdrawal to be considered.

Spigel and Ogilvie (1985) presented field measurements, laboratory experiments and computer modelling results for two periods during which different selective withdrawal policies were followed in the operation of the Upper Huia reservoir in New Zealand. The major conclusion drawn from the results is that selective withdrawal significantly affects the strength and form of density stratification in reservoirs with residence times (defined as reservoir volume divided by average annual outflow rate) less than or on the order of the summer stratification period. They showed that the stratification may be either strengthened or weakened depending on the withdrawal strategy. Stratification in turn affects dissolved oxygen and water quality regimes. The reservoir simulation model DYRESM has been applied in this study.

Dortch and Holland (1984) presented a numerical procedure for the design of a selective withdrawal intake configuration of a reservoir. The procedure was accomplished through the coupling of a reservoir thermal simulation model and a mathematical optimization algorithm. The reservoir thermal model WESTEX predicted the downstream temperatures and intake temperature profiles. Two nonlinear optimization techniques, a Cyclic Coordinate Search with Golden Section line search and Powell's Method were tested and the first was selected as the better one for the model. This report contains a case study in detail to illustrate the utility of the procedure.

Owens *et al.* (1986) analyzed the thermal stratification characteristics of a flow augmentation reservoir, the Round Valley Reservoir, New Jersey, during three different years. Substantial differences in the thermal stratification regime of the reservoir were observed in response to the changes in meteorological, reservoir operating and light penetration conditions in these three years. The features of stratification observed to be affected included: the depth of the upper mixed layer, the average temperature of the epilimnion, the temperature gradient in the metalimnion, and the average temperature in the hypolimnion.

Ford and Stefan (1980) demonstrated the effects of morphometry and weather conditions on thermal stratification through the analysis of thermal profiles measured in three morphometrically dissimilar, but approximate, temperate lakes over two years. They showed that weather is more important than morphometry in driving thermal stratification.

Busuiocescu and Meon (1993) showed the usefulness of reservoir water quality modelling in providing information for a suitable project design and for the environmental impact analysis. In their study a model that simulates water quality in a reservoir was applied to two planned tropical reservoirs. They further indicated the importance of having a dynamic outlet structure, which could be used to take water from different elevations to improve the quality of water in the downstream river.

2.3.3 Reservoir Operation Optimization for Quality Control

Reservoirs could be used to regulate river flow to control water quality within a river basin. Jaworski *et al.* (1970) developed a mathematical model for determining optimal flow requirements from multiple reservoirs for downstream water quality control. Water quality parameters considered in the model were limited to temperature, dissolved oxygen (DO) and biochemical oxygen demand (BOD). The model was based on the dynamic programming technique. In this study optimal reservoir release sequences were developed for two different criteria; (a) The 'best' water quality for a given flow requirement; or (b) the minimized release rates for a given water quality requirement. The release sequences were dependent on the choice of optimization criteria.

Based on a simplified water distribution scheme of the Netherlands Verhaeghe (1978) studied the optimal water management of a river/reservoir system when both quantity and quality (salinity) aspects are of interest. In this study he used dynamic programming technique to optimize the operation of a reservoir in the system. In that attempt both reservoir volume and salinity concentration were discretized and functional values were determined for each combination of these discrete values. The accuracy of the solution depended on the level of discretization but finer discretizations increased the computations enormously. It has been assumed that the water in the reservoir and the water fed into the reservoir are completely mixed in the reservoir.

Filimowski (1981) presented a method for the control of a system of reservoirs those are dosing salt water into a river. The idea was to prevent permissible concentrations in the river being exceeded during low water conditions. This problem requiring optimization in deciding discharges from particular reservoirs in a given interval has been modelled using linear programming technique.

In a report by Verhaeghe and Tholan (1983) an optimal allocation problem satisfying both quantity and quality objectives has been analyzed. The objective was to minimize the economic losses that occur due to water shortages and bad water quality. Salinity characterized the water quality in this study. The same problem, allocation of water from a river to three irrigation areas via reservoirs was formulated into four problems having different schematizations. To analyze those four problems, four different techniques and combinations thereof were applied. The techniques used were Linear and Nonlinear Programming, Dynamic Programming and the Lagrange Multipliers Method. Complete mixing of water was assumed to be occurring in the reservoirs in their study. In the model developed based on conventional dynamic programming technique, the volume and salt concentration in the reservoir at the end of a particular time period were treated as two state variables.

Kaplan (1981) presented an approach based on an optimization simulation procedure whereby natural process of stratification was used to control the operation of a reservoir such that water quality both within and released from the reservoir is optimized while constraints are met on other beneficial uses like flood control, recreation etc. In this approach an optimization model and a simulation model have been used interactively. The simulation model provides the state vector of the reservoir depth dependent water quality at a certain time. The constrained nonlinear optimization model that uses expected values of inflows during a time interval and depth dependent water quality at the beginning of that time interval maximizes an objective function formulated using water quality indexes for the reservoir and its discharge at the end of the time period. It results in several different local optima of possible sets of releases through outlets at different levels. The simulation model has been used to compare these potential sets of releases by computing water quality indexes. The choice has been made of the 'best' set of releases for the time period and process is repeated proceeding to the next time interval. The water quality parameters considered in this study are temperature, DO, BOD, total dissolved solids (TDS), pH, nitrates and phosphates.

A methodology combining simulation and optimization techniques was presented by Fontane *et al.* (1981) for determining optimal operational guidelines for selective withdrawal structures to meet downstream water temperature objectives. A one-dimensional reservoir thermal simulation model, which simulates the thermal stratification cycle of a reservoir is interfaced with a new method of formulating dynamic programming problems called objective space dynamic programming to develop the optimal operation. The objective space dynamic programming reduces a large multi-dimensional problem to an equivalent one-dimensional problem and therefore eliminates computational difficulties. An advantage of the approach is that the thermal simulation model is retained in its original form rather than having to be restructured to fit explicitly into the optimization model. An objective function related to release temperature deviation from desired target levels is minimized over a part of the stratification cycle in their study. Nevertheless they claim the possibility of extending the approach for evaluating multiple objectives involving water quality parameters besides release temperature.

Orlob and Simonovic (1981) investigated the operation of a reservoir for the control of water quality (Total Dissolved Solids concentration -TDS - in mg/l) downstream. It included the determination of water quality control storage that should be provided in the reservoir and the best operational criteria and schedule for release of this water. Two strategies for release have been examined. The first involves deterministic simulation of reservoir operation using historic hydrology and fixed targets of water quality to be achieved with the water resources development work downstream. The second entails optimal operation to achieve stipulated quality targets with an objective function formulated to include trade-offs between benefits derived from flood control and water supply and penalties incurred in agricultural produces due to failure to meet water quality targets. A reliability programming algorithm was used for this.

Simonovic and Orlob (1981) presented a risk-reliability programming approach developed for optimal allocation of releases for control of water quality (TDS) downstream of a multipurpose reservoir. Simonovic and Orlob (1984) presented the same approach in a more comprehensive form. Their approach allows the evaluation of optimal risk/reliability values. Risk was defined as a probability of not satisfying constraints given in probabilistic form, e.g., encroachment of water quality reservation (storage) on that for flood control. The objective function included agricultural production losses. Those are functions of water quality, and risk-losses associated with encroachment of the water quality control functions on reservations (storages) for flood control, fisheries and irrigation. The approach was demonstrated using data from the New Melons Reservoir on the Stanislaus River in California. Results revealed that an optimum water quality reservation (storage) exists for a given set of quality targets and loss functions. They showed using a sensitivity analysis the dependence of the optimum water quality reservation on agricultural production losses and hydrologic conditions.

Foruria *et al.* (1985) developed a model for simulating the salinity changes in a water supply storage in a semi-arid environment. The model assumes complete mixing in the water storage in the determination of the concentration of salt in the outflowing water even though the salinity distribution in a water storage is not uniform due to the process of mixing and stratification occurring in it. To minimize the disadvantages occurring due to this assumption, a lagging technique was tested for suitability. That is, all salt inflows were assumed to take a user specified time after entering the lake before the associated salt load is reflected in the salt balance. The results obtained from the model indicated that this lagging assumption does not result in an improved salt concentration over that from the instantaneous mixed assumption. They illustrated the use of the model in evaluating alternative management options and their effects on both quality and quantity of water available from the reservoir.

Labadie and Fontane (1986) showed the applicability of the objective space dynamic programming approach for case studies in optimal reservoir operation, and irrigation scheduling. These studies prove the successful applicability of objective space dynamic programming technique to problems involving upto a 30-dimensional state space. In the study on reservoir operation, the objective is to find the optimal strategies for regulating withdrawal ports in a reservoir on a daily basis such that seasonal deviation from target temperature are minimized. They also presented in detail the sufficient conditions for reaching the global optimality in this technique.

Crawley and Dandy (1989) developed models based on iterative linear programming to study the operation of the southern component of the Adelaide Headworks System in Australia. This scheme comprises of 3 reservoirs on 2 rivers including significant pumping of water from a distant river of poor quality thus making water quality, particularly salinity a major consideration in the system operation. Two separate models were developed for the system. Initially, considering water quantity alone in 'water quantity model' and with salinity consideration included subsequently in 'water quality and salinity model' in which optimization and salinity simulation models are run interactively. The salinity simulation model assumes constant inflow to and release from the reservoirs throughout each month and complete mixing within the reservoir during the month. The technique adopted is as follows;

(a) Run the optimization model (to minimize pumping cost plus the damage cost of salt pumped).
(b) Get the optimum monthly operation policies (pumpages and transfers).
(c) Estimate the average monthly salinities in the reservoirs using the simulation model for the solution identified in step (b).
(d) Modify the objective function in the optimization model to include benefit due to salt spillage.

(e) With the new formulation rerun the optimization model and continue the procedure from step (b).

(f) Stop the cycle when convergence is achieved.

Although the technique does not guarantee global optimum the results appeared reasonably efficient.

Dandy and Crawley (1990) extended the application of the models developed based on iterative linear programming described above, to study the operation policy for the total Adelaide Headworks System, which comprises 10 reservoirs on 5 rivers. Water quality (particularly salinity) is an important consideration in the operation of this system. The results indicated that the optimization model offers the potential for improved operation policy compared with historical operation concerning the quality of water.

Dandy and Crawley (1992) presented the above described study of examining the development of an operating policy for a reservoir system in which water quality (salinity) is an important consideration in more detail. It comprises the formulation of the optimization procedure including the modelling of salinity in a reservoir based on complete mixing assumption.

Martens and Stokes (1990) developed a computer-based decision support system to assist in making decisions on the operation of two reservoirs to improve the release quality (supply salinity). The reservoirs are located in series. The agricultural developments in the catchment area of the lower reservoir have resulted in unacceptable increases in inflow salinities to that reservoir. The upper reservoir is expected to improve the irrigation supply salinities (from the lower reservoir) by releasing fresh water to the lower reservoir in years of high salinity and/or low storage. It also will enable more efficient scouring of saline inflows in winter from the lower reservoir. The decision support system comprises two main components: a forecast of the reservoir storage levels using a catchment rainfall-runoff model and an indication of the importance of scour decisions on the reservoir salinity in the immediate future estimated by the adoption of an algorithm from a reservoir dynamics simulation model DYRESM.

Yekom Consulting Engineers in collaboration with SOGREAH (Shiati, 1995) has carried out a study on salinity control and reservoir management of the Jarreh reservoir in Iran, recently. In that study, natural mixing was assumed to be working within the reservoir. Further, the fluctuation of salt concentration of inflows was assumed to be totally damped by the inertia of the reservoir. Therefore, the salt concentration of outflows was approximately equal to the average concentration in the reservoir. Based on these approximations a global balance approach of reservoir operation, drived by the balance of volumes was suggested to be used in operation policy derivation. The whole methodology of deriving operating policies comprises three steps. At first step, optimal operation rule for the reservoir is resolved by global balance method. As the second step, a detailed study of salinity stratification in the reservoir is performed with the results of the first step. This step yields the water quality of irrigation releases as outputs. At the third step, if the outputs of the second step are not satisfactory, adjustments are provided either in the criteria for the first step or in the operation rule of reservoir.

2.4 Review of Different Techniques in Reservoir Operation for Quality Control

From the foregoing review it is clear that there have been relatively few studies of optimum reservoir operation in which water quality in the reservoirs has been considered. However, due to the increasing demand for water of good quality, the consideration of the quality aspects in the reservoir operation optimization has become very important.

Modelling of even a conservative substance like salt concentration of the release from a reservoir is complex. The assumption of completely mixing of water in the reservoir throughout the year reduces the complexity involved with a stratified reservoir (which is the real case) up to a certain extent. In such a problem besides the continuity equation for water quantity, another continuity equation for salt exists. The continuity equation for the quantity and the continuity equation for the salt content of water in the reservoir are to be maintained. The salt concentration in the reservoir at each point in time is nonlinearly related to the volume and flow variables in the salt balance equation.

To analyze a reservoir optimization problem with quality aspects (salt concentration) using conventional dynamic programming technique, Verhaeghe (1978) and Verhaeghe and Tholan (1983) decomposed it into stages considering two state variables. Those are the reservoir storage volume and the salt concentration in the reservoir, at the end of a particular period. Both reservoir storage and salinities were discretized in this method. In the reservoir operation problem analyzed in their study, the manipulation of the inflows was possible. At each stage two decisions were made namely, on the inflow into the reservoir and on the release from the reservoir. Therefore, it was possible to determine the two decisions uniquely when the state variables (volume and concentration) at the beginning and at the end of the interval are specified.

In those studies an average value of salt concentration (average of the initial and final reservoir salt concentrations) over a particular decision interval was used as the salt concentration in the releases in the decision making. However, the salt concentration is a continuously varying function of flow and storage variables. Therefore, the above simplification would be correct if the time distribution of the salt concentration is linear, which is not the case. Note that the salt balance equation (mass balance) has been used to calculate the salt concentration at the end of the interval.

Further, their approach is applicable when the inflow to the reservoir can be controlled besides the release (or final storage). If the decision variable is only the storage volume at the end of the interval (or release from the reservoir during the interval) the problem cannot be solved using conventional dynamic programming technique treating the concentration of salt also as a state variable. Besides, the use of the average value of salt concentration neglecting its nonlinear distribution within the time interval, in estimating the release salt concentration, also may affect accuracy.

In their analysis large discretization intervals (both state variables) were applied initially. This optimization showed the approximate location of the optimum. Knowing this, in the next step discretizations with smaller intervals were constructed around the approximate location. This procedure improved the accuracy with double computation time. They stated that alternatively a larger number of smaller intervals could be considered to obtain a better accuracy. However, this is less attractive due to the exponential increase in the computation time.

In the present study in Chapter 6 the modelling of the reservoir operation optimization problem including quality aspects (salt concentration) will be attempted considering the reservoir storage volume as the only state variable. Complete mixing of water in the reservoir during the time interval will be assumed. The nonlinear distribution of salt concentration in the reservoir over the time interval will be explicitly considered. Incremental dynamic programming technique (a nearest neighbour technique - a version of DP) will be used in the model.

The use of reservoir outlet works incorporating selective withdrawal structures is a primary method for controlling the quality of release. The optimum operation of these selective withdrawal structures is beneficial. To analyze such a problem, the dynamic programming technique may be applicable (suitable) because of the sequential decision nature of the problem and the ability of DP to handle system nonlinearities conveniently.

Fontane *et al.* (1981) and Labadie and Fontane (1986) presented a technique for solving high dimensional dynamic programming problems that condition optimal solutions on the one-dimensional objective-space rather than the multi-dimensional state-space. In this approach, a one-dimensional dynamic programming formulation in objective-space replaces a high dimensional dynamic programming problem involving the usual discretization of the state-space.

They showed how the problem of determining optimal selective withdrawal structure operations can be solved over an objective-space without the need to include the original state variables (vectors of average salt concentration and/or volume of layers of the reservoir) in the DP optimal value function. This, termed the objective-space dynamic programming approach could reduce the original multi-dimensional problem to a one-dimensional dynamic programming problem.

In the application of the objective-space dynamic programming procedure to the above problem (operation of a selective withdrawal structure), the optimal value of the objective function is determined initially. Then the release policies are decided (set) to meet this objective function value. A detailed description of the methodology could be found in the above mentioned two references. There could be infinite variety of ways to exactly meet the specified discrete objective bounds found at the first step. In other words, this method would normally result in an infinite set of optimal reservoir release policies that could achieve any particular objective target or bound specification.

Objective-space dynamic programming formulation involves discretizations over an "accumulated" objective-space. Therefore, it is important that the algorithm is relatively insensitive to the level of discretization. That is, the practicality of the algorithm is diminished if the interval must be reduced to an extremely small value before reasonably good solutions are obtained.

However, it may still be beneficial to use the objective-space approach for obtaining initial solutions, which can be further refined by other methods. It should be noted, however, that sensitivity to discretization interval and grid size also can be a serious difficulty in state-space-dynamic programming and is certainly not a unique problem with the objective-space approach.

Labadie and Fontane suggest that the problems should be solved under various discretization schemes and the resulting solutions compared. As in any optimization procedure requiring discretization, a good deal of experience may be required to define appropriate levels in the application of this technique.

Crawley and Dandy (1989), Dandy and Crawley (1990), and Dandy and Crawley (1992) adopted an approach combining optimization and simulation techniques to derive operation policies for a system of reservoirs. Water quality (salinity) was an important consideration in the operation of that system. They formulated a model that simulates salinity in a reservoir and it was run with an optimization model that considers only the quantity requirement, in an iterative fashion. The steps involved in the procedure are given in Chapter 2.3.3.

Their optimization (quantity) model was based on linear programming technique. In the quality model complete mixing of water was assumed. This is a simplification compared with the real behaviour of stratification occurring in reservoirs. The results indicated that improved operation policies with respect to reducing the cost involved (due to water of poor quality) could be derived from the methodology. Investigating the potentiality of using their basic approach employed in combining optimization and simulation models to derive operating policies for a stratified reservoir is of interest. Their quality model, which assumes complete mixing of water could be replaced by a reservoir stratification simulation model that represents the real behaviour in a reservoir. Such a model enables the prediction of the quality of water withdrawn through outlets at different levels in a reservoir.

Dandy and Crawley used linear programming technique in their study. The nonlinear objective function in their study was piecewise linearized to fit to the linear programming technique. In water resources systems the objective function and the constraints are most of the time nonlinear. In order to use linear programming technique over simplifications to the problem are required and this makes the results unrealistic most of the time. To overcome that, the linear programming technique can be replaced by dynamic programming technique. Dynamic programming technique can handle nonlinearities conveniently.

Further, this approach demonstrates the viability of linking simulation (reservoir hydraulics model) and optimization in such a way that the basic structure of the simulation model is not compromised to fit into an optimizing algorithm. This is important because simulation modelling has achieved a large degree of acceptance among water system managers and practitioners, but formal optimization tools are often regarded with a high degree of skepticism. The model presented in Chapter 5 of the present study has been formulated based on the above methodology of combining an optimization model and a simulation model, which are interacting in an iterative fashion.

The models that simulate reservoir hydraulics could be used in designing selective withdrawal structures. However, their use can be extended for developing improved operational strategies for selective withdrawal structures. Kaplan (1974) combined a water quality simulation model and a nonlinear optimization technique to determine the operation of a selective withdrawal structure with respect to various water quality parameters (temperature, DO, BOD, TDS, pH, nitrates and phosphates). A scalar water quality index was developed to commensurate and prioritize several different water quality objectives so that a single objective optimization technique could be used. Kaplan's model operates on a period-by-period basis and does not directly include anticipation of future conditions.

In that study the results (quality of water from the prescribed optimum operation) are compared with the quality of inflow only. However, the mere presence of a reservoir may lead (affect) to changes in the quality of water whatever the release policy may be. Therefore, a comparison with a historical release pattern or a policy in which only the quantity has been considered in its derivation is more acceptable to indicate the value of the results obtained. One of the methodologies adopted in the present study in Chapter 4 is based on the basic principles of Kaplan's procedure. Here, a sophisticated reservoir simulation model (DYRESM) has been used. Besides, releasing water of desired quality, scouring of poor quality water from the reservoir would improve its quality. This is also included in the model developed in Chapter 4.

To overcome the primary weakness of this methodology of making decisions period-by-period, integration of a SDP optimization model to the optimization procedure is also suggested. SDP model considers the stochasticity of the inflows explicitly.

A number of studies have examined the use of reservoirs for control of downstream water quality (Jaworski *et al.*, 1970; Orlob and Simonovic, 1981; Simonovic and Orlob, 1981; Simonovic and Orlob, 1984). In all cases, water quality in the reservoir was not modeled. The regulation of streamflows needed to assimilate or dilute waste loads have been studied.

3 Application

3.1 General

The Shapur-Dalaki river basin is located in South-West Iran (long. 52° 20', 50° 45'E, lat. 30° 02', 28° 45'N) and covers parts of Fars and Bushehr provinces as shown in Figure 3.1. The uplands of the basin are mountainous with a maximum elevation of 3000 m above MSL. The altitude decreases to about 20 m at the confluence of the Shapur and Dalaki rivers in the coastal plain.

The total drainage area is approximately 10,000 Sq.km, of which the Shapur river and its tributaries drain 4110 Sq.km of the northern region and the Dalaki river and its tributaries drain 5800 Sq.km of the southern region. The rivers join to form the Helleh river, which debouches into the Persian Gulf.

3.2 Climate

The climate of the Shapur-Dalaki basin is classified as arid; (Shiati, 1991) the average annual rainfall is below 20 percent of the total annual potential evaporation. The degree of aridity is less only in the higher parts of the basin, where the precipitation is higher.

Except in occasional wet years, most precipitation is confined to the winter months in this basin. The dry season lasts from April to October. The total annual rainfall decreases southwards towards the coastal plains and the Persian Gulf. Mean value varies between 600 mm in the upper part of the basin to less than 200 mm along the coast as shown in Figure 3.2 and they are closely related to the elevation of the terrain. Rainfall occurs mainly during the six months of November through April with a peak in mid-winter. In the mountains, part of the winter precipitation falls as snow. The snow cover, however, does not last beyond the end of March. There is only erratic rainfall during the summer season. Maximum and minimum rainfall occur respectively in January and July.

Daily values of precipitation are quite variable. In winter, daily amounts of over 40 mm are rather frequent. They cause considerable runoff from steep, impermeable and sparsely

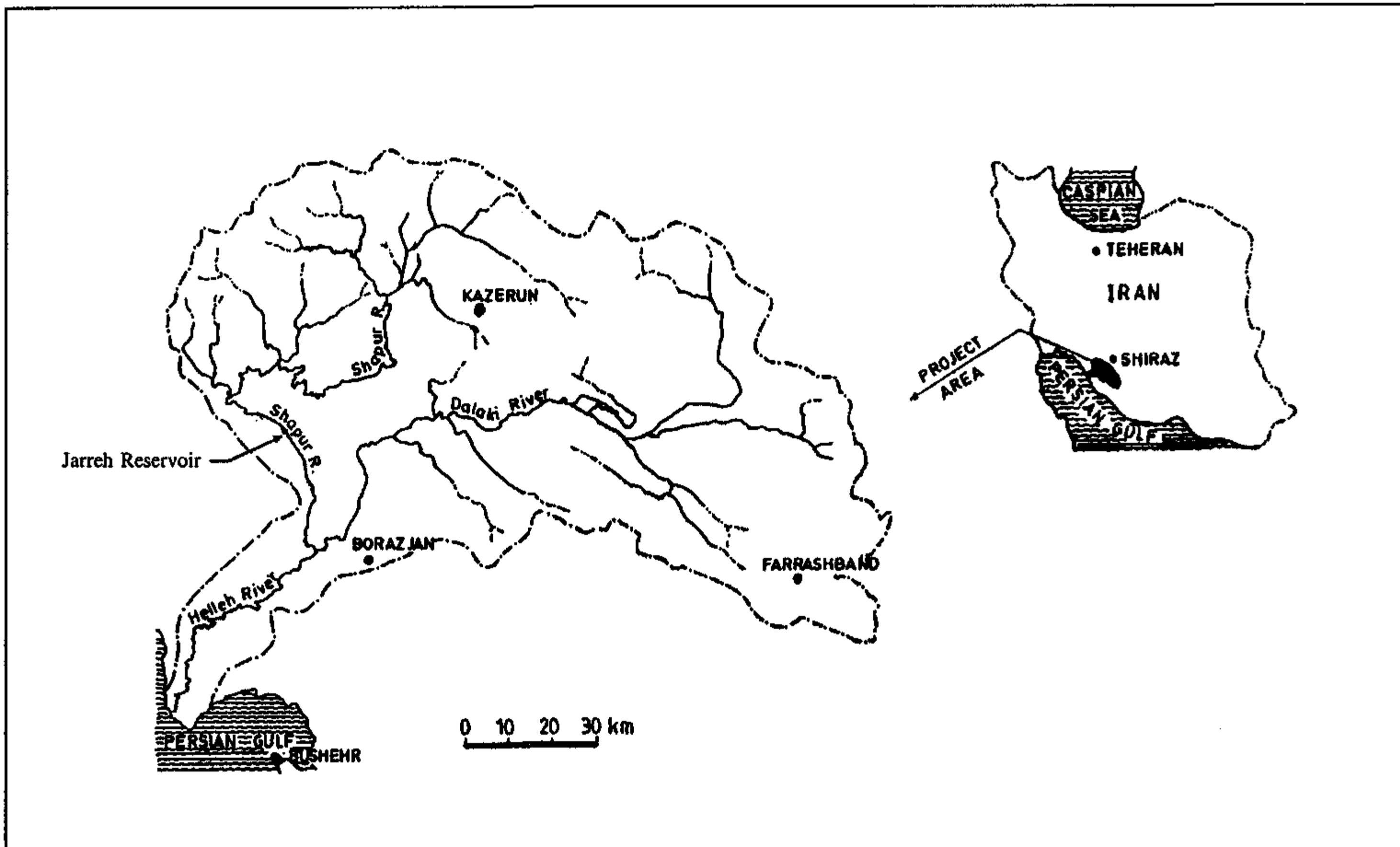

Figure 3.1 The Shapur-Dalaki Basin

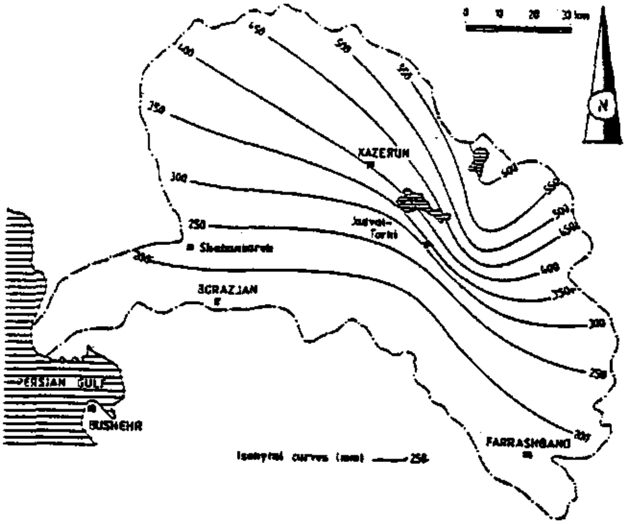

Figure 3.2 Mean Annual Precipitation in the Shapur-Dalaki Basin

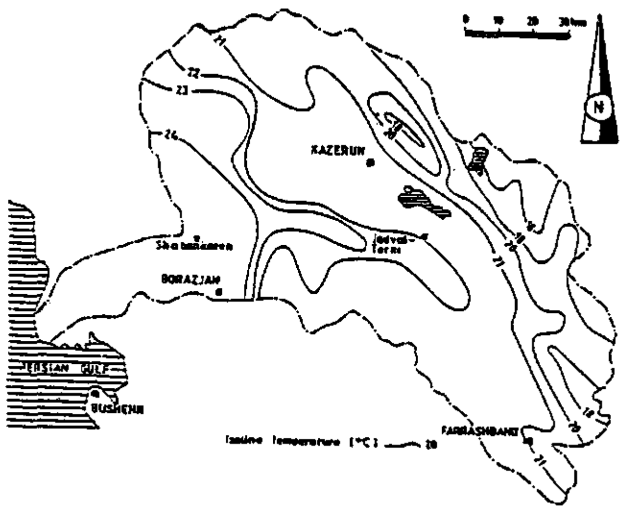

Figure 3.3 Mean Annual Temperature in the Shapur-Dalaki Basin

vegetated hillslopes. There is also considerable variation from year to year. Whereas the wettest year on record (1975-76) had 390 mm measured at Shabankareh Station (Figure 3.2) the driest year (1962-63) did not give more than 73 mm.

In the Shapur-Dalaki basin, a great variation of mean temperature is observed over the year. The mean annual values range between 16°C in the highest (northern) part of the basin and 24°C in the south-western coastal plain as shown in Figure 3.3. The maximum and minimum temperatures occur in July/August and January/February, respectively. Frosts are common in the interior, but rare in the coastal plain. Daily variation in temperature is very high in all parts of the basin. The annual potential water evaporation is high. The total annual evaporation, measured with a Class-A pan, exceeds 3000 mm. After correction for the Class-A pan, the mean annual potential evapotranspiration becomes approximately 2000 mm. The mean yearly values of relative humidity in this area are around 55%, and follow a clear seasonal trend. The monthly averages are upto 72% in January, decreasing steadily to 40% in summer.

Wind velocity has been measured only at Bushehr (Figure 3.2), along the coast, where it is considerable. Wind velocity ranges from 18 km/hr in March to 12 km/hr in June. No data about wind velocities in other parts of the basin are available. But the wind is more feeble further inland. In Shiraz, for instance, the average yearly velocity is only 9 km/hr.

3.3 Hydrology

In this arid climate, recharge of groundwater by winter rains or snowmelt is possible in the limestone areas. The permeable character of these rocks and the thin soil cover promotes such recharges. The outflow of groundwater to the headwaters of the rivers causes a permanent flow in streams like the Renjan and Shirin rivers.

On the other hand, some areas (Miocene formations) are nearly impermeable. Besides, surface runoff from these areas is promoted by the steep slopes and the sparse vegetation. Some small springs occur, probably associated with fault zones. They often yield highly saline water. In the coastal plain, sandy aquifers occur locally, but their water is often too salty to be used for irrigation.

The average annual flows in the Shapur and the Dalaki are about 530 MCM/yr and 425 MCM/yr respectively. The variation of flows from year to year is considerable. Over the period of observation, the annual discharge varies between 124-1270 MCM for the Dalaki river and between 162-992 MCM for the Shapur river. The discharge mainly occurs during winter, and reach a maximum in February.

Average monthly flows in the rivers during the period of observation show a greater variability over the year. The monthly flows also show a greater variability from year to year, still more than the annual totals. These irregularities are due to the vagaries of the climate. The flow in both rivers is permanent, even in dry years, which is an indication for a contribution by outflowing groundwater.

On a daily scale the irregularities are still more pronounced. Especially the impermeable and mostly steeply sloping shales and siltstone cause an almost immediate runoff after heavy rains.

3.4 Water Quality

The Shapur and Dalaki rivers are primarily originating from karstic springs, which yield waters of excellent quality. Further downstream, they are passing through large areas with salt domes and saline erodible formations. As a consequence, they increasingly become contaminated by salts. The severe erosion of these scarcely vegetated and soft materials results in very high silt contents of this water. If the formations are saline, also salts are liberated during this process. Therefore, the runoff carries a considerable salt load although the concentration during these events remains low due to dilution.

If heavy rains are followed by a dry period, the capillary rise will concentrate salts at freshly exposed surfaces, from which they may be dissolved by a following rain. In this way, light rains may result in highly saline runoff from such areas. The Shekastian river (a tributary of the Shapur) for instance, which drains an area largely occupied by the salty Gachsaran formation, has low concentrations but high salt loads during high discharges and high concentrations but lower salt loads at low flows, with salinity sometimes approximating that of sea water.

The high salt contents of water form an obstacle to its use for irrigation. The average total dissolved solids of the river water are listed in Table 3.1.

Table 3.1 Average Total Dissolved Solids (TDS) for the Shapur and Dalaki Rivers

River	Summer (ppm)	Winter (ppm)
Shapur:		
Khesht gauge	2720 - 2780	1740 - 1800
Jarreh gauge	3700 - 4000	2130 - 2440
Dalaki:		
Jireh gauge	1540 - 1830	920 - 1380
Sarghanat gauge	3680 - 3800	1850 - 2110

3.5 Agriculture and Land Use

In the Shapur-Dalaki basin, agriculture has been practiced for centuries. The inland basins filled with fertile alluvial soils and parts of the coastal plain are intensively cultivated. The steep hills and mountains and the saline parts of the coastal plains are used for grazing, mainly with sheep.

The following limitations are found to impede the agricultural development of the alluvial plains:

- shortage of water.
- salinity of water.
- adverse chemical and physical soil properties.

According to Yekom Consult. Engrs. (1980), out of 86000 ha of irrigable lands about 46000 ha could be irrigated through the implementation of several water resources development projects within this basin.

The high salinity - of sodium chloride type - only allows the farmers to grow crops such as date palm, barley, wheat and alfalfa that have sufficient tolerances to salinity.

Soil salinity and sordicity in the coastal plain near Borazjan are major constraints to successful farming in this area. Most of the saline-sodic soils in this plain suffer from high water tables and inadequate drainage. Only along the main rivers, where the natural levees provide sufficient natural drainage, highly productive date plantations are found. Elsewhere, drainage is needed to prevent water logging and salinization.

3.6 Water Resources Development

The Shapur and Dalaki rivers possess a regime of flash floods in winter. During the summer drought their flow falls to very low values. Therefore, only a storage dam could regulate the flow of the river needed to create the conditions necessary for developing the agricultural resources. In addition, salinity can be regulated and improved by careful management of such reservoirs. Several feasible water resource developments for the Shapur-Dalaki basin have been proposed by Yekom Consult. Engrs. (1980). These works include the construction of several storage dams and diversion weirs to irrigate about 46000 ha of land area.

There is a limited potentiality for developing groundwater resources in the alluvial plains due to both quantity and quality of such waters. However, there are plans to abstract ground water from relatively abundant reserves of groundwater such as existing in the Karstic Asmari limestone formations in the south of the Kazerun plain. Even though agriculture has been practiced for centuries in the Shapur basin the shortage of water is found to impede the agricultural development.

3.7 Jarreh Reservoir

The construction of the Jarreh storage dam to irrigate about 13,000 ha in the down stream Borazjan plain is one of the projects coming under the Water Resources Development plan for the Shapur-Dalaki basin. The location of this reservoir is shown in Figure 3.1. The behaviour of the salt-affected Jarreh reservoir is of great concern. The catchment management measures to reduce salinity are less effective in the sparsely-vegetated Shapur-Dalaki basin since the existence of salty formations hamper the plant growth. Shiati (1991) showed that the Jarreh reservoir can regulate and reduce the salt concentration of the irrigation water to a range between 1500 and 2400 ppm from a range between 900 and 4000 ppm. The careful management of the reservoir may further improve the quality of the water released. Therefore, a comprehensive study on the operation of the Jarreh reservoir for the improvement of water quality is vital.

The projected irrigation demands (Shiati, 1991) to be supplied from the Jarreh reservoir are given in Table 3.2. The plan of the Jarreh reservoir is illustrated in Figure 3.4. Effective storage-surface area-elevation relationships of the Jarreh reservoir and the characteristic water levels are shown in Figure 3.5 and Figure 3.6 respectively. The salient features of the dam and the reservoir are summarised in the Table 3.3.

Table 3.2 Monthly Irrigation Demands (for 13,000 ha)

Month	Irrigation Demand (MCM/month)
January	17.5
February	23.0
March	34.0
April	26.5
May	19.5
June	22.0
July	26.5
August	30.0
September	27.0
October	22.0
November	10.5
December	12.0
Total annual demand	270.5

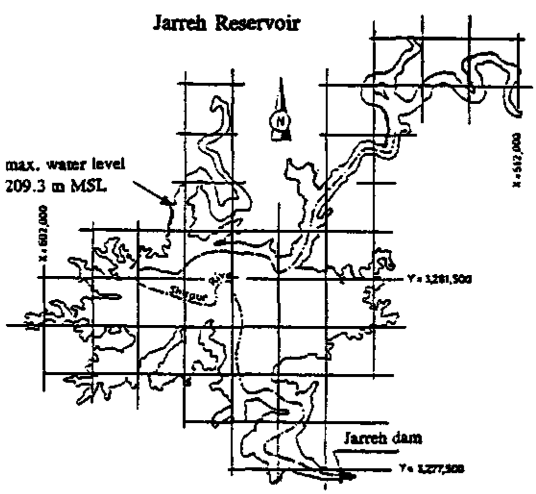

Figure 3.4 Plan of the Jarreh Reservoir

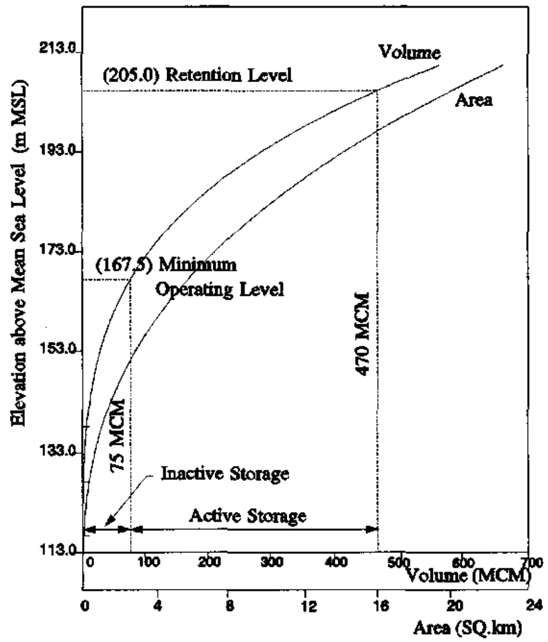

Figure 3.5 Characteristic Curves of the Jarreh Reservoir

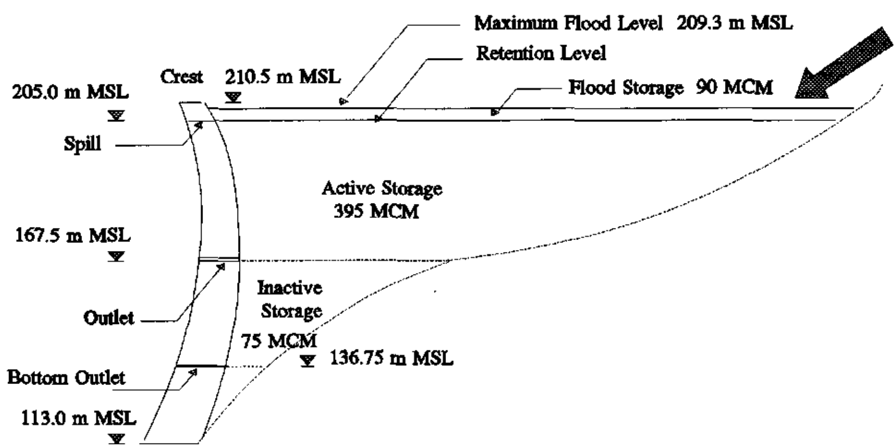

Figure 3.6 Characteristic Water Levels of the Jarreh Reservoir

Table 3.3 Salient Features of the Jarreh Dam and Reservoir

Reservoir			
Normal high water level (Retention level)		205.0	m MSL
Normal storage capacity		470.0	MCM
Minimum water surface level		167.5	m MSL
Minimum storage capacity (Dead storage)		75.0	MCM
Maximum flood level		209.3	m MSL
Water surface area (at normal retention level)		19.5	Sq.km
Dam			
Type	Concrete Arch Dam (Double curvature)		
Elevation at crest		210.5	m MSL
Length at crest		215.0	m
Minimum thickness of dam (at elevation 205.0 m MSL)		3.0	m
Maximum thickness of dam (at elevation 125.0 m MSL)		11.0	m
Spillway			
Number of spillways: 3 (two morning glory and one overflow spillway)			
Morning glory spillway (right bank)	Maximum capacity	1200.0	m^3/s
	sill elevation	205.0	m MSL
Morning glory spillway (left bank)	Maximum capacity	1200.0	m^3/s
	sill elevation	205.0	m MSL
Overflow spillway	Maximum capacity	1650.0	m^3/s
	sill elevation	205.0	m MSL
Total discharge at 209.3 m MSL		4400.0	m^3/s

** Source : Yekom Consulting Engineers (1980)

4 Stepwise Optimization-Simulation Model

Reservoirs get density stratified due to difference in density caused by temperature, dissolved substances and suspended solids. Therefore, the quality of water, even if it is characterized by simple parameters like temperature and salinity, varies with depth. This facilitates in obtaining water of different quality from a reservoir by withdrawing from outlets located at various levels. In this way reservoirs could be managed to supply water of high quality besides merely satisfying the quantity requirements (e.g., Kaplan, 1981; Fontane *et al.*, 1981). This chapter presents an approach for the optimal operation of a reservoir (including quality aspects) relying on the natural process of stratification occurring in it.

4.1 Methodology : Stepwise Optimization-Simulation Model

In this approach, a one stage optimization model and a simulation model are used in a stepwise interaction. A one-dimensional reservoir simulation model "DYRESM" (Imberger *et al.*, 1978) is employed to simulate the stratification of the reservoir. The simulation model DYRESM provides the space vector of the reservoir depth dependant water qualities, namely density, temperature and salinity at a certain time. These depth dependent water qualities at the beginning of the time interval are used by a constrained nonlinear optimization model. It optimizes an objective function formulated based on the quality of the water discharged during the time interval from the outlets at different levels. This optimization model has been developed based on the Method of Feasible Directions for constrained minimization introduced by Zoutendijk (1960).

At the optimization stage the reservoir is assumed to be equivalent to the parallel configuration of a number of smaller hypothetical reservoirs as shown in Figure 4.1. This number is equal to the number of outlets in the outlet structure of the reservoir. There is no communication between these parallel hypothetical reservoirs. The outlet elevations determine the storage volume of each hypothetical reservoir. It is also assumed that there are two openings at each outlet. Through one outlet water is withdrawn to satisfy downstream quantity demand, while the other is used for scouring/flushing the reservoir. In this study water quality status is characterized by salinity only.

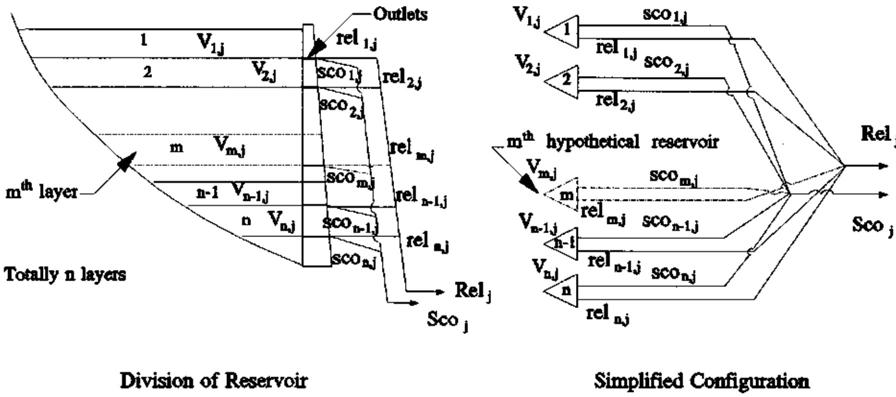

Figure 4.1 Division of the Reservoir and Simplified Configuration

Equation (4.1) through Equation (4.4) define the releases, scour volumes and their salinities during any period j (j=1,2,...,N).

Total release during period j in MCM,

$$Rel_j = \sum_{i=1}^{n} rel_{i,j} \tag{4.1}$$

Total scour volume during period j in MCM,

$$Sco_j = \sum_{i=1}^{n} sco_{i,j} \tag{4.2}$$

Release salinity during period j in ppm,

$$C_{rel,j} = \frac{\sum_{i=1}^{n} C_{i,j} * rel_{i,j}}{\sum_{i=1}^{n} rel_{i,j}} \tag{4.3}$$

Scour salinity during period j in ppm,

$$C_{sco,j} = \frac{\sum_{i=1}^{n} C_{i,j} * sco_{i,j}}{\sum_{i=1}^{n} sco_{i,j}} \tag{4.4}$$

Where,

$C_{i,j}$ = outflow salinity through the outlet i during period j in ppm,
N = total number of periods,
n = number of outlets,
$rel_{i,j}$ = release through the outlet *i* during period j *in* MCM, and
$sco_{i,j}$ = scour volume through the outlet i during period j in MCM, (This is the amount of water released to reduce the salinity build-up in the reservoir).

4.1.1 Optimization Step

The objective in the operation of the reservoir is to find the useful releases $rel_{i,j}$'s and scour volumes $sco_{i,j}$'s, which minimize the weighted sum of squared deviation of release salinity from a target for release salinity and squared deviation of scour salinity from a target for scour salinity during each time period j.

$$O.F. = \underset{j}{\text{Minimize}} \left[W_1 \ (C_{rel,j} - C_{trg,j})^2 + W_2 \ (C_{scour,j} - \hat{C}_{trg,j})^2 \right] \tag{4.5}$$

If, $C_{rel,j} \leq C_{trg,j}$;then $C_{rel,j} - C_{trg,j} = 0,$ and

if, $C_{scour,j} \geq \hat{C}_{trg,j}$;then $C_{scour,j} - \hat{C}_{trg,j} = 0$

The optimization is subjected to the following constraints.

Downstream quantity demand is always supplied, provided water is available in the reservoir.

$$Rel_j = \sum_{i=1}^{n} rel_{i,j} = Dem_j \tag{4.6}$$

If not, (i.e., if $S_j \leq Dem_j$) the amount available in the reservoir is released.

$$Rel_j = S_j \tag{4.7}$$

The total discharge from the reservoir during a time period is constrained by an allowable maximum limit.

$$Rel_j + Sco_j = \sum_{i=1}^{n} (rel_{i,j} + sco_{i,j}) \leq A_j \tag{4.8}$$

The total discharge from an outlet elevation is constrained by its discharge capacity.

$$0 \leq rel_{i,j} + sco_{i,j} \leq B_i \quad ; \ i=1,2,...,n \tag{4.9}$$

Nevertheless, if the stored volume of water in the respective hypothetical reservoir at the beginning of the time period is less than B_i, the total discharge is limited to the stored volume.

$$0 \leq rel_{i,j} + sco_{i,j} \leq V_{i,j} \quad ; \; i=1,2,...,n \tag{4.10}$$

Where,

A_j = allowable discharge (release + scour) from the reservoir during period j in MCM,

B_i = the total allowable discharge through the outlet i in MCM,

$C_{trg,j}$ = target release salinity during period j in ppm,

$\hat{C}_{trg,j}$ = target scour salinity during period j in ppm,

Dem_j = downstream demand during period j in MCM,

S_j = volume of water stored in the reservoir at the beginning of period j in MCM,

$V_{i,j}$ = initial storage volume of sub-reservoir i in period j in MCM, and

W_1 and W_2 are weightages.

Inflows during each time step are neglected in the optimization stage. The ADS (Automated Design Synthesis: Version 1.10), a nonlinear algorithm developed by Vanderplaats (1985) is used to optimize the nonlinear constrained objective function. It has been developed based on the principles of the "Feasible Directions Method", a nonlinear technique applicable for constrained problems. This iterative technique falls into the category of "Gradient Methods". In this method, search steps are taken through the feasible region starting from a feasible point that satisfies all constraints until the optimum is reached. During each step the decisions of defining the direction that is feasible and the size of the step in the selected direction are taken. A detailed description of the optimization method is presented in Appendix A.

Several optimizations are carried out starting from different feasible initial solutions. These optimizations result in a few different local optima of possible sets of releases through the outlets situated at different levels. Out of these, five local optima (if the total is more than five) giving the least objective function values are selected for further investigation. Only five are selected to keep the number of alternatives to be investigated, small. These are the possible gate openings each of which giving a mixed discharge of high quality satisfying the operating constraints during the time period considered.

4.1.2 Simulation Step

Then the simulation model DYRESM is used to compare these potential sets of releases/gate openings. A description of the model DYRESM is given in Appendix B.

At this step the reservoir operation is simulated for the five selected sets of gate openings during the time period. On contrary to the optimization step, which has been carried out in a pseudo-steady environment the actual inflows and inflow salinities are considered in the simulation stage. These will lead to different stratification patterns within the reservoir.

The final choice among the preselected five alternative release policies is based on the results of the simulation. Both the 'real' release salinities and the salinity of the water remaining in the reservoir will be estimated by the simulation. The actual gate opening policy is associated with the 'best' release policy as confirmed by the simulation. Once the choice is made of the 'best' set of releases for the time period the computation proceeds to the next time interval.

4.1.3 Optimum Operation

The optimum operation pattern for a longer period (year) is obtained by proceeding in steps of smaller time periods (month). The optimum operation pattern obtained thus could be interpreted as a sequence of local optima. Figure 4.2 displays the optimization approach.

In this period-by-period based technique the anticipation of future conditions is not directly incorporated into the decisions made during a certain period. Therefore, these decisions made sequentially can be regarded as myopic.

4.2 SDP Incorporated Optimization-Simulation Model

Water quality objectives are considered secondary in the operation of most reservoirs in practice. Instead reservoir operation policies are derived based on the primary purposes such as water supply (for drinking and irrigation), hydroelectric generation and flood control. Once the total quantity of water to be released from the reservoir is specified based on the primary purposes, it may be possible to improve the quality of water supplied by making these releases through the outlets at different elevations.

In the approach presented in this chapter, a reservoir operation optimization model developed considering the long term interest of satisfying the downstream quantity requirement is employed to obtain the total amount of water to be released from the reservoir in a time period (month). This optimization model was developed based on stochastic dynamic programming (SDP) technique. It considers the satisfaction of the downstream quantity requirement only. Once the total quantity to be released in a month is established, the next step is to decide the most desirable way to make the releases from the outlets at different elevations to improve the quality of water supplied during that period. The optimization-simulation procedure in the previous chapter is capable in this task. The incorporation of the SDP model into the decision process enriches the optimization-simulation procedure (presented previously) by giving due attention to the future uncertainty regarding inflows.

Therefore, the whole process of deriving operating policies for the reservoir is in two levels. They are;

(i) deriving operation policies for the reservoir based on a SDP model that considers quantity only, and

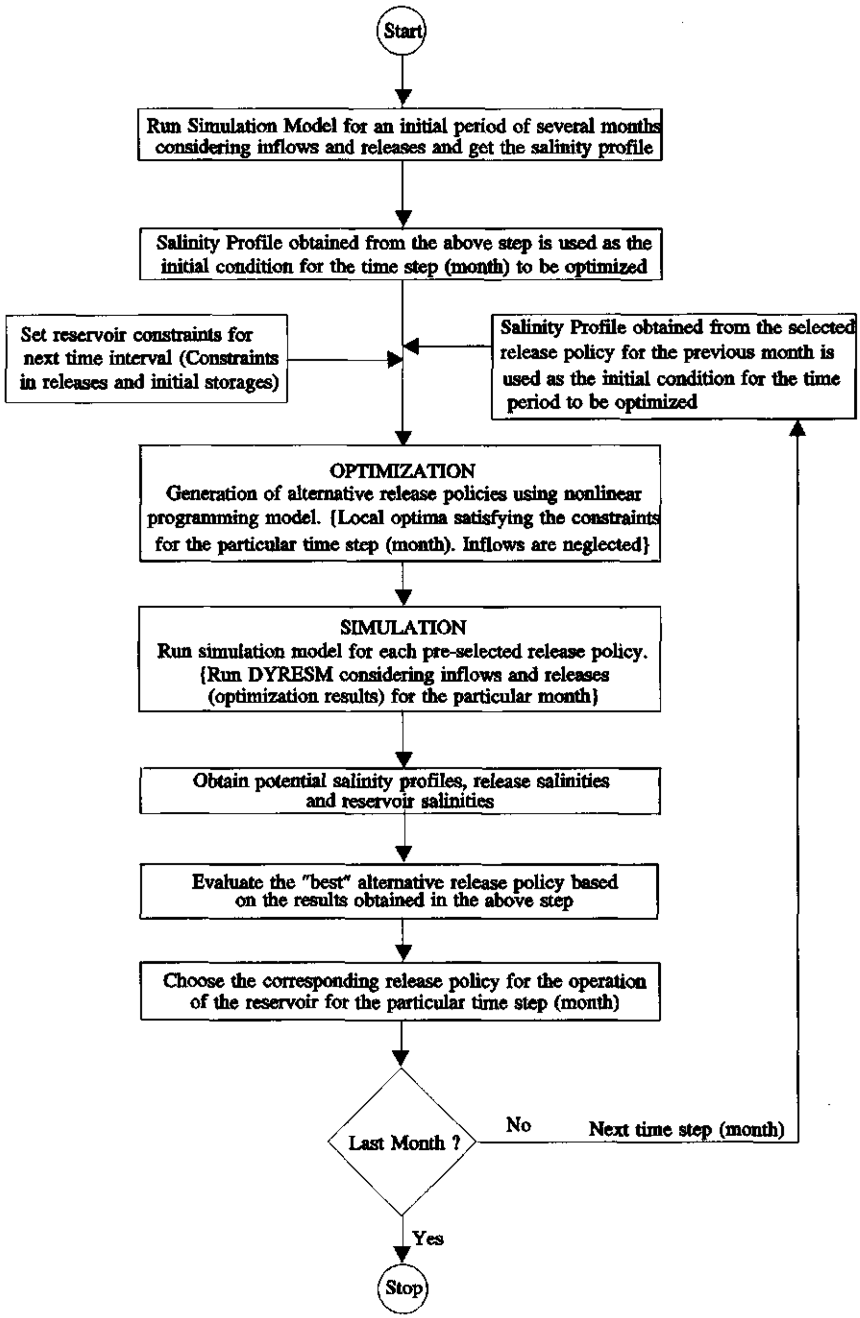

Figure 4.2 Methodology Flowchart : Stepwise Optimization-Simulation Model

(ii) deciding the releases and scour volumes and the outlet elevations for releasing these volumes based on the stepwise optimization-simulation procedure. The total of the useful releases and scour volumes is the SDP defined discharge for the particular period obtained at the above step.

There are several studies reported in water resources literature where solution to reservoir operation problems has been tackled through algorithms comprising of several levels both in space and time (e.g., Simonovic and Marino, 1980; etc.).

4.2.1 Stochastic Dynamic Programming Model

SDP is an optimization model based on Bellman's principle of optimality (Bellman, 1957). Application of SDP to water resources systems has been investigated by many authors (Goulter and Tai, 1985; Kularathna, 1992; Bogardi *et al.*, 1994 and many more). Huang *et al.* (1991) described four classes of SDP models that can be used in the reservoir operation optimization based on current or past inflow and conditional and unconditional inflow transitional probabilities. In the model developed for this study, one of those types, in which the unconditional probability distribution of inflow represents stochasticity inherent in the inflows has been used. Because the linear correlations between inflows of two consecutive periods (month) were observed to be insignificant. In the formulation of the model the time periods were considered as stages. The stored volumes of water in the reservoir at the beginning of the time periods represent the state of the system. The decisions to be taken at each stage are the quantities of water to be released. That can be identified by specifying the storage volume at the beginning of the next stage. As inflows are also defined as a state variable in SDP formulations, the model has a two-dimensional state variable consisting of the storage volume and the inflow to the reservoir.

The state variables, inflow to the reservoir and reservoir storage volume, were discretized to represent them by a finite number of characteristic values as required by dynamic programming (DP). The backward stochastic dynamic programming algorithm (Loucks *et al.*, 1981) was used for optimizing the reservoir operation. The SDP procedure starts by initiating the value of the objective function at the last stage to zero, or to any other arbitrary constant value. The backward algorithm by stages is continued until a stable policy and constant expected annual return from the operation of the reservoir has been found. One iteration cycle comprises 12 stages (months) of computation. The cumulative expected return grows up by setting the value of all output states of each iteration to the value of corresponding input states of the last iteration.

After a few iterations the increase in value for any state over a period of one year becomes constant and independent of the state. This is the expected annual return from the operation of the reservoir. The stabilization of the expected annual increment of the optimum value is used as the criterion that determines convergence of the algorithm. The operation policy designated by the SDP model developed in this study is a set of rules specifying the storage level at the beginning of the next month for each combination of storage level at the beginning of the current month and inflow during the current month.

4.2.2 Formulation of the SDP Model

The system configuration used in this model is displayed in Figure 4.3.

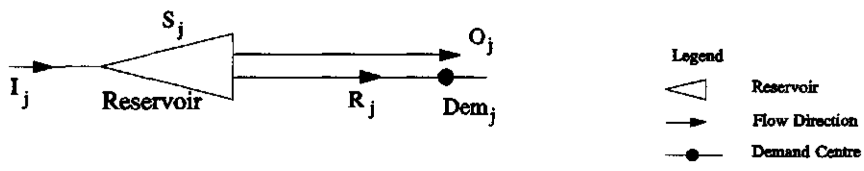

Figure 4.3 System Configuration : SDP Model

The objective function used in this model is to minimize the expected value of one sided squared deviation of the releases from the demands over the total period. It is expressed in mathematical terms as,

$$\text{O.F.} = \text{Min}\ \mathscr{E}\left[\sum_{j=1}^{N}(R_j - Dem_j)^2\right] \tag{4.11}$$

$$\text{If,}\quad R_j \geq Dem_j \ ;\ \text{then}\quad R_j - Dem_j = 0.0$$

Where,

$\mathscr{E}$ = denotes the expectation,
Dem_j = downstream demand during period j in MCM,
R_j = the total discharge from the reservoir during period j in MCM, and
N = number of time steps in a year.

It is assumed that the reservoir has 'n' number of outlets. The allowable release from the reservoir depends on the volume of water stored in the reservoir at the beginning of the month (ref. Figure 4.1 for the definition of 'm'). That is, if the amount of water stored in the reservoir at the beginning of the time period (month) is upto the m^{th} sub-reservoir, then water could be released through the outlets upto m^{th} sub-reservoir only. Thus, the maximum discharge is the total of the maximum allowable discharges of the sub-reservoirs upto the m^{th} one. i.e.,

$$\text{If,}\quad \sum_{i=1}^{m-1} V_{i,j} \leq S_j \leq \sum_{i=1}^{m} V_{i,j} \tag{4.12}$$

$$\text{then,}\quad 0 \leq R_j \leq \sum_{i=1}^{m} B_i \quad ;\ j=1,2,...,N$$

The variables are as defined before.

The storage of the reservoir during any stage must be within the limits of minimum and maximum live storage capacity.

$$S_{min} \leq S_j \leq S_{max} \quad ; \ j=1,2,.....,N \tag{4.13}$$

Where,
S_{max} = maximum storage of the reservoir in MCM, and
S_{min} = minimum storage of the reservoir in MCM.

State transformation equation is according to the principle of continuity.

$$S_{j+1} = S_j + I_j - R_j - E_j - O_j \tag{4.14}$$

Where,
E_j = evaporation in period j in MCM,
I_j = inflow during period j in MCM, and
O_j = spill in period j in MCM.

The recursive equation for SDP optimization is expressed as follows;

$$F^n_j(k,p) = \underset{l}{Min} \left\{ B_{kplj} + \sum_q P_q^{j+1} * F^{n-1}{}_{j+1}(l,q) \right\} \tag{4.15}$$

Where,

B_{kplj}	=	squared deviation of the release from demand when the system changes from state k to state l when inflow class is p in stage j,
$F^n_j(k,p)$	=	the accumulated expected value of squared deviation of release from the demand obtained from the optimal operation of the system over the last n stages,
P_q^{j+1}	=	unconditional probability of inflows (Probability that the streamflow to the reservoir at month j+1 falls in state q),
k	=	the storage state of the reservoir at the beginning of month j,
l	=	the decision space consisting of the representative values of reservoir storage states at the beginning of the subsequent month,
p	=	the inflow state space consisting of the representative values of the inflow states during stage j, and
q	=	the inflow state space consisting of the representative values of the inflow states during stage j+1.

The outline of the SDP procedure is displayed in Figure 4.4.

4.2.3 Optimum Releases and Scour Volumes

Then the optimization-simulation procedure in the Chapter 4.1 is used to determine the optimal releases and scour volumes from the outlets at different elevations. The inclusion of the quality consideration appears at this step. The optimal monthly discharges obtained from the developed SDP policy are used as constraints in releases (A_j in Eq.4.8) at this step.

Figure 4.5 presents the method described in Chapter 4.2.

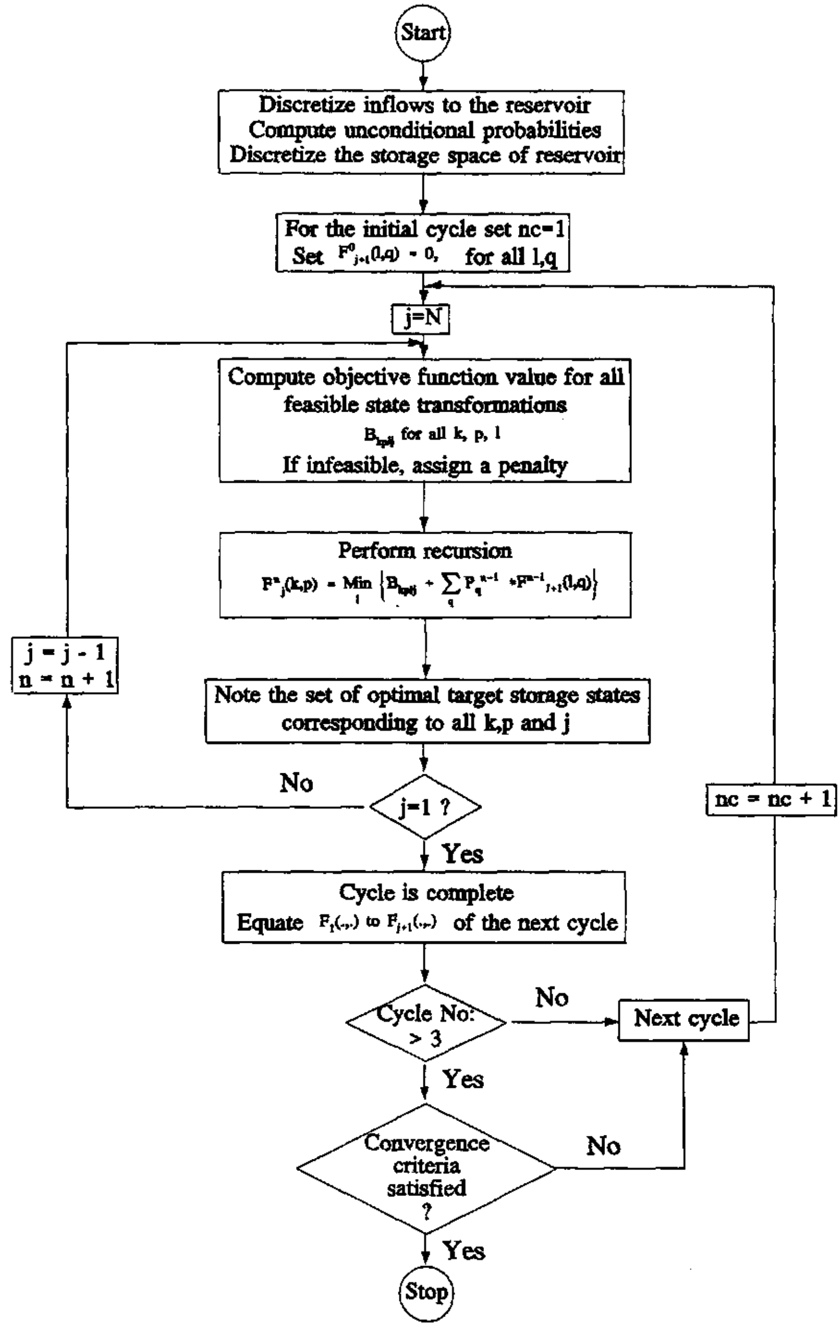

Figure 4.4 Flowchart of the SDP Model

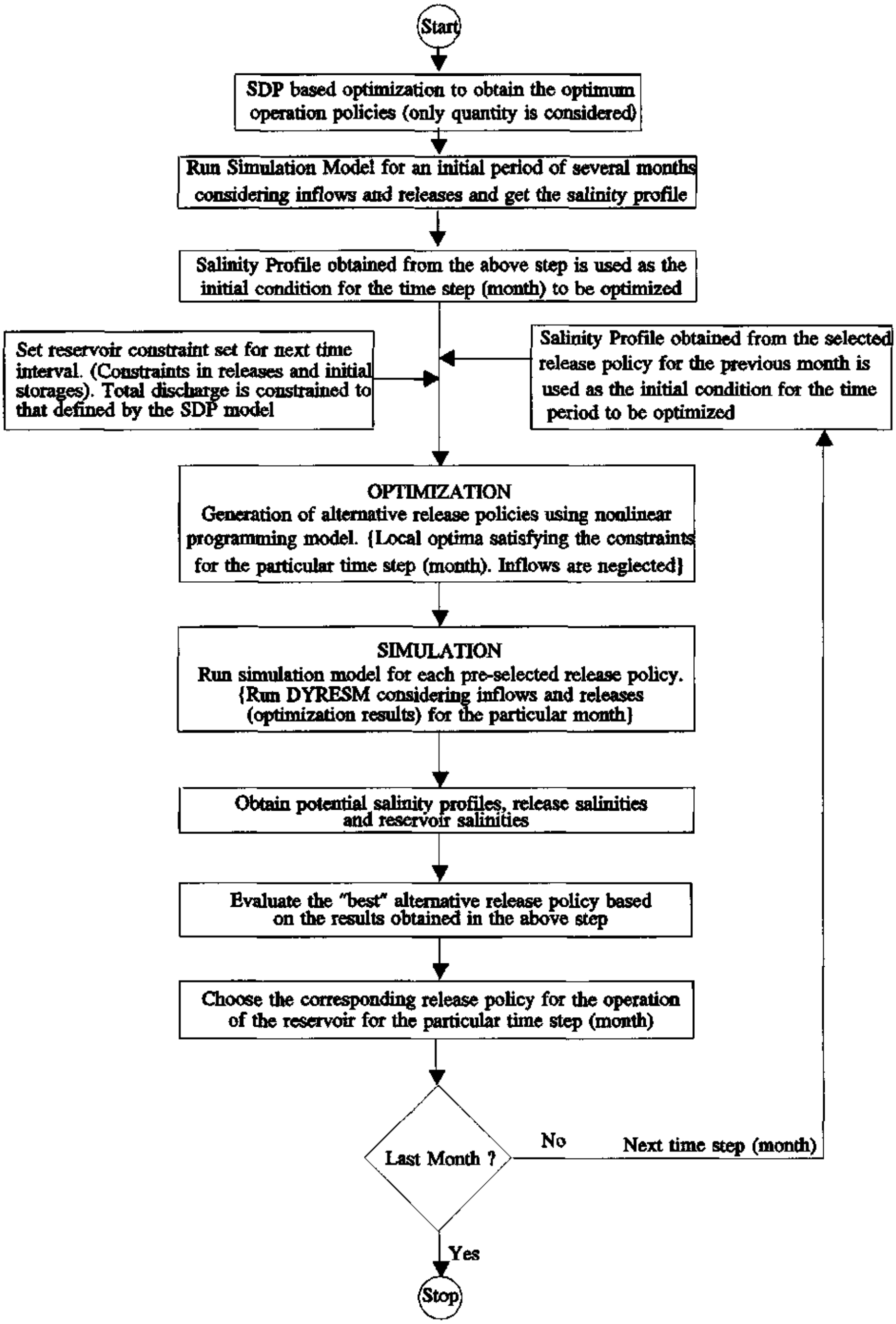

Figure 4.5 Methodology Flowchart : SDP Incorporated Optimization-Simulation Model

4.3 Analysis and Results

4.3.1 Division of the Jarreh Reservoir

The Jarreh reservoir has two outlets at elevations, 136.75 m MSL and 167.5 m MSL. However, in this study it is assumed that the outlet structure has outlets at three different elevations as shown in Figure 4.6. It is also assumed that each outlet comprises two openings that could be operated independently. Through one water is withdrawn to satisfy downstream quantity demand while the other is used for scouring (flushing) the reservoir. Based on the number of outlets the reservoir is assumed to be equivalent to the parallel configuration of three smaller hypothetical reservoirs. As shown in Figure 4.6, the storage capacities of the top hypothetical reservoir, the middle hypothetical reservoir and the bottom hypothetical reservoir are 182 MCM, 213 MCM and 72 MCM respectively. The outlet elevations determine the storage volume of each hypothetical reservoir. In this study salinity characterizes the water quality.

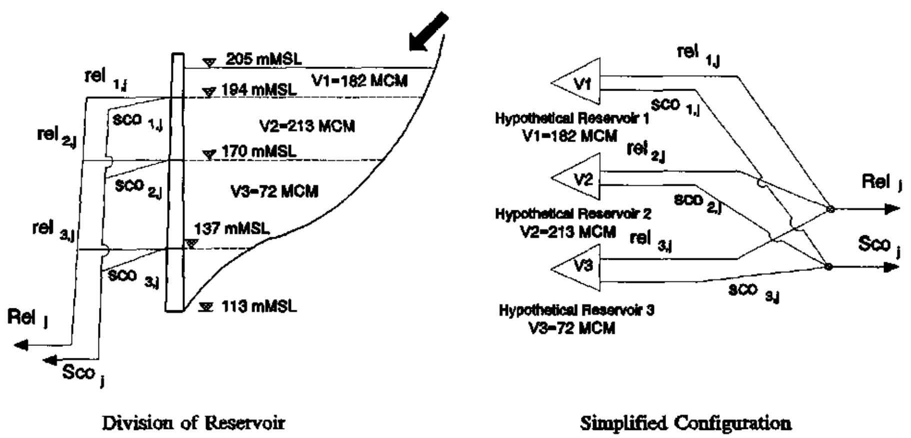

Figure 4.6 Division of the Jarreh Reservoir and Simplified Configuration

4.3.2 Applicability of DYRESM to the Jarreh Reservoir

The dynamic reservoir simulation model DYRESM as developed by Imberger *et al.* (1978) was used to simulate the salinity in the Jarreh reservoir. DYRESM is a one-dimensional numerical model for the prediction of temperature and salinity in small and medium sized reservoirs and lakes.

The assumption of one-dimensionality in spatial variation of parameters is usually made in a stratified reservoir. Because of stratification, vertical motions are inhibited, longitudinal and transverse variations play a secondary role and the variation over the vertical become the most important contribution to the first-order balances of mass, momentum and energy.

Therefore, in applying the one-dimensional model DYRESM to the Jarreh reservoir, it is needed to verify whether the conditions for that reservoir are indeed one-dimensional in the sense outlined. The constraints imposed by such a one-dimensional model may best be quantified by defining a series of non dimensional numbers (Imberger and Patterson, 1981). Those numbers are the Wedderburn number, densimetric (internal) Froude number and ratio of internal Rossby radius of deformation and reservoir width. These indicators are very briefly defined below.

Wedderburn number (W)

This number compares the hydrostatic pressure gradient force with the friction force in the momentum equation applied to the homogeneous mixed upper layer in the reservoir.

$$W = \frac{\acute{g}h}{u_*^2}\,\frac{h}{L} \qquad (4.16)$$

Where, $\acute{g}$ is the effective reduced gravity across the thermocline, h is depth of the mixed layer, L is the reservoir length scale and u_* is the surface shear velocity. Spigel and Imberger (1980) have shown that for W>O(1) the departure from one-dimensionality is minimal. For O(h/L)<W<O(1) the departure is severe but may be successfully parameterized, and for W<O(h/L) the lake overturns.

Densimetric (internal) Froude number (F_r)

This number compares the momentum force represented by an average flow-through velocity with the internal gravitational force tending to maintain stability.

Inflows do not lead to severe vertical motions in the reservoir provided the internal Froude number,

$$F_I = \frac{u}{(\acute{g}H)^{1/2}} < 1 \qquad (4.17)$$

Where, u is inflow velocity, $\acute{g}$ is the reduced gravity between the surface reservoir water and the inflow and H is the reservoir depth.

The outflow dynamics are governed by a similar Froude number criterion,

$$F_o = \frac{Q}{(\acute{g}^{1/2}H^{5/2})} < 1 \qquad (4.18)$$

Where, Q is the outflow discharge and $\acute{g}$ is the reduced gravity between the surface and bottom water.

Ratio of the internal Rossby radius of deformation and reservoir width (R)

This number compares the internal gravitational force with the Coriolis force

$$R = \frac{(\acute{g}h)^{1/2}}{f\ B} \tag{4.19}$$

Where, ǵ is the effective reduced gravity over depth h, h is the depth of the interface, f is the Coriolis frequency and B is the maximum width of the reservoir. R>1 is the criterion for the absence of rotational effects and therefore of the absence of a slope of the interface due to earth rotation.

Shiati (1991) examined whether the conditions for the Jarreh reservoir are one-dimensional by computing these non dimensional numbers. He calculated these values for a few days, which are typical for various times of the year. His results are shown in Table 4.1.

Table 4.1 Values of the Criteria for One-dimensionality in the Jarreh Reservoir (Source: Shiati, 1991)

Criteria	days of 1982					
	82005	82080	82120	82220	82320	82350
Wedderburn No.(W)	0.88	10.07	260.98	217.91	39.60	10.97
Internal Froude No.						
(F_I)	0.0025	0.0095	0.0011	0.00016	0.0018	0.0059
(F_o)	0.0017	0.0015	0.0004	0.00062	0.0004	0.0007
Ratio of Rossby No. and width (R)	0.87	2.0	5.36	7.57	1.98	1.11

The computed values of the non dimensional numbers in Table 4.1 suggest that the reservoir is strongly stratified for most of the time. That is, the Jarreh reservoir meets all theoretical constraints of one-dimensionality. Hence, the model DYRESM is applicable to the Jarreh reservoir. Similarly Patterson *et al.* (1984) showed the applicability of model DYRESM to two reservoirs (the Wellington reservoir in Western Australia and the Kootenay lake in British Colombia) based on the one-dimensional assumption using above non dimensional numbers.

4.3.3 Application of Stepwise Optimization-Simulation Model

4.3.3.1 Optimization-Simulation Procedure

The period from January 1982 to December 1984 (3 years in all) has been considered in the analysis. These three years were selected as this period includes the wet year 1982, median year 1983 and dry year 1984 out of a total period of 15 years (1975 - 1989) for which data are available.

The suggested optimization-simulation method proceeds in monthly steps. The target release salinity is 1000 ppm while the target scour salinity is 2500 ppm. The allowable releases through the top, middle and bottom outlets are 60 MCM/month, 60 MCM/month and 30 MCM/month respectively. Equal weightages were given to the two components in the objective function (i.e., W_1=0.5, W_2=0.5 in Eq.4.5). The monthly irrigation demands are given in Table 3.2. This section demonstrates the calculations involved in one step of the procedure. The month March in the median year, 1983 is selected for this purpose.

Optimization

The initial salinities of the three (sub) hypothetical reservoirs are the end of month average salinities of them obtained in the previous month. Table 4.2 shows the initial sub reservoir salinities for the month of March 1983. The total irrigation demand in this month is 34.0 MCM. The initial reservoir storage is 467 MCM.

Table 4.2 Initial Salinities of the Three Hypothetical Reservoirs - March 1983

Hypothetical Reservoir	Reservoir Salinity (ppm)	Reservoir Volume (MCM)
(1) Top	1833	182
(2) Middle	1833	213
(3) Bottom	1850	72

The optimization model that has been developed based on the "Method of Feasible Directions" uses these data. The decisions to be made are the releases and the scour volumes through each outlet. Since there are outlets at three different elevations the total number of decision variables is 6. The optimization technique requires an initial feasible solution to start the optimization. Therefore, the initial decision space is divided into a grid by discretizing the domain of each decision variable into three equally spaced intervals. This gives 4 discrete values for each decision variable making the total number of alternatives to $4^6 = 4096$. But for the optimization, only the alternatives those satisfy the constraints (i.e., feasible alternative sets) are chosen as the initial feasible solutions. The optimizations are carried out for each of these feasible initial solutions and they end in several local optima (releases through the three outlets and the scour volumes through the three outlets). If the total number of truly different local optima exceeds 5, the five local optima having least objective function values are selected for further investigation. In this study individual flows were allowed to vary ±5% and still considered identical. The five local optima obtained in March 1983 are presented in Table 4.3.

Simulation

Then the stratification model DYRESM is used to compare these sets of releases. The reservoir operation was simulated for these five sets of releases separately. At this stage the inflows and inflow salinities are taken into account. The total release in the month is distributed among the days according to the distribution of inflow to the reservoir in the month. This was adopted to avoid/minimize the spill, if high inflows occur within a few days in a month. Note that the model DYRESM uses daily data. Table 4.4 shows the monthly average release and scour salinities, average salinities of spills and end of month reservoir salinities (reservoir average) for the five alternative release policies.

Table 4.3 The Candidate Optimum Release Policies - March 1983

Option	Release Volume (MCM)			Scour Volume (MCM)		
	Top	Middle	Bottom	Top	Middle	Bottom
1	16.6	17.4	0.0	0.0	42.5	21.5
2	17.4	16.6	0.0	42.5	0.0	21.5
3	34.0	0.0	0.0	0.0	45.0	19.0
4	0.0	34.0	0.0	45.0	0.0	19.0
5	20.3	13.7	0.0	0.0	45.0	18.8

Table 4.4 Monthly Average Release and Scour Salinities, Average Spill Salinities and End of Month Reservoir Salinities for the Five Alternative Release Policies

Option	Release and Scour Salinity (ppm)			Spill Salinity (ppm)	Reservoir Salinity (ppm)
	Top Outlet	Middle Outlet	Bottom Outlet		
1	1807	1837	1877	1822	1797
2	1804	1839	1881	1825	1800
3	1807	1839	1875	1827	1799
4	1806	1844	1883	1822	1797
5	1807	1835	1876	1815	1798

The monthly average release and scour salinities (Eq.4.1 through Eq.4.4) from the reservoir are as given in Table 4.5. The selection among the alternatives was made based on a performance index computed as;

Index = W_1 (monthly avg. release salinity) + W_2 (end of month avg. reservoir salinity).

The weightages W_1 and W_2 used in the study were 0.8 and 0.2 respectively. These reflect the higher gravity given for improving the quality of water supplied, compared with improving the quality of water in the reservoir.

Table 4.5 Monthly Average Release and Scour Salinities, End of Month (average) Reservoir Salinities and Performance Indices : for Alternative Release Policies

Option	Release Salinity (ppm)	Scour Salinity (ppm)	Reservoir Salinity (ppm)	Performance Index $W_1=0.8$, $W_2=0.2$
1	1822	1851	1797	1817
2	1821	1830	1800	1817
3	1807	1850	1799	1806
4	1844	1829	1797	1835
5	1819	1848	1798	1815

By comparing the five alternatives the third alternative that gives the minimum value for the performance index was chosen as the operational policy for the month. The end of month reservoir salinities obtained by adopting this release policy are used as the initial reservoir (three hypothetical reservoirs) salinities in the following period (month).

Operation Pattern for the Whole Year

By repeating this procedure in monthly steps the operation pattern for the whole year was obtained. The optimum operation pattern obtained for the median year is given in Table 4.6.

Table 4.6 Optimum Operation Pattern for the Year 1983

Month	Release Volume (MCM)			Scour Volume (MCM)		
	Top	Middle	Bottom	Top	Middle	Bottom
January	17.5	0.0	0.0	0.0	54.9	21.5
February	0.0	23.0	0.0	25.0	0.0	0.0
March	34.0	0.0	0.0	0.0	45.0	19.0
April	0.0	26.5	0.0	27.9	0.0	17.6
May	0.0	9.8	9.8	2.3	1.2	0.0
June	0.0	0.0	22.0	0.0	0.0	0.0
July	0.0	0.0	26.5	0.0	0.0	0.0
August	0.0	0.0	30.0	0.0	0.0	0.0
September	0.0	0.0	27.0	0.0	0.0	0.0
October	0.0	0.0	22.0	0.0	0.0	0.0
November	0.0	10.5	0.0	0.0	0.0	0.0
December	12.0	0.0	0.0	0.0	0.0	0.0

4.3.3.2 Comparison of Optimum Operation with Releasing Through One Outlet

The optimum reservoir operation patterns from the proposed methodology were obtained by;

(a) allowing excess water (spill) to spill without being used for scouring/flushing the reservoir, and
(b) utilising excess water (spill) for scouring/flushing the reservoir.

And the resulted operation patterns were compared with the following two pre-decided operations;

(c) releasing only the downstream quantity demand through the top outlet during the whole period, and
(d) releasing only the downstream quantity demand through the bottom outlet during the whole period.

The daily release salinities in the wet, median and dry year are compared from Figure 4.7 to Figure 4.9.

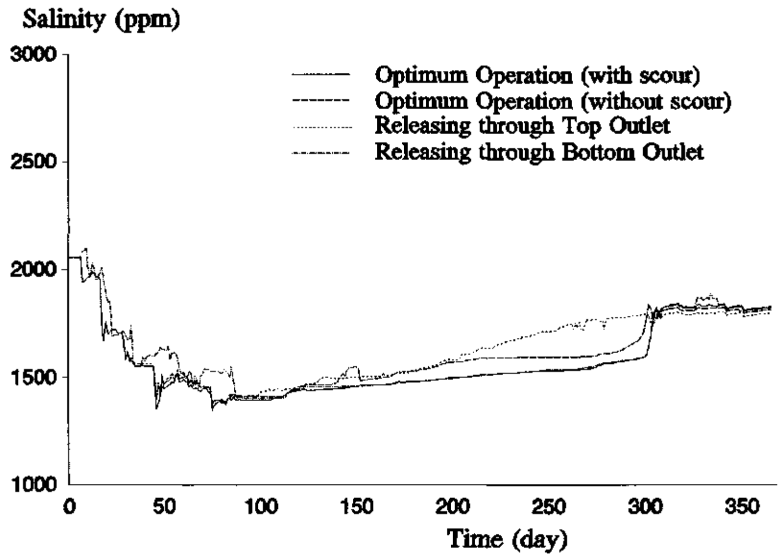

Figure 4.7 Comparison of Release Salinity - Wet year (1982)

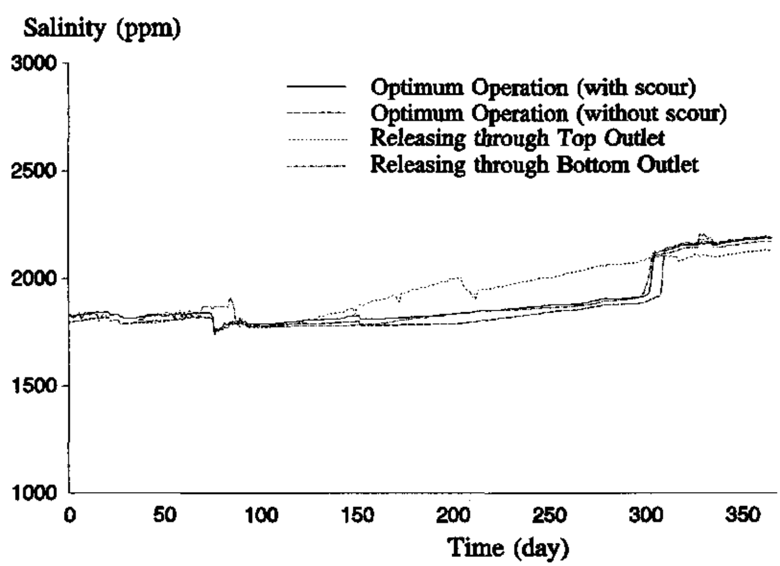

Figure 4.8 Comparison of Release Salinity - Median year (1983)

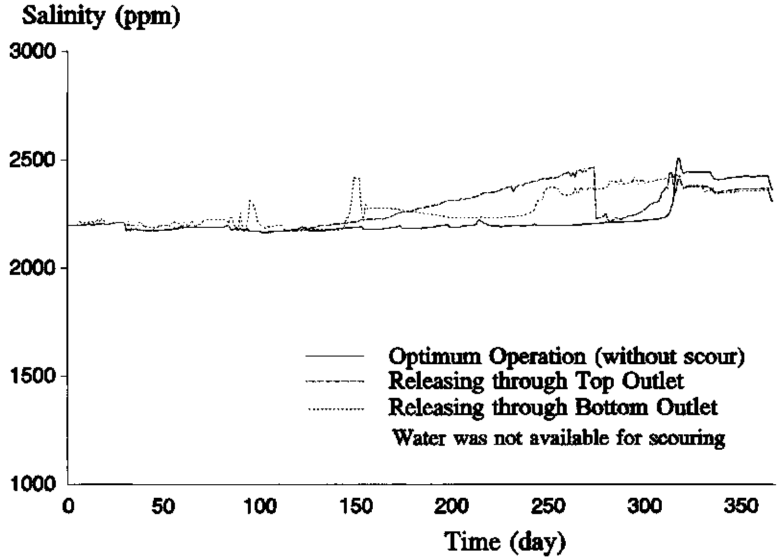

Figure 4.9 Comparison of Release Salinity - Dry year (1984)

The release salinities obtained from releasing according to the optimum operation (releasing only demands) were noted to be lesser than that obtained from releasing either totally through the top outlet or totally through the bottom outlet, most of the time. Releasing through the top outlet throughout the year is observed to be the most inferior operation alternative. The optimum operation obtained with utilizing the spills for scouring the reservoir is the most preferred one. The release salinity obtained by releasing through the bottom outlet is less compared to the other operation patterns generally from April to October. However, this operation has resulted in poor quality water during the balance period of the year.

Incoming river flows may sometimes spread out on the lake surface if they are less dense than reservoir water, or may plunge to the bottom or to some intermediate level of vertical buoyancy where an internal density current is formed. The river water density depends on its concentration of dissolved salts and suspended solids, and its temperature.

The high saline warm inflow to the reservoir from April to October (summer period) mixes with the warm top layers in the reservoir. This results in water of high salinity concentration at the top layers compared to the bottom. Therefore, the water drawn from the bottom layers during this period is of less salinity. But this policy contributes to a gradual build-up of a very high salinity level in the reservoir. The very rapid rise in release salinity is evident at the beginning of the winter period (November). This is the result of the mixing (surface layer deepening) commencing to occur in the winter (mixing with saltier upper regions) with the consequent increase in the release salinity. This is apparent in all the three years. Nevertheless, the quality of the release water obtained from the optimum operation is better than the two reference operations (releasing through top or bottom outlet throughout the year) during the crucial period of summer stratification.

The results obtained for the three different years, wet year, median year and dry year are almost similar. Note that as there was no spilling during the year 1984 an optimum operation with scouring is not available. Figure 4.10 through Figure 4.12 show the reservoir average salinities during wet year, median year and dry year respectively.

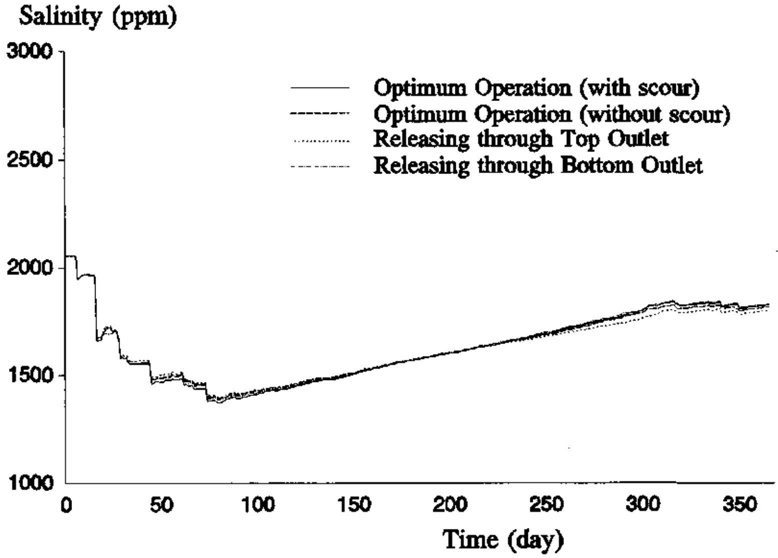

Figure 4.10 Comparison of Reservoir Salinity - Wet year (1982)

The reservoir average salinity obtained by making releases totally through the top outlet is the lowest in all the years. But this is at the expense of the highest release salinity resulted in the operation alternative. However, these figures indicate that the reservoir average salinities do not vary much for the different operation alternatives. It implies that the influence of the release pattern on the resulting reservoir average salinity is not vital, provided the total release volumes are the same. The concentration of salinity in inflows is high during summer. These high salinity inflows increase the reservoir average salinity during summer considerably. The above mentioned figures indicate this.

Figure 4.13 through Figure 4.15 display the cumulative distribution of release salinity for the different alternative operation patterns in the wet, median and dry year respectively. In wet year and median year the cumulative salinity distributions obtained from the optimum operation are noted to be close to that obtained by releasing through the bottom outlet. However, in the dry year about 86% of the time the salinity achieved from operating the reservoir according to the optimum pattern was better compared with releasing through a single outlet throughout the year. However, about 40% of the time in a year the release salinities obtained from different operation patterns are observed to be similar. The optimum operation pattern obtained for the whole period is given in Table 4.7.

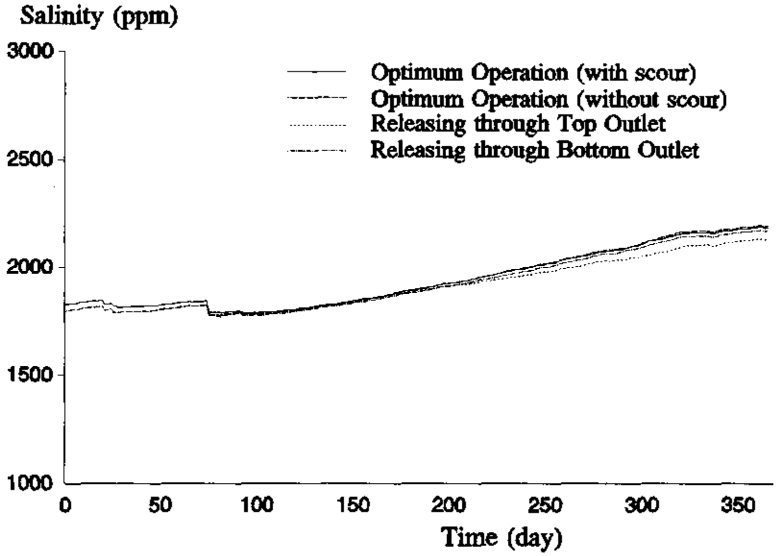

Figure 4.11 Comparison of Reservoir Salinity - Median year (1983)

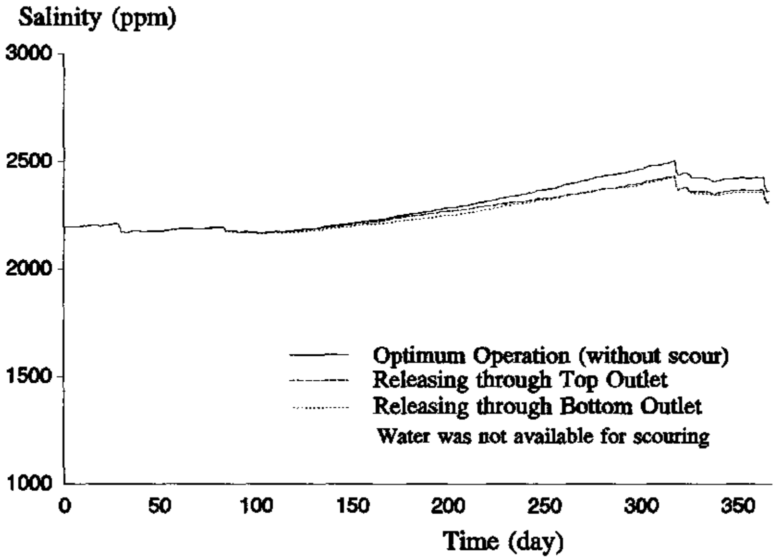

Figure 4.12 Comparison of Reservoir Salinity - Dry year (1984)

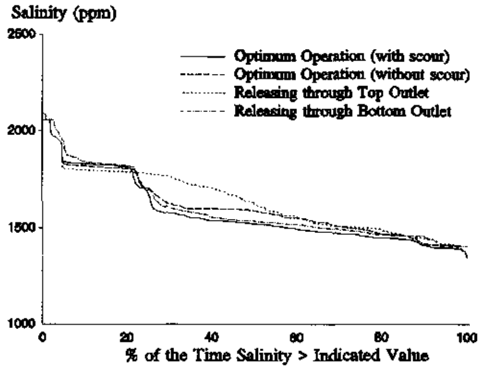

Figure 4.13 Cumulative Distribution of Release Salinity - Wet year (1982)

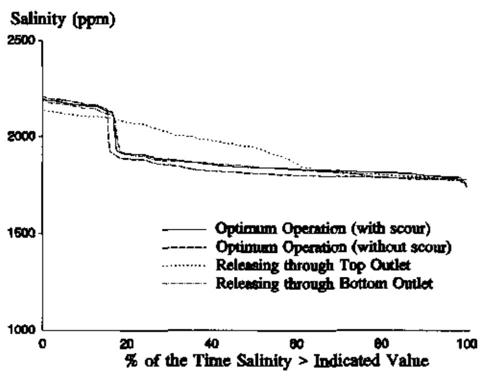

Figure 4.14 Cumulative Distribution of Release Salinity - Median year (1983)

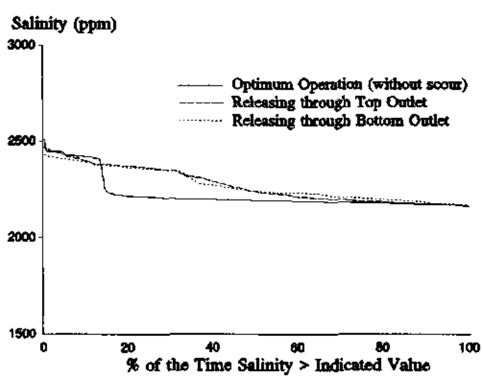

Figure 4.15 Cumulative Distribution of Release Salinity - Dry year (1984)

Table 4.7 Optimum Monthly Discharges through the Three Outlets : Stepwise Optimization-Simulation Method

Year	Month	Operation without Scour Monthly Releases (MCM)			Operation with Scour Monthly Releases (MCM)			Operation with Scour Monthly Scours (MCM)		
		Top	Mid	Bot	Top	Mid	Bot	Top	Mid	Bot
1982	Jan	0.0	17.5	0.0	0.0	17.5	0.0	0.0	0.0	0.0
	Feb	23.0	0.0	0.0	23.0	0.0	0.0	0.0	48.0	23.7
	Mar	34.0	0.0	0.0	17.0	17.0	0.0	43.0	43.0	30.0
	Apr	0.0	0.0	26.5	0.0	13.3	13.3	39.3	39.2	0.0
	May	0.0	19.5	0.0	0.0	0.0	19.5	7.5	0.0	0.0
	Jun	0.0	0.0	22.0	0.0	0.0	22.0	0.0	0.0	0.0
	Jul	0.0	0.0	26.5	0.0	0.0	26.5	0.0	0.0	0.0
	Aug	0.0	0.0	30.0	0.0	0.0	30.0	0.0	0.0	0.0
	Sep	0.0	0.0	27.0	0.0	0.0	27.0	0.0	0.0	0.0
	Oct	0.0	0.0	22.0	0.0	0.0	22.0	0.0	0.0	0.0
	Nov	0.0	10.5	0.0	0.0	10.5	0.0	0.0	0.0	0.0
	Dec	6.0	6.0	0.0	12.0	0.0	0.0	18.8	0.0	22.1
1983	Jan	8.8	8.8	0.0	17.5	0.0	0.0	0.0	54.9	21.5
	Feb	11.5	11.5	0.0	0.0	23.0	0.0	25.0	0.0	0.0
	Mar	34.0	0.0	0.0	34.0	0.0	0.0	0.0	45.0	19.0
	Apr	13.3	0.0	13.3	0.0	26.5	0.0	27.9	0.0	17.6
	May	0.0	19.5	0.0	0.0	9.8	9.8	2.3	1.2	0.0
	Jun	0.0	0.0	22.0	0.0	0.0	22.0	0.0	0.0	0.0
	Jul	0.0	0.0	26.5	0.0	0.0	26.5	0.0	0.0	0.0
	Aug	0.0	0.0	30.0	0.0	0.0	30.0	0.0	0.0	0.0
	Sep	0.0	0.0	27.0	0.0	0.0	27.0	0.0	0.0	0.0
	Oct	0.0	0.0	22.0	0.0	0.0	22.0	0.0	0.0	0.0
	Nov	0.0	0.0	10.5	0.0	10.5	0.0	0.0	0.0	0.0
	Dec	0.0	12.0	0.0	12.0	0.0	0.0	0.0	0.0	0.0
1984	Jan	8.8	8.8	0.0	17.5	0.0	0.0	0.0	0.0	0.0
	Feb	11.5	11.5	0.0	0.0	23.0	0.0	0.0	0.0	0.0
	Mar	34.0	0.0	0.0	34.0	0.0	0.0	0.0	0.0	0.0
	Apr	26.5	0.0	0.0	26.5	0.0	0.0	0.0	0.0	0.0
	May	0.0	19.5	0.0	0.0	19.5	0.0	0.0	0.0	0.0
	Jun	0.0	22.0	0.0	0.0	0.0	22.0	0.0	0.0	0.0
	Jul	0.0	26.5	0.0	0.0	0.0	26.5	0.0	0.0	0.0
	Aug	0.0	0.0	30.0	0.0	0.0	30.0	0.0	0.0	0.0
	Sep	0.0	0.0	27.0	0.0	0.0	27.0	0.0	0.0	0.0
	Oct	0.0	0.0	22.0	0.0	0.0	22.0	0.0	0.0	0.0
	Nov	0.0	0.0	10.5	0.0	0.0	10.5	0.0	0.0	0.0
	Dec	0.0	12.0	0.0	0.0	12.0	0.0	0.0	0.0	0.0

4.3.4 SDP Incorporated Optimization-Simulation Model

4.3.4.1 SDP Optimization

The first step in this approach is to derive optimum operation policies for the reservoir using the SDP model. The optimization considers the downstream quantity requirement only. In this study the total reservoir storage and the dead storage of the reservoir are assumed to be 470 MCM and 75 MCM respectively. The allowable maximum release from the reservoir in a month is 150 MCM. The optimum operational policy for the reservoir was obtained by using the SDP model for the available record of 15 years. The operating policy designated by the model is a set of rules specifying the storage level at the beginning of the next month for each combination of storage level at the beginning of the present month and inflow during the month.

The years 1982, 1983 and 1984, which are the wet year, median year and dry year in the record of the available inflow time series were selected for the analysis. The initial storage volume of the reservoir was assumed to be 185 MCM. The monthly releases that would result if the reservoir is operated according to the developed operation policy are shown in Table 4.8 for the wet year (1982), for example.

Table 4.8 *Monthly Releases from the SDP Model - Wet year (1982)*

Month	Initial Storage (MCM)	Inflow (MCM)	Evaporation (MCM)	Demand (MCM)	Release (MCM)	Spill (MCM)
Jan	185.00	219.26	0.054	17.50	32.13	0.00
Feb	372.08	208.67	0.044	23.00	110.71	0.00
Mar	470.00	339.60	0.026	34.00	150.00	189.63
Apr	470.00	108.96	0.020	26.50	108.94	0.00
May	470.00	30.42	0.019	19.50	30.40	0.00
Jun	470.00	12.29	0.016	22.00	31.86	0.00
Jul	450.42	7.52	0.024	26.50	27.08	0.00
Aug	430.83	8.52	0.029	30.00	47.66	0.00
Sep	391.67	9.23	0.059	27.00	28.75	0.00
Oct	372.08	38.51	0.084	22.00	38.42	0.00
Nov	372.08	63.05	0.129	10.50	23.75	0.00
Dec	411.25	81.45	0.132	12.00	42.15	0.00

4.3.4.2 Optimization-Simulation Procedure

The monthly discharges defined by the SDP operating policy are used as the pre-decided releases from the reservoir (A_j's in Eq.4.8) in the optimization-simulation model. The consideration of the quality of the water supplied from the reservoir is taken into account at this step. The optimization-simulation procedure (same as described previously) is followed in monthly steps moving in the forward direction. At the beginning of each month the maximum discharge that would be allowed during the month is read from the developed SDP based operational policy.

The reservoir is assumed to be equivalent to the parallel configuration of three smaller hypothetical reservoirs. The division of the reservoir is similar to that assumed in Chapter 4.3.1. Allowable releases through the top, middle and bottom outlets are 60 MCM/month, 60 MCM/month and 30 MCM/month respectively. The target release salinity is 1000 ppm and the target scour salinity is 2500 ppm. This procedure provides the monthly optimum releases and scour volumes to be made through the outlets at different elevations.

4.3.4.3 Comparison of Optimum Operation

The optimum operation obtained from the methodology was compared with the following two operations;

(a) releasing only the downstream quantity demand through the top outlet during the whole period, and
(b) releasing only the downstream quantity demand through the bottom outlet during the whole period.

The release salinities obtained are compared from Figure 4.16 through Figure 4.18.

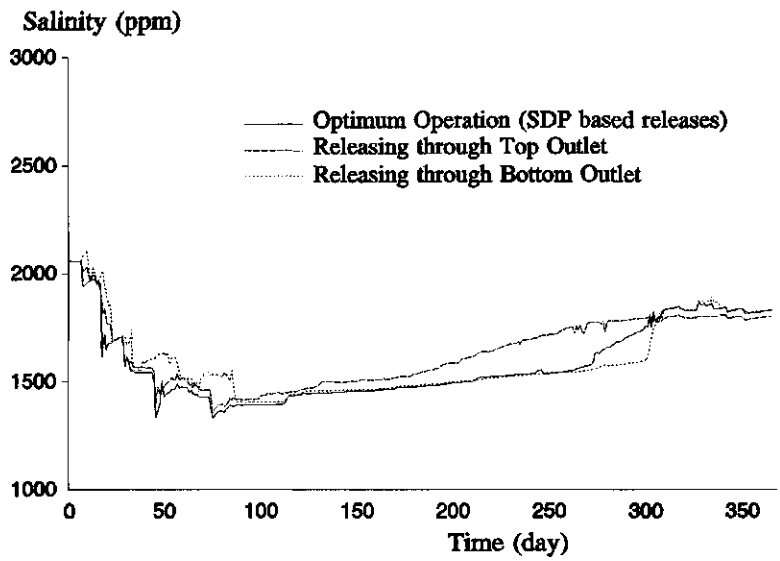

Figure 4.16 Comparison of Release Salinity : SDP Releases Vs. Releases Through a Single Outlet - Wet year (1982)

The concentration of salinity in releases obtained from the optimum operation was observed to be the lowest, most of the time. The salinity distributions for the three different operation alternatives are almost similar to the distributions presented in Chapter 4.3.3.

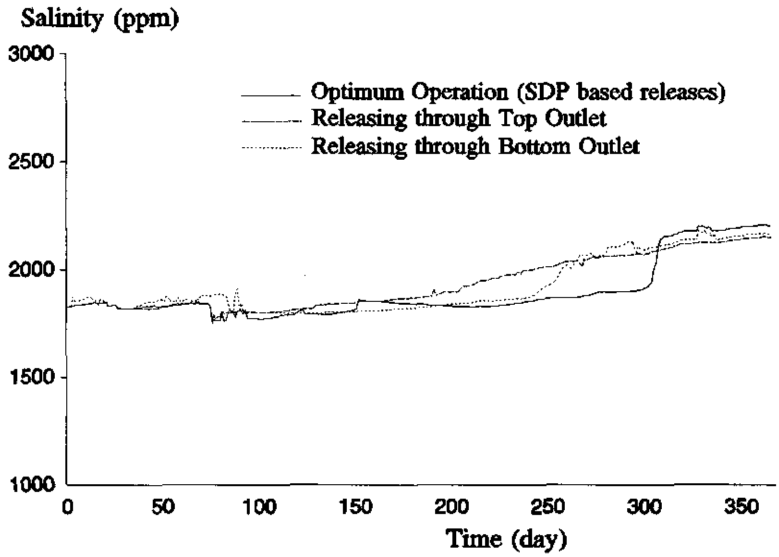

Figure 4.17 Comparison of Release Salinity : SDP Releases Vs. Releases Through a Single Outlet - Median year (1983)

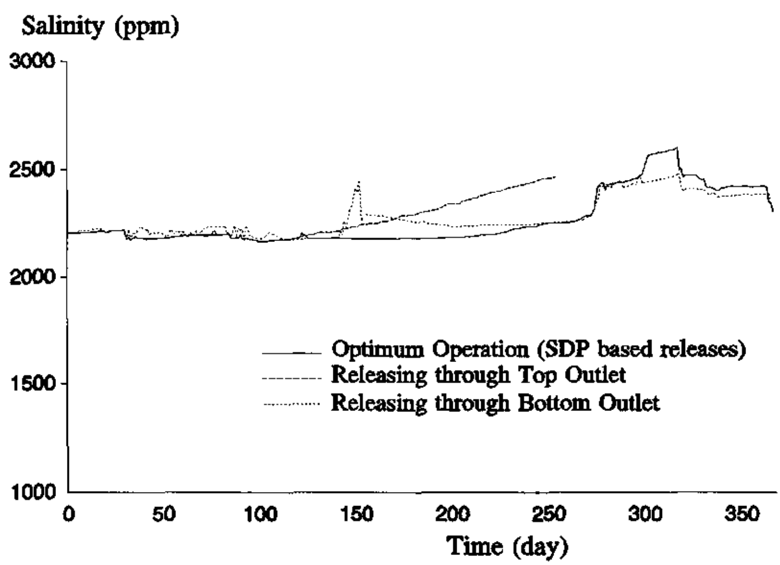

Figure 4.18 Comparison of Release Salinity : SDP Releases Vs. Releases Through a Single Outlet - Dry year (1984)

The explanations given in that chapter to describe the behaviour of the reservoir are valid here too. In the dry year water was not released through the top outlet from October to December as the water level in the reservoir was below the top outlet elevation. Therefore, in Figure 4.18 the release salinity distribution obtained by making releases through the top outlet is upto September only.

During the first nine to ten months (Jan - Sep, Oct) the scouring policy had the obvious effect of reducing the average salinity in the releases. However, during the last two to three months this release policy had a detrimental influence since water withdrawn for scouring during the initial period was of lower salinity than the average salinity in this latter period. As this water of lower salinity was wasted as scour during the initial months, the strategy had an adverse effect. This is unavoidable due to the uncertainty involved with future inflows.

Figure 4.19 through Figure 4.21 show the reservoir average salinity distributions during wet year, median year and dry year respectively. The reservoir average salinities do not vary much for the different operation alternatives. Imberger and Hebbert (1980) also observed a similar behaviour in the operation of the Wellington reservoir in Western Australia. The improved operation of that reservoir with scouring resulted in improvements in release quality, but its effect on the average reservoir salinity was very small. However, during the summer in the dry year (1984) the reservoir average salinity increases due to the loss of large quantity of water by scouring.

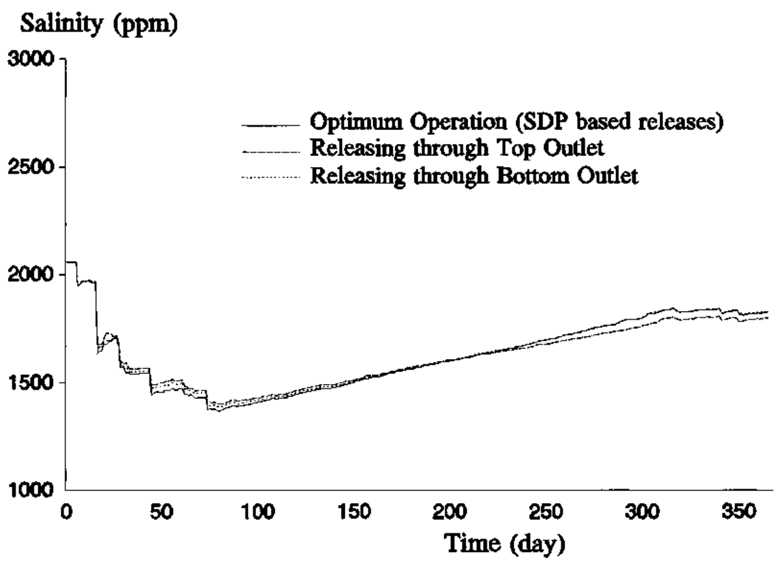

Figure 4.19 Comparison of Reservoir Salinity : SDP Releases Vs. Releases Through a Single Outlet - Wet year (1982)

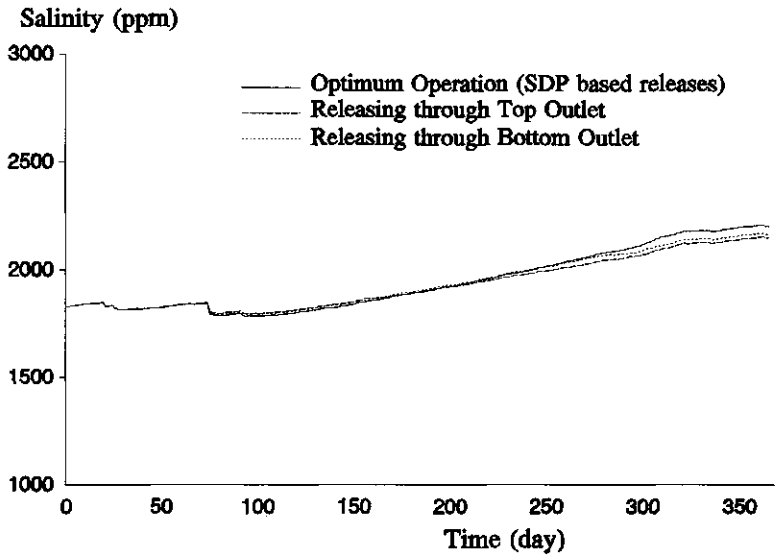

Figure 4.20 Comparison of Reservoir Salinity : SDP Releases Vs. Releases Through a Single Outlet - Median year (1983)

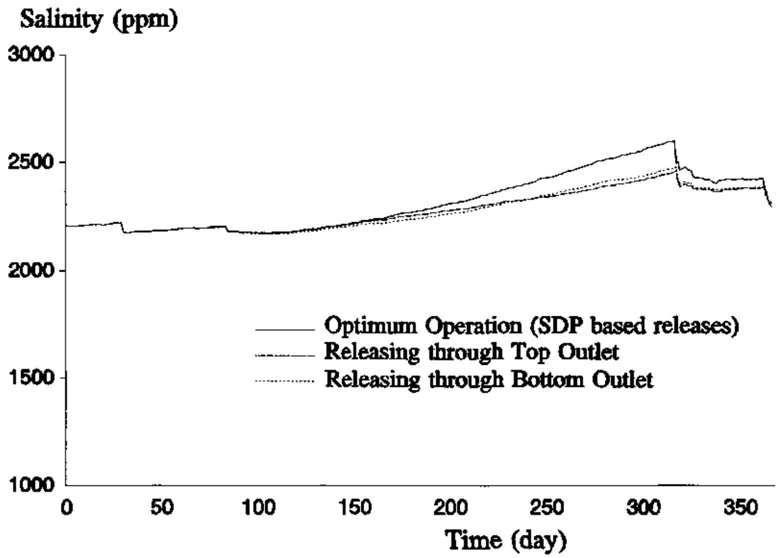

Figure 4.21 Comparison of Reservoir Salinity : SDP Releases Vs. Releases Through a Single Outlet - Dry year (1984)

The optimum operation pattern obtained for the three years are given in Table 4.9. Note that the total discharge from the reservoir (Total release + Total scour volume) in each month is constrained by the SDP based release obtained for that particular month.

Table 4.9 Optimum Monthly Discharges through the Three Outlets - SDP Incorporated Model

Year	Month	Release Volume (MCM)			Scour Volume (MCM)		
		Top	Middle	Bottom	Top	Middle	Bottom
1982	Jan	0.0	17.8	0.0	0.0	7.2	7.2
	Feb	23.0	0.0	0.0	9.5	52.5	24.6
	Mar	34.0	0.0	0.0	26.0	60.0	26.4
	Apr	0.0	0.0	26.5	41.3	41.1	0.0
	May	0.0	3.1	16.4	8.0	2.9	0.0
	Jun	0.0	0.0	22.0	6.8	0.0	0.0
	Jul	0.0	0.0	26.5	0.0	0.0	0.0
	Aug	1.3	1.3	27.4	0.0	10.0	0.0
	Sep	0.0	13.5	13.5	0.0	0.0	0.0
	Oct	0.0	22.0	0.0	10.0	0.0	0.0
	Nov	0.0	3.9	6.6	9.4	0.0	0.0
	Dec	12.0	0.0	0.0	0.0	0.0	28.0
1983	Jan	17.5	0.0	0.0	0.0	34.5	18.0
	Feb	0.0	23.0	0.0	28.0	0.0	0.0
	Mar	34.0	0.0	0.0	0.0	45.0	19.0
	Apr	26.5	0.0	0.0	0.0	14.2	30.0
	May	0.0	19.5	0.0	0.0	2.5	3.0
	Jun	0.0	0.0	22.0	7.1	0.0	3.9
	Jul	0.0	0.0	26.5	0.0	0.0	0.0
	Aug	0.0	0.0	30.0	15.0	0.0	0.0
	Sep	0.0	0.0	27.0	0.0	0.0	0.0
	Oct	0.0	0.0	22.0	0.0	5.6	2.4
	Nov	0.0	4.6	5.9	0.0	7.0	0.0
	Dec	0.0	12.0	0.0	0.0	0.0	0.0
1984	Jan	0.0	17.5	0.0	0.0	0.0	7.5
	Feb	11.5	11.5	0.0	0.0	0.0	0.0
	Mar	0.0	34.0	0.0	0.0	8.0	0.0
	Apr	26.5	0.0	0.0	0.0	22.5	0.0
	May	0.0	0.0	19.5	7.7	7.7	0.0
	Jun	0.0	0.0	22.0	0.0	3.0	0.0
	Jul	0.0	0.0	26.5	0.0	12.7	0.0
	Aug	0.0	0.0	30.0	0.0	9.4	0.0
	Sep	0.0	0.0	27.0	0.0	17.8	0.0
	Oct	0.0	10.5	11.5	0.0	5.7	0.0
	Nov	0.0	10.6	0.0	0.0	0.0	17.4
	Dec	0.0	12.0	0.0	0.0	7.8	7.8

Table 4.10 shows the total annual release and scour volumes from the reservoir through the different outlets. The volume of water used for flushing the reservoir in wet year was observed to be about 58% of the total discharge made through the reservoir. This was

reduced to 47% and 33% in median year and dry year respectively. The releases have been through the bottom outlet most of the time. During the latter part of spring, summer and early part of autumn the releases were through the bottom outlet in all the three years.

Table 4.10 Quantities and Percentages of Annual Discharges

Year	Releases (MCM)			Scour (MCM)		
	Top	Middle	Bottom	Top	Middle	Bottom
1982	70.3	61.6	138.9	111.0	173.7	86.2
1983	78.0	59.1	133.4	50.1	108.8	76.3
1984	38.0	96.1	136.8	7.7	94.6	32.7
Total	186.3	216.8	409.1	168.8	377.1	195.2
	23 %	27 %	50 %	23 %	51 %	26 %

Table 4.11 shows the salt balance in the reservoir for different operation alternatives in the three years. The reservoir operations were carried out for the three years separately. In each year the initial reservoir conditions were kept the same to make the comparison consistent. The results in Table 4.11 indicate that the salt load in the releases obtained from optimum operation is the smallest compared with the other operations in all the three years. However this reduction is small. The salt load in the reservoir at the end of the year is less in SDP incorporated optimum operation in all the three years. This improvement obtained in preventing salinity build up in the reservoir is appreciably high. This is a primary objective in the reservoir operation. The optimum operation prevents or reduces the spilling of water and uses these water for flushing the reservoir. It has reduced the reservoir salt load considerably. For example in the median year about 345×10^6 kg of salt is removed from the reservoir by spilling when releases are made either through the top outlet or the bottom outlet. Nevertheless, the optimum operation removes about 436×10^6 kg of salt from the reservoir by flushing/scouring. This reduces the salinity build-up in the reservoir significantly.

Table 4.11 Salt Balance for the Reservoir in 1982, 1983 and 1984

Year	Option	Ini. Reser Salt load 10^6 kg	Inflow Salt load 10^6 kg	Release Salt load 10^6 kg	Scour Salt load 10^6 kg	Spill Salt load 10^6 kg	Fin. Reser Salt load 10^6 kg
1982	Optimum	370	1693	426	567	265	805
	Top	370	1693	432	-	792	839
	Bottom	370	1693	427	-	777	859
1983	Optimum	805	903	517	436	-	755
	Top	805	903	519	-	345	844
	Bottom	805	903	522	-	344	842
1984	Optimum	755	637	610	308	-	474
	Top	755	637	603	-	-	789
	Bottom	755	637	615	-	-	777

4.3.5 Comparison of Continuous Operation for Five Years

At this step the reservoir operations were carried out continuously for 5 years. The 5 year period includes the wet year (1982), median year (1983), dry year (1984) and the following two years (1985, 1986). The inflow to the reservoir and the concentration of salinity of the inflows during this period are shown in Figure 4.22 and Figure 4.23 respectively. When the inflows are high (in winter) their concentration of salinity is low. In contrast, the smaller quantities of warm inflows during summer are characterized by high salinity concentration.

Four different operation alternatives were adopted for comparison. They are, optimum operation (optimum releases with SDP release constraints), optimum operation (optimum releases without scouring), releasing through the top outlet throughout the period and releasing through the bottom outlet throughout the period. The resulting release salinity and reservoir salinity distributions are presented in Figure 4.24 and Figure 4.25 respectively. The release salinity distributions show that the optimum operation (without scouring) results in improvements in spring, summer and early part of autumn in all the years compared with releasing through a single outlet throughout the total period. In the optimum operation water releases are through the bottom outlet during this period. During the summer stratification period a thin layer of saltier water is formed at the top layer (epilimnion). Therefore, the overall salinity in the reservoir increases after each turnover in winter. This results in a rapid rise in the salinity in the releases.

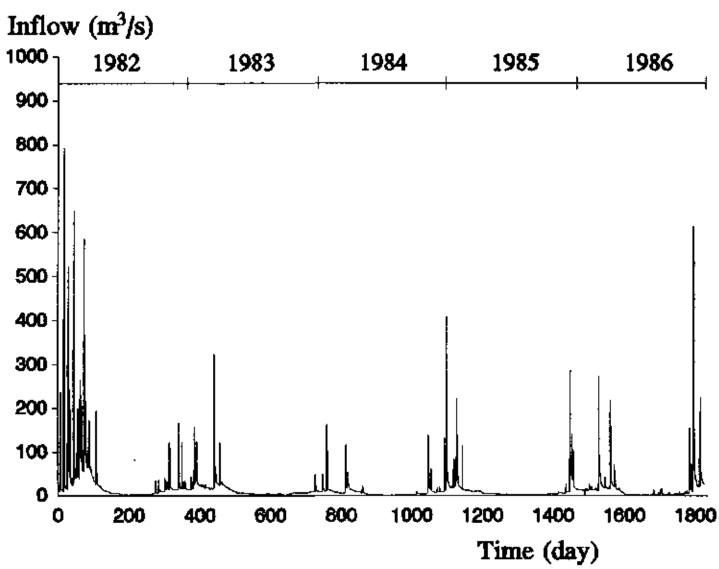

Figure 4.22 Inflow to the Jarreh Reservoir : 1982-1986

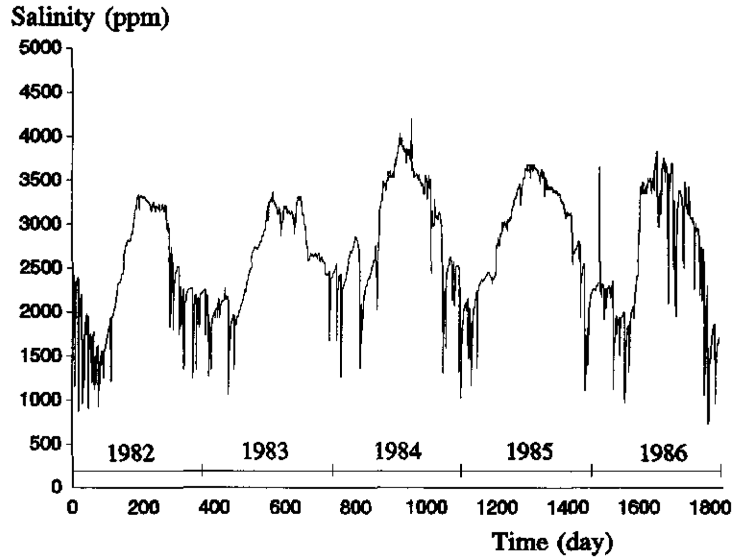

Figure 4.23 Concentration of Salinity of Inflow : 1982-1986

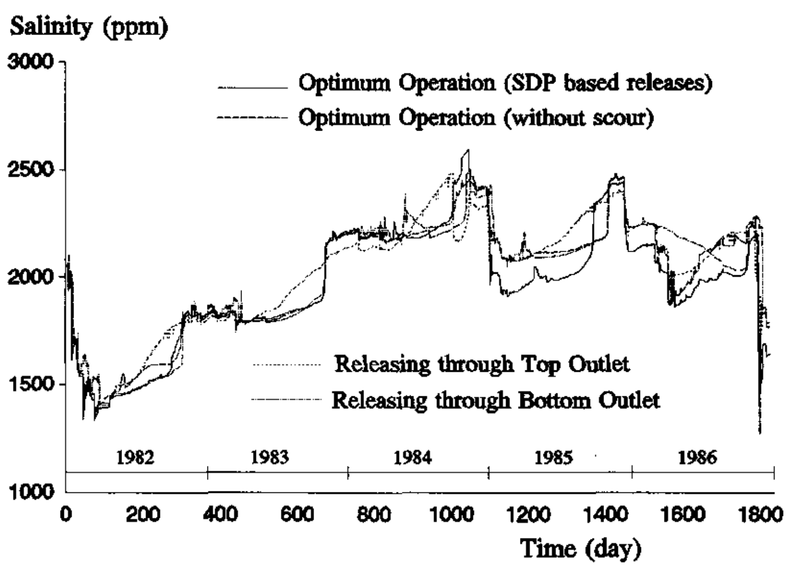

Figure 4.24 Comparison of Release Salinity : 1982-1986

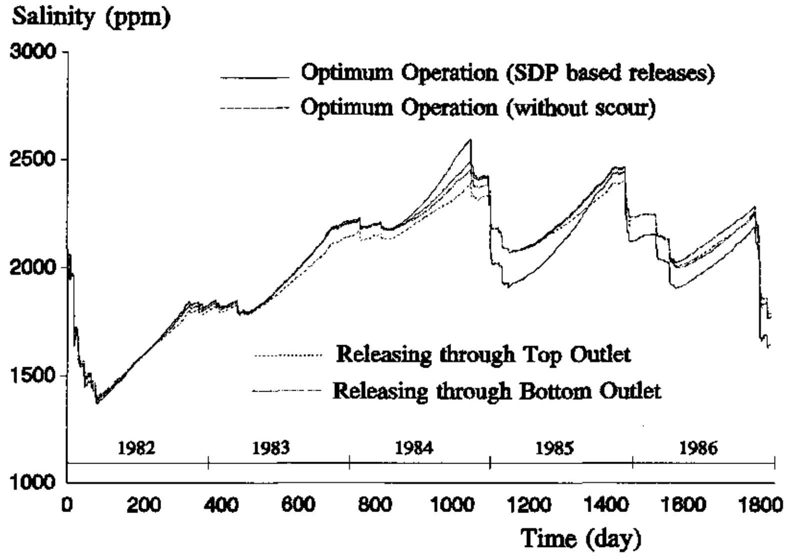

Figure 4.25 Comparison of Reservoir Salinity : 1982-1986

Releasing through the bottom outlet throughout the total period is observed to be resulting in salinity concentrations in releases close to that obtained from the optimum operation without scour. However, during the initial few months in each year, releasing through the bottom outlet is inferior to the optimum operation (without scour).

The severe storm experienced during the first four months in 1982 brought a large amount of water of less salinity into the reservoir. This improved the quality of water in the reservoir notably. Consequently, the concentration of salinity of the water supplied from the reservoir is considerably low during this period. The wet year is followed by the median year and then by the dry year. The annual total inflow successively reduces and therefore, the reservoir salinity and as a result the release salinity continue to increase during this period of three years. However, during the two years followed by this dry spell, the inflow remains at an average level.

The reservoir average salinities obtained by releasing through the bottom outlet throughout the total period do not differ much from that obtained from the optimum operation (without scour). The reservoir average salinity obtained when the releases are made through the top outlet is observed to be less than that from the above two operations for most of the time. However, this is at the expense of the higher salinity level in the releases.

The reservoir average salinity increases continuously during summer in all the operations. During winter periods salinity appears to be remaining at relatively steady levels or decreasing considerably. This is due to the high inflows of low salinity received in winter.

In the optimum operation (with SDP discharges), scouring causes a loss of considerably large quantity of water from the reservoir in the dry year, 1984. This makes the reservoir average salinity concentration high during the latter part of that year. However, scouring at the end of the dry year has brought the salinity level in the reservoir to a very low value compared with the other operations. A similar reduction in the reservoir salinity level is observed in the following two winter periods too. Even though scouring has not caused apparent improvements in the release salinity during the dry spell (1982-1984), it has produced considerable improvements in the release salinity level in the following two years. Figure 4.26 shows the monthly average release salinities, the monthly average reservoir salinities and the average (monthly) scour salinities for the 5 years period.

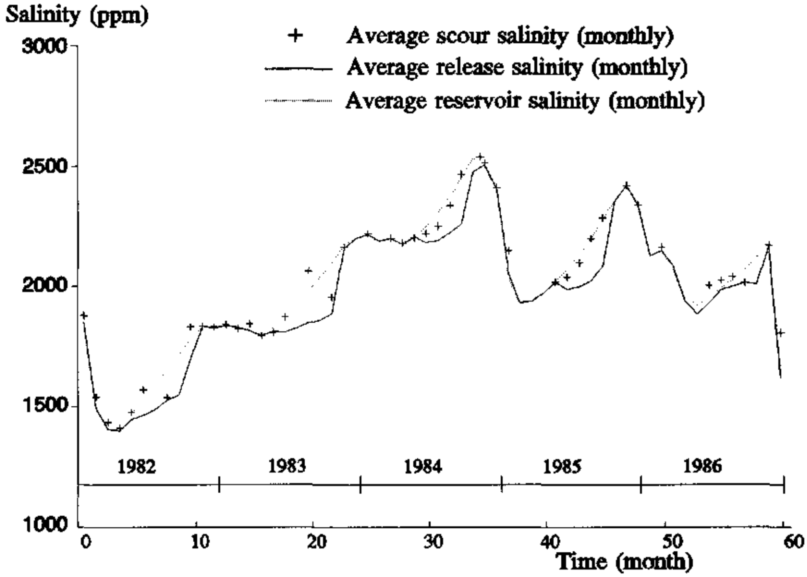

Figure 4.26 Comparison of Scour Salinity with Average Reservoir and Release Salinities

In the first three years the water withdrawn as scouring during the initial part of the year is of lower salinity than the average salinity in the reservoir during the latter part of the respective year. Note that, during each month scouring has been carried out, the scour salinity is higher than release salinity. Due to the increase in the inflow salinity the reservoir salinity has increased towards the end of the year. The above behaviour is unavoidable as the methodology proceeds in period-by-period steps associated with uncertainty regarding inflows. But in the last two years the salinity concentration of the scours is high in comparison to the reservoir average salinity in the latter part of the year. Therefore, in these two years scouring has been effective in improving the quality of water supplied from the reservoir.

Table 4.12 presents salt balance for the reservoir for the different operation patterns. The final reservoir salt load obtained from the optimum operation with SDP releases is the lowest. This is due to scouring occurred in that operation alternative. The amount of salt removed in this operation as scouring is higher than the salt removed with spill in the other operation patterns. Therefore, scouring is helpful to reduce the salt build-up in the reservoir.

Table 4.12 Salt Balance for the Reservoir for Five Years : 1982-1986

Operation	Ini. Reser Salt load 10^6 kg	Inflow Salt load 10^6 kg	Release Salt load 10^6 kg	Scour Salt load 10^6 kg	Spill Salt load 10^6 kg	Fin. Reser Salt load 10^6 kg
Optimum (with SDP releases)	370	4991	2655	1617	303	786
Optimum (no scour)	370	4991	2703	-	1801	857
Releasing through Top Outlet	370	4991	2690	-	1826	845
Releasing through Bottom Outlet	370	4991	2727	-	1795	839

Figure 4.27 through Figure 4.30 shows salinity distributions in the reservoir for the four different operation alternatives. Figure 4.31 through Figure 4.34 are the temperature distributions for these different cases. The yearly cycle is evident in these figures. The marked difference in the thermocline structure among these figures is due to the change in the withdrawal pattern. Many researchers (Spigel and Ogilvie, 1985; Owens *et al.*, 1986) reported that the operating conditions of a reservoir affect its stratification regime.

The optimum operation pattern is to release through the bottom outlet during summer. These figures show that during summer (July-October) a thin layer of warm and brackish water is formed at the top, above the level of the thermocline. This brackish water layer persists up to late autumn. Therefore, the salinity at the top outlet elevation is higher than that at the bottom outlet elevation during this period. Therefore, the above decision to release through the bottom outlet is apparent. In the proposed methodology the total discharge (release + scour volume) from the reservoir is limited to the SDP defined release for the particular month. Due to this constraint, the total removal of the high salinity top layer was not possible during some months.

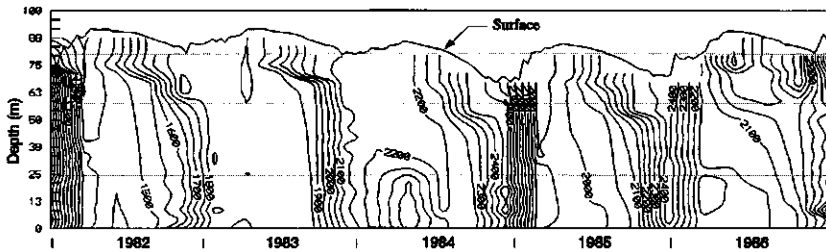

Figure 4.27 Salinity Distribution in the Reservoir - Optimum Operation (SDP Releases)

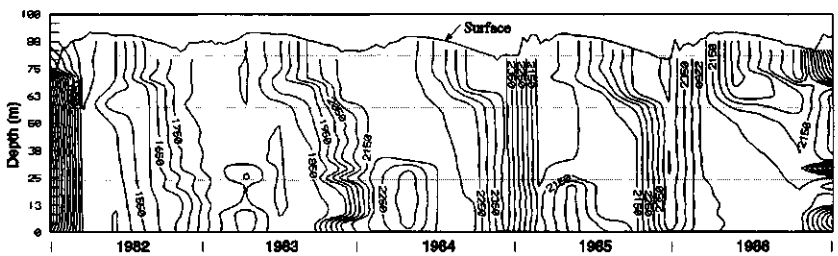

Figure 4.28 Salinity Distribution in the Reservoir - Optimum Operation (No Scour)

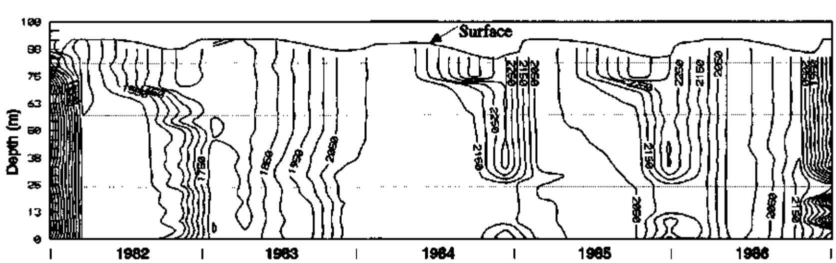

Figure 4.29 Salinity Distribution in the Reservoir - Releasing Through Top Outlet

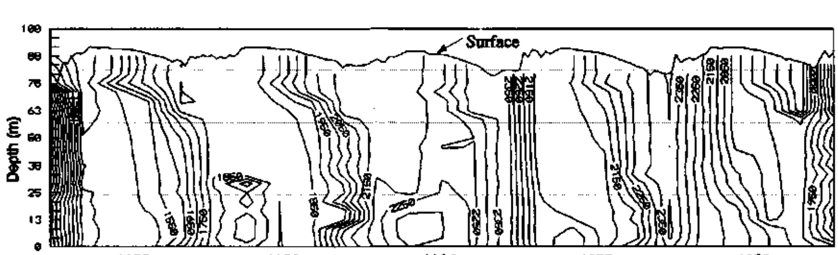

Figure 4.30 Salinity Distribution in the Reservoir - Releasing Through Bottom Outlet

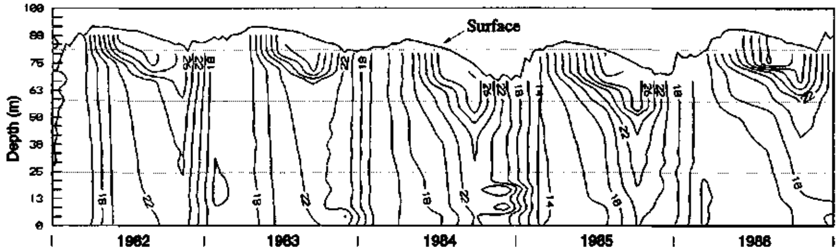

Figure 4.31 Temperature Distribution in the Reservoir - Optimum Operation (SDP Releases)

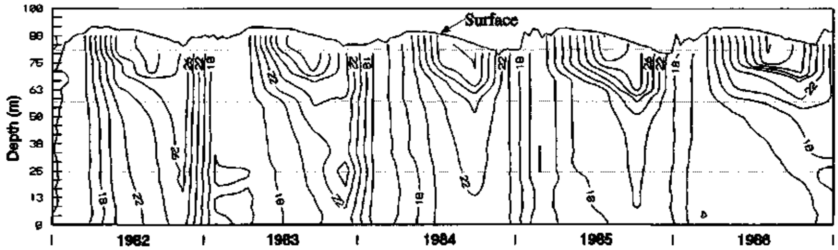

Figure 4.32 Temperature Distribution in the Reservoir - Optimum Operation (No Scour)

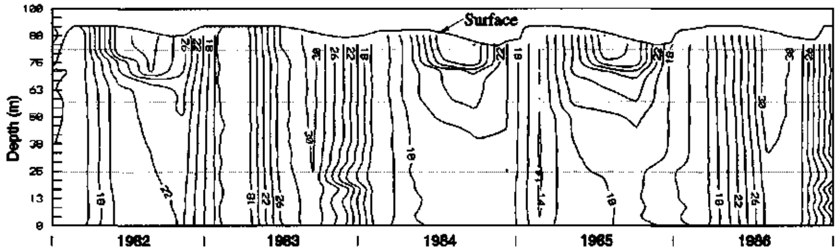

Figure 4.33 Temperature Distribution in the Reservoir - Releasing Through Top Outlet

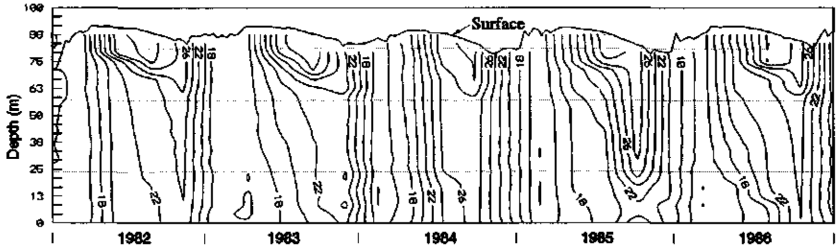

Figure 4.34 Temperature Distribution in the Reservoir - Releasing Through Bottom Outlet

5 Iterative Optimization-Simulation Model

Models that simulate reservoir dynamics are used to evaluate the ability of selective withdrawal structures to meet the quality objectives in reservoirs. These mathematical models use hydrologic and meteorologic data to simulate the thermal stratification cycle in a reservoir. Although the use of these simulation models has been primarily oriented towards the design of selective withdrawal structures, those are excellent mechanisms for developing improved operational techniques. This chapter presents an iterative technique, combining an optimization model and a reservoir dynamics simulation model to operate a reservoir for the improvement of the quality of water released while satisfying the quantity demand.

5.1 Methodology : Iterative Optimization-Simulation Model

In this methodology an optimization model that furnishes optimum releases from a reservoir and a simulation model that simulates reservoir dynamics are operated in an interactive fashion. The optimization model has been developed based on Incremental Dynamic Programming (IDP) technique (Larson, 1968). Achieving both quantity and quality objectives are considered in this model. The one-dimensional reservoir simulation model "DYRESM" simulates reservoir dynamics. A similar approach was used to develop an operating policy for a reservoir system by Dandy and Crawley (1992) in which water quality was an important consideration. In that study a separate model of salinity in reservoirs (assuming completely mixing of water in the reservoirs) was run interactively with an optimization model (based on linear programming technique) in an iterative fashion until convergence to the optimal policy was achieved.

In the present study the reservoir is assumed to have two outlets at two different elevations. Based on this, the reservoir is made to be equivalent to the parallel configuration of two hypothetical reservoirs in the IDP optimization model as shown in Figure 5.1. It is also assumed that there are two openings at each outlet elevation that could be operated independently. Through one water is withdrawn to satisfy downstream irrigation demand, while the other is used for scouring/flushing the reservoir.

Water always enters the upper layer (sub-reservoir 1). At the end of each month if sub-reservoir 2 is not full, water is transferred from upper layer (sub-reservoir 1) to make it full. If sufficient water is available in the upper reservoir (sub-reservoir 1) to make the lower one full, there will be water in both sub-reservoirs at the end of the month. If not, there will be water only in sub-reservoir 2 at the end of the month. Transfer in Figure 5.1 is the amount of water transferred from the upper layer to the lower layer.

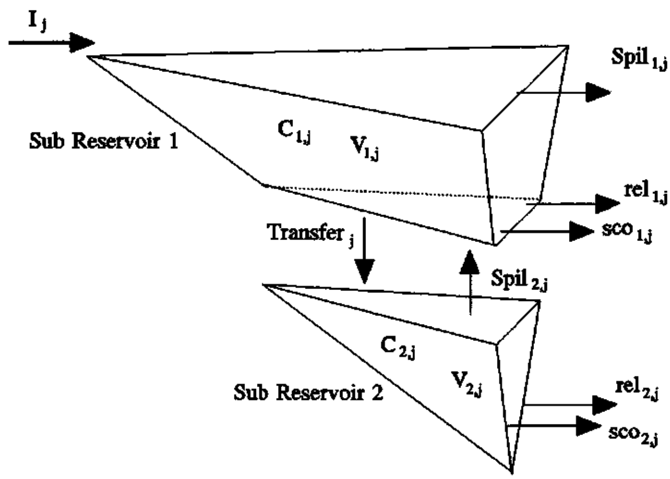

Figure 5.1 Simplified Configuration of the Reservoir : Iterative Model

Note that in the model presented in Chapter 4, the optimization-simulation procedure advances in monthly steps, each comprising an optimization phase and a simulation phase. The small hypothetical reservoirs are treated as independent at the optimization phase. Whereas at the simulation step (the state transformation step in the procedure) the whole reservoir (total of the hypothetical reservoirs) is considered. When the procedure reaches the following time step, the reservoir is again represented by smaller hypothetical reservoirs for the optimization. The number of hypothetical reservoirs depends on the availability of water at the beginning of the month. The uppermost reservoir could be full or partly full while all the others (beneath) are full.

In contrast, in the IDP optimization model presented in this chapter (Chapter 5), one optimization cycle comprises several shorter time steps (months). The smaller hypothetical reservoirs cannot be considered as independent during the whole period of the optimization cycle. Transfer of water between hypothetical reservoirs during each month is needed to fulfil the continuity of the reservoir. That is, at the beginning of each month of the total optimization period (year) except the top hypothetical reservoir, all the others must be apparently full. Therefore, in the IDP optimization model, to ensure this requirement, transfer of water between the smaller hypothetical reservoirs during each month is needed.

One optimization cycle consists of twelve months (one year). The optimization procedure commences by simulating the reservoir operation for the whole period (one year) employing DYRESM. This is called the initialization step. At this step the releases are made through a single outlet. That is, withdrawal of water is through either the top outlet or the bottom outlet throughout the year. However, releasing through a single outlet is not a compulsory requirement. It was executed as such solely for convenience. The impact of the initial condition (the outlet used at the initial step) on the final results will be examined. The initial releases made are the downstream demands only. This simulation provides the average salinities of the two hypothetical reservoirs at the end of each time period (month).

These are assumed to be the initial average salinities of the two hypothetical reservoirs at the beginning of the subsequent months. The optimization problem is to decide monthly releases and scours to be made from each outlet (two hypothetical reservoirs) during the total period (one year). It is further assumed that the salinity of the releases and/or scours made from a hypothetical reservoir during a month is equal to the initial salinity in that reservoir. That is, the inflow salinities are neglected at the optimization stage. Minimizing the weighted summation of squared deviations of release from the demand, and release and scour salinities from their target values is the objective in this optimization.

The optimization problem can be put into the format of a multi stage decision process, the total number of stages being 12. Each stage represents one month. The combination of the two smaller hypothetical reservoirs in a month belongs to a stage. A model based on IDP technique has been developed for this optimization. Only the inflow volumes are considered in the IDP model. Inflow salinities are not taken into account. Figure 5.2 shows one stage of the decomposed problem. There are two state variables (volumes of the two reservoirs) and four decision variables (releases and scours from the two reservoirs) as shown. A brief description of the IDP algorithm and the formulation of the reservoir optimization model is given in the next section.

Then the IDP model is run using the reservoir average salinities obtained from the initialization step. It results in releases and scours to be made monthly from the two outlets (or from the two hypothetical reservoirs) of the reservoir. These are the optimum releases and scours if the reservoir average salinities remain constant at the initial monthly concentrations throughout the months. But this assumption is not valid as the salinity depends on the inflow, the outflow, the reservoir volume and on the thermal structure in the reservoir.

At the next step the reservoir operation is simulated employing the DYRESM model with the releases and scours (through different elevations) obtained at the above step (optimization). The inflow salinities are considered at this step. This simulation provides the actual salinities of the releases and scours, and salinity in the reservoir. The resulting average salinities of the two hypothetical reservoirs at the end of each month are different from the previous values already used in the IDP model. Therefore, the previous reservoir salinities in the IDP model are replaced by the new values and it is run again to find the optimum operation pattern. If the resulting operation pattern from the optimization is the same as that obtained at the previous optimization, the procedure stops. Otherwise the procedure is repeated iteratively until the operation pattern obtained at two consecutive iterations (the optimization step in an iteration) become similar, which is the convergence criterion as described below.

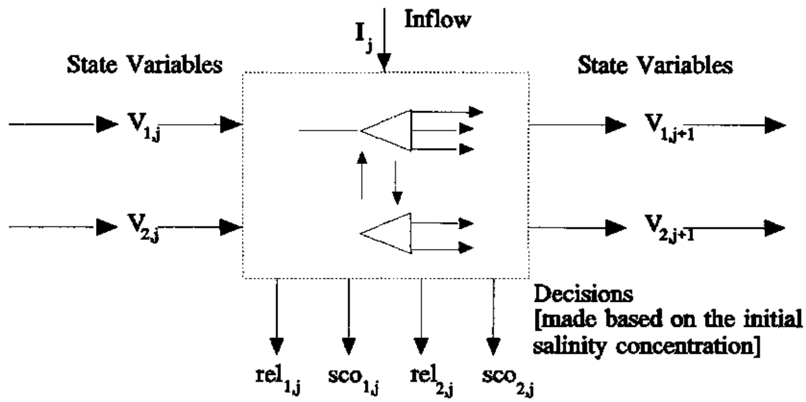

Figure 5.2 One Stage (i^{th} stage) in the Decision Process

One iteration cycle comprises a run of the simulation model and a run of the optimization model. At each stage (month) in the optimization phase an operation policy (release and scour quantities and the outlets they are released) for that stage is determined. After continuing the iterations a couple of times, a stable operation policy can be obtained. This implies that the operation policy for a specific month will not change from iteration to iteration. When this condition is reached the convergence criterion of stabilization of the operation policy is achieved. Once the convergence is achieved, the resulting operating pattern is the optimum operation. The methodology flowchart is presented in Figure 5.3.

5.1.1 Incremental Dynamic Programming Algorithm

Incremental Dynamic Programming (IDP) is an iterative procedure, which considers only a limited state space for a given iteration run. The general scheme of IDP procedure is represented by the flow diagram in Figure 5.4. The IDP procedure starts with an initial feasible solution, which can be visualized for a reservoir as a trajectory of the storage vector along the subsequent stages (time periods). Only an imaginary corridor around the initial feasible solution is considered as the feasible state space to derive an improved solution (a new trajectory of the state vector along the time periods). A corridor is then defined around the new trajectory and the procedure is repeated (iteration) until a pre-specified convergence criterion is satisfied. This completes one cycle of the IDP algorithm. It is to be indicated that IDP needs the initial and final stages of the system to be known. Those stages are not changed during the iteration.

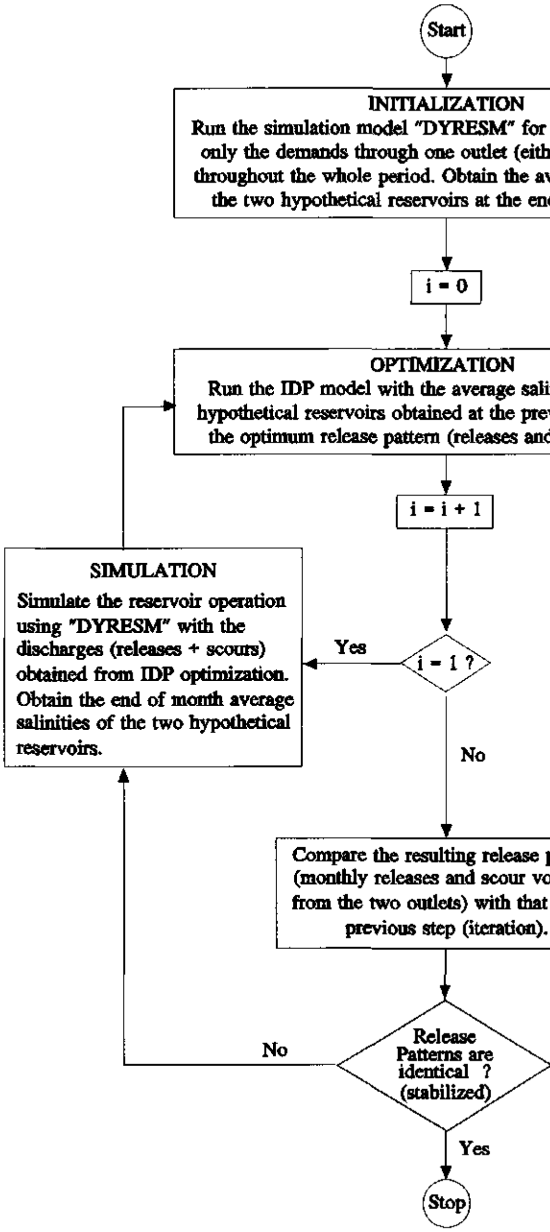

Figure 5.3 Methodology Flowchart : Iterative Method

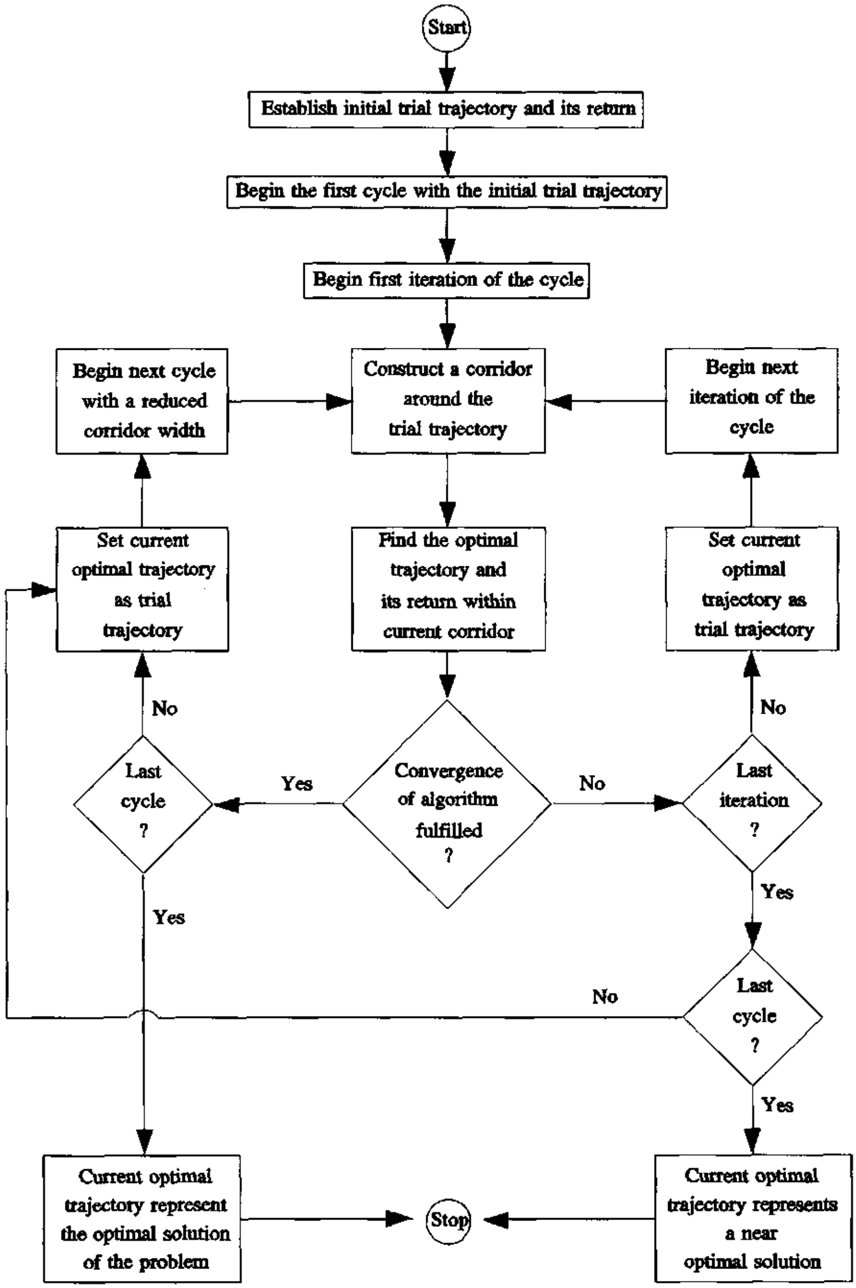

Figure 5.4 Flowchart of Incremental Dynamic Programming Algorithm

In the next cycle, a corridor of a lesser width is considered around the optimal solution of the previous cycle and the iterations will be repeated. For each iteration of a cycle, the optimal trajectory within a given corridor and its return are determined by the conventional DP methodology. A new iteration is needed if the convergence criterion is not satisfied. The number of cycles for the entire procedure and the allowable maximum number of iterations per cycle are to be pre-specified.

5.1.2 Model Formulation

Figure 5.1 shows the system configuration. The objective function is to minimize the summation of the weighted one sided squared deviation of total release from demand, and release and scour salinities from their respective target values.

$$O.F. = \mathrm{Min}\sum_{j=1}^{N}\left[W_1(Rel_j - Dem_j)^2 + W_2(C_{rel,j} - C_{trg,j})^2 + W_3(C_{sco,j} - \hat{C}_{trg,j})^2\right] \quad (5.1)$$

The optimization is subjected to the following constraints.

The total discharge from each sub-reservoir is constrained by the discharge capacity of the outlet;

$$0 \le rel_{i,j} + sco_{i,j} \le B_i \quad ; \ (i=1,2 \ ; \ j=1,2,...,N) \quad (5.2)$$

Downstream quantity demand has to be always satisfied. It is an implicit objective introduced in to the optimization. If the reservoir is empty due to low inflows the model cannot be used to derive operation policies that satisfy downstream mandatory releases. Note that the model can be used in such a situation with this constraint relaxed.

$$Rel_j \ge Dem_j \quad ; \ (j=1,2,...,N) \quad (5.3)$$

The storage of each sub-reservoir during any stage is constrained by its maximum capacity.

$$0 \le V_{i,j} \le Vmax_i \quad ; \ (i=1,2 \ ; \ j=1,2,...,N) \quad (5.4)$$

where,

B_i = the total allowable discharge (release + scour) from sub-reservoir i in MCM,
$C_{rel,j}$ = release salinity during period j in ppm (Eq.4.3),
$C_{sco,j}$ = scour salinity during period j in ppm (Eq.4.4),
$C_{trg,j}$ = target release salinity during period j in ppm,
$\hat{C}_{trg,j}$ = target scour salinity during period j in ppm,
Dem_j = downstream irrigation demand during period j in MCM,
N = total number of periods,

$Rel_j = \sum_{i=1}^{2} rel_{i,j}$ = total release from the reservoir during period j in MCM,

$V_{i,j}$ = storage of sub-reservoir i at the beginning of period j in MCM,
$Vmax_i$ = maximum storage of sub-reservoir i in MCM,
W_1, W_2, W_3 = weightages,
$rel_{i,j}$ = release from sub-reservoir i during period j in MCM,
$sco_{i,j}$ = scour volume from sub-reservoir i during period j in MCM, and

State Transformation Equation

For sub-reservoir 2

The total discharge from sub-reservoir 2 is decided from the following equation. (Note that $V_{i,j}$'s are already fixed in IDP procedure).

$$V_{2,j+1} = V_{2,j} - (rel_{2,j} + sco_{2,j}) \tag{5.5}$$

a). If the total discharge is less than the allowable limit.

i.e., If $V_{2,j+1} < Vmax_2$ and $(rel_{2,j} + sco_{2,j}) \leq B_2$

Then $V_{2,j+1}$ is made equal to $Vmax_2$ by transferring water (transfer j) from sub-reservoir 1 if water is available in it. (Because at the end of the period lower layer has to be full if there is water in the upper layer).

$$V_{2,j+1} + Transfer_j \rightarrow V_{2,j+1} = Vmax_2 \tag{5.6}$$

i.e., In Eq.(5.5) $V_{2,j+1}$ is always made equal to $Vmax_2$ at the end of each stage.

b). If the total discharge exceeds the allowable limit (outlet capacity).

i.e., If $V_{2,j+1} < Vmax_2$ and $(rel_{2,j} + sco_{2,j}) > B_2$

Then the discharge in excess is transferred ($Spil_{2,j}$) to the upper layer and only the allowable amount is released through the outlet.

$$Spil_{2,j} = (rel_{2,j} + sco_{2,j}) - B_2$$

and therefore, $V_{2,j+1}$ is made equal to $Vmax_2$ as follows.

$$V_{2,j+1} + Transfer_j - Spil_{2,j} \rightarrow V_{2,j+1} = Vmax_2 \tag{5.7}$$

For sub-reservoir 1

Total discharge from sub-reservoir 1 is decided from the following equation.

$$V_{1,j+1} = V_{1,j} + I_j - (rel_{1,j} + sco_{1,j}) - \textbf{Tranfer}_j + \textbf{Spil}_{2,j} - E_j \tag{5.8}$$

Where,

E_j = evaporation from the reservoir in period j in MCM,

I_j = inflow to the reservoir in period j in MCM, and

$Spil_{i,j}$ = spill from sub-reservoir i in period j in MCM.

However, it is possible that sub-reservoir 1 ends empty. If $V_{1,j+1} = 0$ and $rel_{1,j}+sco_{1,j} = 0$, sub-reservoir 1 will be empty while sub-reservoir 2 will be full. And if $V_{1,j+1} = 0$ and $res_{1,j}+sco_{1,j} < 0$, sub-reservoir 1 will be empty and sub-reservoir 2 will not be full.

Recursive Equation

The DP recursive equation is formulated as,

$$F^*_{j+1}(S_{j+1}) = \underset{rel_{i,j}, sco_{i,j}}{\text{Min}} \left\{ SQD_j(S_j,S_{j+1}) + F^*_j(S_j) \right\} \quad ; (i=1,2 \quad ; j=1,2,...N) \tag{5.9}$$

Where,

$rel_{i,j}$ and $sco_{i,j}$ are the decisions associated with the state transformation from S_j to S_{j+1}.

$F^*_{j+1}(S_{j+1})$ is the minimum accumulated value of the objective function from stage 0 to stage j+1, when the state at stage j+1 is S_{j+1} . and,

$$SQD_j(S_j,S_{j+1}) = \left[W_1(Rel_j - Dem_j)^2 + W_2(C_{rel,j} - C_{trg,j})^2 + W_3(C_{sco,j} - \hat{C}_{trg,j})^2 \right]$$

5.1.2.1 Construction of Corridors

A corridor composed of three values of the state variable is constructed around the initial trajectory whenever possible. In general, the corridor is defined symmetrically around the trial trajectory of state variables as described in the following.

If the state at the beginning of stage j is (V_{1j}, V_{2j}), then the 3 boundary points of the corridor with regard to V_{1j} can be defined as: $(V_{1j} - \Delta_1)$, V_{1j}, and $(V_{1j} + \Delta_1)$. Similarly, the 3 boundary points for V_{2j} can also be defined as $(V_{2j} - \Delta_2)$, V_{2j}, $(V_{2j} + \Delta_2)$, where Δ_1 and Δ_2 are the corridor half-widths for state variables 1 and 2 respectively. These imply the identification of 9 points in the two dimensional storage space. However, asymmetrical corridors may result if the boundaries of the corridors exceed the minimum or maximum limits of live storage capacities. Larger corridor widths are used for the initial cycles, which ensure that the optimal trajectories are obtained within a small number of iterations. Since the initial trajectory for any later cycle is the optimal trajectory for its preceding cycle and thus closer to the optimality than the initial one, smaller corridor widths can be used for later cycles to search for the optimal trajectory.

After the construction of a corridor around the trial trajectory, the optimal trajectory and the corresponding objective function value within the corridor should be sought. This is to be done by means of a conventional dynamic programming algorithm however restricting the computations of the state transformations only to those values of the state variables defined by the corridor.

5.1.2.2 Tests for Convergence

As indicated previously, the optimal trajectory for a given corridor width will be obtained iteratively. The improvement of the return from trajectories of subsequent iterations decrease as the iterations progress. The largest improvement corresponds to the first iteration. Therefore, the convergence criterion can be expressed as,

$$\delta_i = \frac{F_i^* - F_{i-1}^*}{F_1^* - F_0^*} \quad ; \quad i=1,2,...,I \tag{5.10}$$

Where,

F^*_i = the return from the optimal trajectory for the i-th iteration of a given cycle,
F^*_0 = the return from the initial trial trajectory, and
I = maximum number of iterations per cycle.

If, during any of the intermediate cycles, the iterative process yields a value of δ_i that does not represent a significant improvement in the return; that is

$$\delta_i \leq \varepsilon \quad ; \quad i=1,2,...,I \tag{5.11}$$

the computational cycle will be terminated. The next cycle starts with a smaller corridor considered around the optimal trajectory of the completed cycle.

For every iteration of the final cycle the following test will be made to determine the convergence of the algorithm toward the solution of the optimization problem.

$$\frac{F_i^* - F_{i-1}^*}{F_{i-1}^*} \leq \lambda \tag{5.12}$$

Where, λ is an arbitrary convergence criterion, which terminates the IDP procedure once the above criterion is satisfied. The trajectory that yields the optimum return is identified as the solution of the optimization problem. In the present study ε and λ were assigned the values of 0.00001 and 0.0001 respectively.

5.2 Analysis and Results

5.2.1 Division of the Jarreh Reservoir

The Jarreh Reservoir is assumed to be having two outlets at the elevations 136.7 m MSL and 184.0 m MSL in this study. It is also assumed that each outlet comprises two openings that could be operated independently. This enables releasing of water for satisfying downstream quantity demand and for scouring/flushing the reservoir from each outlet elevation. Based on these two outlets the reservoir is assumed to be equivalent to the parallel combination of the two hypothetical reservoirs. Their storage capacities are 300 MCM and 168 MCM, as shown in Figure 5.5. Maximum allowable releases through the upper outlet and the lower outlet are 60 MCM/month and 30 MCM/month respectively. Target release salinity is 1000 ppm and target scour salinity is 2500 ppm. Weightages W_1, W_2 and W_3 are 0.5, 1 and 1 respectively. Note that there are three components in the objective function. Transfer is not restricted. Table 3.2 shows the monthly irrigation demands.

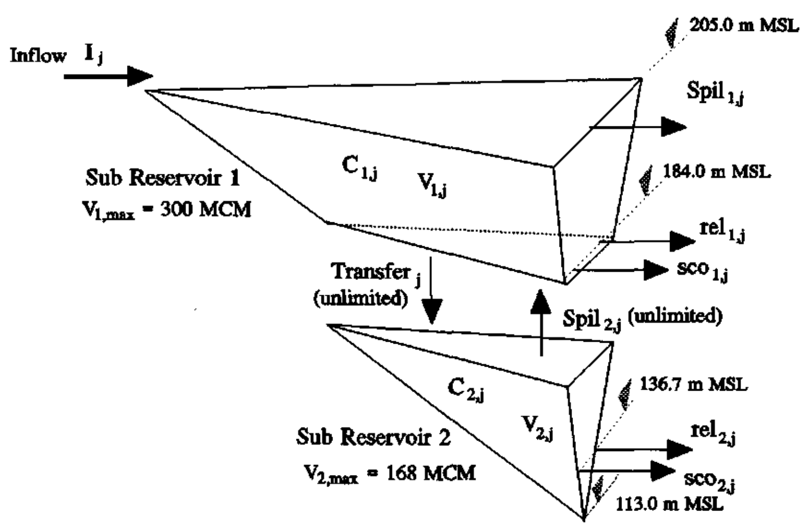

Figure 5.5 Simplified Configuration of the Jarreh Reservoir : Iterative Model

5.2.2 Optimization

The period from January 1982 to December 1984 (three years) has been considered in the analysis. This period includes the wet year 1982, median year 1983, and dry year 1984 out of a total period of 15 years (1975-1989) for which data are available. However, the total time duration considered in an optimization-simulation cycle is limited to one year. Therefore, optimum operation patterns for the 3 years were obtained separately.

5.2.2.1 Comparison of Impact of the Initial Condition

Analysis was started with the wet year 1982. The optimization procedure was initialized by releasing only the downstream quantity demands through the top outlet throughout the year. The optimization-simulation cycles were carried out until the convergence with respect to the operation pattern was achieved. At the fifth cycle the operation pattern (release and scour volumes and the outlets they are released) was observed to be similar to the preceding one (optimum operation pattern at the fourth cycle). That is, the operation pattern obtained at the fourth iteration is the optimum because it is repeated at the fifth cycle. Therefore, iterations stop after the fifth one as the convergence criterion is satisfied. Figure 5.6 shows the release salinities at a few iteration steps in the optimization procedure including the initial step and the final optimum result.

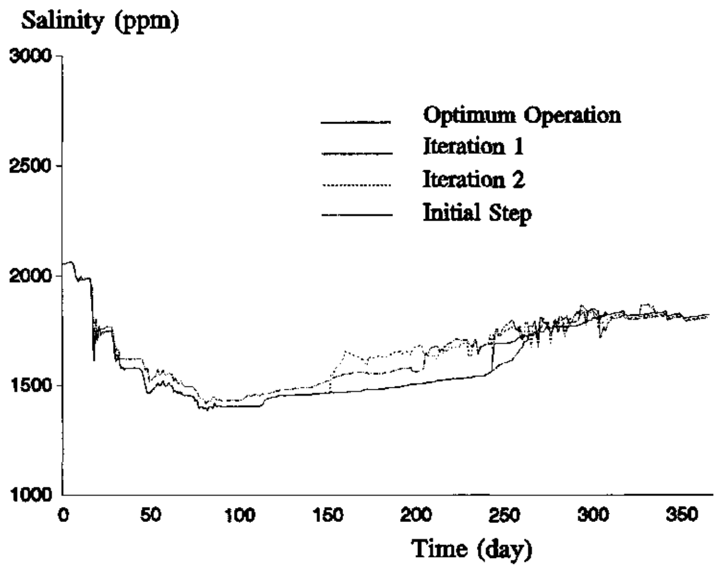

Figure 5.6 Release Salinities at Iteration Steps - Wet year (1982)
Started with Releasing Through Top Outlet

It was of interest to investigate the impact of the initial condition has on the final optimum operation pattern. To study that, the optimization procedure was repeated with initially releasing only the downstream quantity demands through the bottom outlet throughout the year. At this step the optimum was reached after three iterations. The release salinities at the successive iteration steps are shown in Figure 5.7.

The optimum operations obtained from the above two different cases were compared and found to be the same. The release salinities corresponding to these two initial conditions and final optimum operation are compared in Figure 5.8. The results indicate that independent of the initial condition the methodology finally converges to the same optimum operation pattern.

The optimum salinity distribution is more close to the release salinity distribution obtained by releasing initially totally through the bottom outlet, compared with that obtained by releasing initially totally through the top outlet. This might be the reason for reaching the optimum in a lesser number of iterations when started with initially releasing through the bottom outlet.

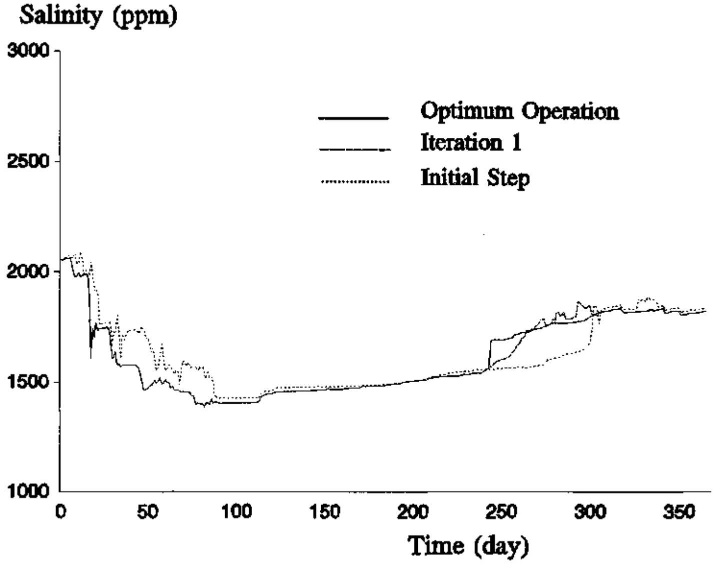

Figure 5.7 Release Salinities at Iteration Steps - Wet year (1982) Started with Releasing Through Bottom Outlet

The applicability of the methodology was tested for median year, 1983 and dry year, 1984 too. The two initial conditions (releasing through top outlet and releasing through bottom outlet) and the optimum results obtained for the median year and dry year are shown in Figure 5.9 and Figure 5.10, respectively. From these results it is apparent that immaterial of the initial condition the methodology converges to the optimum.

The annual averages of release salinities for the three different years are given in Table 5.1. The reason for the increase in the release salinity from 1982 through 1983 to 1984 is due to the continuing increase in the inflow salinity from 1982 to 1984 (wet year to median year and then to dry year). According to these results the operation pattern resulting from the proposed methodology seems to be superior to releasing through a single outlet throughout the year. At the beginning of winter a sudden rise in the salinity is observed in all the years. This is due to the starting of the mixing of the saltier water layer left in the reservoir. At the end of autumn a saltier layer is left at the top of the reservoir and when it is mixed, the reservoir salinity rises rapidly.

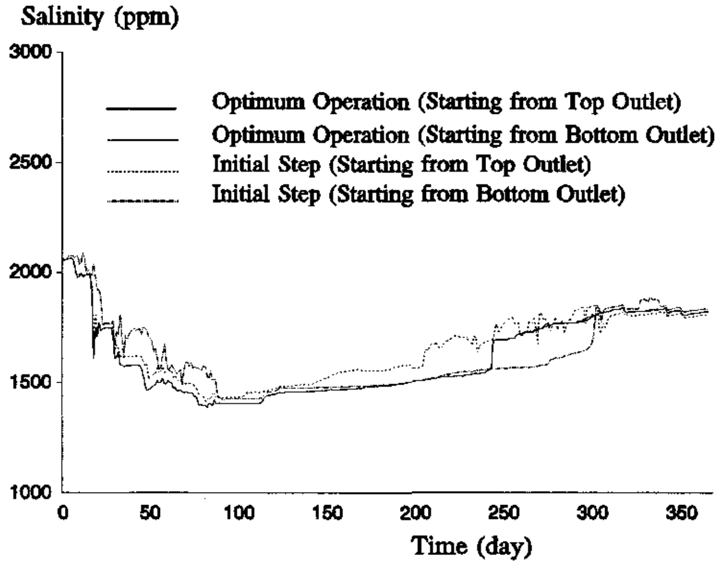

Figure 5.8 Comparison of Optimum Operations - Wet year (1982)

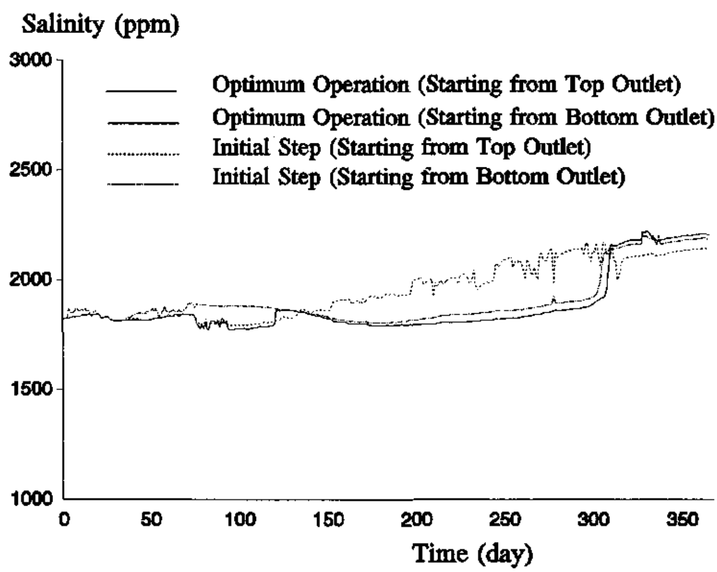

Figure 5.9 Comparison of Optimum Operations - Median year (1983)

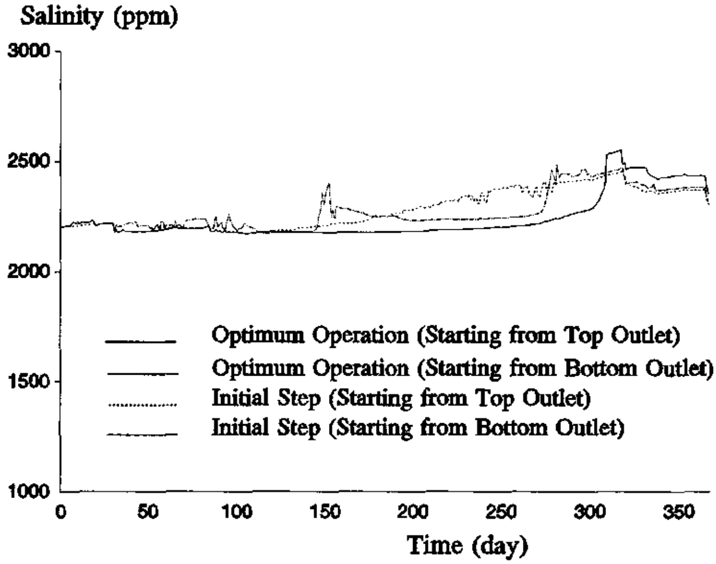

Figure 5.10 Comparison of Optimum Operations - Dry year (1984)

Table 5.1 Average Release Salinities for the Three Years

Year	Mean release salinity (ppm)		
	Releasing through top outlet	Releasing through Bottom outlet	Optimum operation
1982	1658	1627	1615
1983	1951	1906	1879
1984	2281	2275	2241

The number of iterations required to reach the optimum for all the three years are compared in Table 5.2. When started with initially releasing through the bottom outlet the number of iterations required to reach the optimum was always less for the Jarreh reservoir.

Table 5.2 Number of Iterations Required to Reach the Optimum

Year		Started with releasing through	
		Top outlet	Bottom outlet
Wet year	1982	4	3
Median year	1983	6	3
Dry year	1984	7	2

5.2.2.2 Comparison of Releases and Scours

The annual releases and scours made through the two outlets in the three years are given in Table 5.3. The initial and final storage volumes are fixed in the optimization.

Table 5.3 Total Annual Releases Through Two Outlets

Year	Release/Scour		Top	Bottom	Total
Wet Year	Release	(MCM)	145.77	124.73	270.50
1982	Scour	(MCM)	207.33	111.53	318.60
Median Year	Release	(MCM)	113.02	157.48	270.50
1983	Scour	(MCM)	102.54	118.61	221.15
Dry Year	Release	(MCM)	95.56	174.94	270.50
1984	Scour	(MCM)	12.06	39.24	51.30

In the wet year 1982, the total amount of water released for scouring is higher than that released for satisfying the downstream demand. The percentages of the releases and scours are 46% and 54% respectively. In the wet year water is available in excess and therefore, more water is used for scouring the reservoir. This results in a drop in the reservoir salinity level with the consequent lowering of the salinity in the releases. Also in the wet year the releases as well as the scours are mostly made through the top outlet. In the median year (1983) scour volume is less than the releases. It is observed that most of the releases and the scours are made through the bottom outlet in this year in contrast to the wet year. The releases are through the top outlet during autumn (Sep.-Nov.) in wet year and through the bottom outlet in the median year. In the median year the low inflows of high salinity concentration received during autumn, mixed with the upper layers of the reservoir. That made the releases from the bottom outlet to be of better quality compared with that from the top outlet during the latter part of the year.

In the dry year (1984) the scour volume is very little. This is apparently due to the scarcity of water during the dry year. Similar to the median year, most of the releases and the scours are made through the bottom outlet during this year. The optimum monthly releases and scours are presented in Table 5.4.

In the wet year the releases are through the bottom outlet during spring and summer. The inflows to the reservoir have a higher salinity concentration during this period. This warm water with a high salinity concentration mixes with the warm surface layers in the reservoir. This makes the salinity concentration of the upper layers high. Therefore, the releases made through the bottom layers have a lesser salinity concentration. In autumn the inflows get colder. When these inflows enter the reservoir they move to the bottom, because the surface layers in the reservoir are still warmer than inflows. Therefore, the salinity concentration of the lower part of the reservoir increases and releases are made through the top outlet. In winter the reservoir water gets mixed. Then there should not be a difference between releasing from the top outlet and the bottom outlet. But it is observed that the water is released from the top outlet.

Table 5.4 Optimum Monthly Releases and Scour Volumes

Year	Month	Releases (MCM)		Scours (MCM)	
		Top	Bottom	Top	Bottom
1982	Jan	17.5	0.0	40.6	30.0
	Feb	23.0	0.0	36.4	30.0
	Mar	34.0	0.0	26.0	30.0
	Apr	0.0	26.5	60.0	0.0
	May	0.0	19.5	10.2	0.0
	Jun	0.0	22.0	6.7	0.0
	Jul	0.0	26.5	10.4	0.0
	Aug	0.0	30.0	14.2	0.0
	Sep	27.0	0.0	0.0	11.6
	Oct	22.0	0.0	0.0	7.4
	Nov	10.5	0.0	0.0	1.9
	Dec	12.0	0.0	2.5	0.0
1983	Jan	17.5	0.0	29.4	30.0
	Feb	23.0	0.0	0.0	28.4
	Mar	34.0	0.0	26.0	30.0
	Apr	26.5	0.0	14.5	30.0
	May	0.0	19.5	5.1	0.0
	Jun	0.0	22.0	3.7	0.0
	Jul	0.0	26.5	5.4	0.0
	Aug	0.0	30.0	6.9	0.0
	Sep	0.0	27.0	5.5	0.0
	Oct	0.0	22.0	3.7	0.0
	Nov	0.0	10.5	0.0	0.0
	Dec	12.0	0.0	1.0	0.0
1984	Jan	0.0	17.5	0.0	12.5
	Feb	23.0	0.0	0.0	1.6
	Mar	34.0	0.0	0.0	3.6
	Apr	26.5	0.0	0.0	2.1
	May	0.0	19.5	1.2	0.0
	Jun	0.0	22.0	1.5	0.0
	Jul	0.0	26.5	2.2	0.0
	Aug	0.0	30.0	2.8	0.0
	Sep	0.0	27.0	2.2	0.0
	Oct	0.0	22.0	1.5	0.0
	Nov	0.0	10.5	0.0	19.5
	Dec	12.0	0.0	0.0	0.0

The monthly scours during spring and summer are through the top outlet. This is because the top part of the reservoir has a higher salinity concentration during this period as described earlier. In the autumn the scours are through the bottom as the reservoir bottom layers are more saline during that period. In the wet year as there is excess water available during the winter period, scours are made through both the top and bottom outlets.

In median year and dry year the releases from the bottom outlet starts by the end of the spring and continues till the end of the autumn. In the remainder period the releases are through the top outlet.

In the median year most of the scouring occurs during winter and early spring from both outlets. A very small amount of scouring is observed during the remainder of the year through the top outlet. In the dry year the scouring is very small. This is due to the scarcity of water. However, relatively high scouring volumes are observed in the winter from the bottom outlet.

Although the technique does not guarantee a global optimum the results appear to be reasonably effective compared with releasing through a single outlet throughout the year.

5.2.3 Optimization with One Cycle of Three Years

In this analysis the total period in a single optimization was increased from one year to three years. The three years period is considered in monthly stages totalling the number of stages to 36 in a single optimization. The period analyzed comprised years 1982, 1983 and 1984.

The iterative technique described previously was applied starting with initially releasing through the bottom outlet throughout the total period. The operation pattern (both releases and scours from two outlets) converged to a fixed pattern after six optimization-simulation iterative cycles. The resulting operation pattern was observed to be slightly different to that obtained from the application of the technique for these three years separately. The scour volume has been increased in all the three years. Table 5.5 shows the optimum releases and scours from the different elevations. However, the salinity in the releases do not show significant improvement (or changes) compared with that obtained from separate optimizations for the three years.

The release salinities are compared in Figure 5.11. The three year average salinity was observed to be increased from 1912 ppm (three optimizations, each of one year) to 1916 ppm with the optimization of 3 years duration. Further, the maximum salinity has been increased from 2550 ppm to 2639 ppm (about 90 ppm) to the end of the dry year 1984.

The results indicate that the application of the methodology as a single optimization of a longer time span (of several years) is not superior to several optimizations, each of one year period.

Table 5.5 Optimum Releases and Scour Volumes : Single Optimization for Three Years

Year	Month	Releases (MCM)		Scours (MCM)	
		Top	Bottom	Top	Bottom
1982	Jan	17.5	0.0	42.5	30.0
	Feb	23.0	0.0	37.0	30.0
	Mar	4.0	30.0	56.0	0.0
	Apr	0.0	26.5	60.0	0.0
	May	0.0	19.5	22.9	0.0
	Jun	0.0	22.0	22.8	0.0
	Jul	0.0	26.5	22.8	0.0
	Aug	0.0	30.0	22.8	0.0
	Sep	0.0	27.0	23.0	0.0
	Oct	0.0	22.0	23.0	0.0
	Nov	0.0	10.5	23.0	0.0
	Dec	12.0	0.0	0.0	23.4
1983	Jan	17.5	0.0	0.0	23.6
	Feb	23.0	0.0	0.0	23.5
	Mar	34.0	0.0	0.0	23.7
	Apr	26.5	0.0	0.0	23.6
	May	19.5	0.0	0.0	9.6
	Jun	0.0	22.0	9.7	0.0
	Jul	0.0	26.5	9.5	0.0
	Aug	0.0	30.0	9.7	0.0
	Sep	0.0	27.0	9.8	0.0
	Oct	0.0	22.0	9.8	0.0
	Nov	0.0	10.5	9.7	0.0
	Dec	12.0	0.0	0.0	9.7
1984	Jan	17.5	0.0	0.0	9.8
	Feb	0.0	23.0	9.8	0.0
	Mar	34.0	0.0	0.0	9.9
	Apr	26.5	0.0	0.0	10.0
	May	0.0	19.5	9.9	0.0
	Jun	0.0	22.0	9.9	0.0
	Jul	0.0	26.5	9.9	0.0
	Aug	0.0	30.0	10.1	0.0
	Sep	0.0	27.0	10.0	0.0
	Oct	0.0	22.0	2.0	8.0
	Nov	0.0	10.5	0.0	10.1
	Dec	12.0	0.0	10.0	0.0

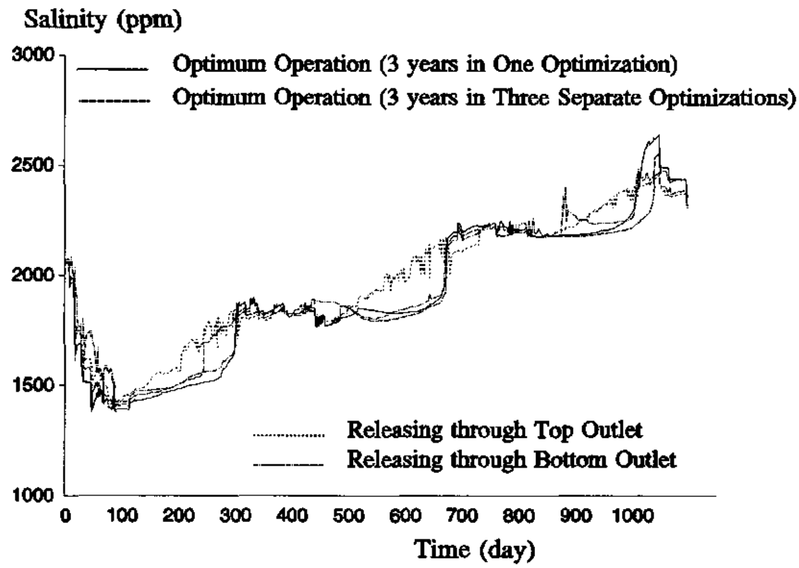

Figure 5.11 Release Salinity : Comparison of Optimization Duration

6 Completely Mixed Reservoir Models

In the derivation of operation policies for a reservoir to be used for quality control, the reservoir can be modelled assuming complete mixing is occurring in it throughout the year. This is a simplification compared with the real behaviour of reservoirs, which undergo mixing and stratification cycles during a year. O'Connor and Mueller (1970) used a completely mixed reservoir model to predict chloride concentration in Great Lakes, USA. There are a few studies of optimum reservoir operation in which water quality in the reservoir has been modelled assuming complete mixing (Verhaeghe and Tholan, 1983; Foruria *et al.*, 1985; Crawley and Dandy, 1989; Dandy and Crawley, 1992).

In this study two optimization models were developed based on the IDP technique for the optimum operation of a reservoir. Both the quantity and the quality of the water supplied from the reservoir are of interest. One model uses only the releases while the other model uses both inflows and releases in the improvement of the quality of the water supplied from the reservoir. Inflow manipulation is achieved by diverting (by-passing) inflows before they reach the body of the reservoir. Outflow manipulation includes release of excess water from the reservoir at appropriate times to flush (cleanse) the reservoir. Nonlinear salt balance constraints are included in both optimization models.

Crawley and Dandy (1989) and Dandy and Crawley (1992) did not include nonlinear salt balance constraints in the optimization model. Instead they used a separate model of salinity in the reservoir and this was run interactively with an optimization model (linear programming based), which considered quantity only. Verhaeghe and Tholan (1983) applied conventional dynamic programming technique to formulate their optimization model and used salt balance equation to calculate the concentration of salt in the reservoir. They assumed that the concentration of salt in the releases in a month to be the average of initial and final salt concentrations in the reservoir in that month. This salt balance equation would be correct only if the time distribution of the concentration of salt would be linear, which is not the case. The salt concentration in the reservoir at each point in time is nonlinearly related to the volume and flow variables (inflow and outflow). The models presented in this chapter are formulated considering the nonlinear distibution of salt concentration in the reservoir over the time interval explicitly.

6.1 Optimization Model 1 : Controlling Discharges Only

In this model only the discharges from the reservoir can be manipulated. Complete mixing is assumed to be occurring in the reservoir. The water resources system is as shown in Figure 6.1. The reservoir is operated on a monthly basis. The rate of inflow, outflow and spill for the reservoir are constant during each time period. The forward algorithm of dynamic programming is used in the optimization procedure. The general scheme of IDP procedure presented in Chapter 5.1.1 is used in the formulation of the model.

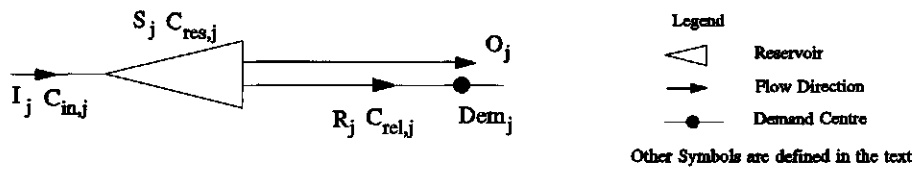

Figure 6.1 System Configuration : Optimization Model 1

The objective function used in the model is to minimize the weighted summation of the squared deviation of the release salinity and the reservoir salinity from the respective target levels over the total period considered. The downstream quantity demand is treated as a constraint.

$$O.F. = \text{Minimize} \sum_{j=1}^{N} \left[W_1(C_{rel,j} - C_{trg,j})^2 + W_2(C_{res,j+1} - \hat{C}_{trg,j})^2 \right] \tag{6.1}$$

Where,

$C_{trg,j}$ = target release salinity during period j in ppm,
$\hat{C}_{trg,j}$ = target reservoir salinity during period j in ppm,
$C_{rel,j}$ = average salinity of release during period j in ppm,
$C_{res,j+1}$ = average salinity of the reservoir at the end of period j in ppm,
N = number of periods,
W_1, W_2 = weightages, and
j = time period (1,2,....,N).

The reservoir storage and release are assumed to be the state variable and decision variable, respectively. The minimization is subjected to the constraints in storage volume, release and conservation of salt.

Storage volume constraint

The storage volume at the beginning of the first period and at the end of the last period are fixed. For all the other periods it belongs to the set of admissible storage volume.

$$S_{min} \leq S_{j+1} \leq S_{max} \quad ; \quad j=1,2,...,N-1 \tag{6.2}$$

S_{j+1} is the storage volume at the end of period j in MCM. S_{max} and S_{min} are the maximum and minimum storage volumes of the reservoir in MCM.

Release constraint

The maximum release from the reservoir is limited to the allowable release through the outlet. The minimum release is specified by the downstream irrigation demand, which is an implicit objective to be satisfied in the operation of the reservoir.

$$R_{min,j} \leq R_j \leq R_{max} \qquad ; \qquad j=1,2,...,N \qquad (6.3)$$

R_j is the release during period j in MCM. R_{max} is the maximum allowable release through the outlet in MCM, and $R_{min,j}$ is the irrigation demand during period j in MCM.

Conservation of salt

The constraint that represents the conservation of salt in the reservoir is,

$$S_{j+1}C_{res,j+1} = S_jC_{res,j} + I_jC_{in,j} - R_jC_{rel,j} - O_jC_{o,j} \qquad (6.4)$$

Where,

$C_{in,j}$ = average salinity of inflow during period j in ppm,
$C_{o,j}$ = average salinity of spill during period j in ppm,
I_j = inflow during period j in MCM, and
O_j = spill during period j in MCM.

Other variables are as defined before. The evaporation terms do not enter the salt balance as it is assumed that no salt is contained in the evaporating liquid.

The following equations are used to assess the salinity in the reservoir at the end of period j. The derivation of these equations is described in Chapter 6.4 (the derivation of these equations is given separately as the main aim of this subchapter is to present the formulation of the optimization model).

If the reservoir volume is changing during period j,

$$C_{res,j+1} = \frac{1}{(Q_j+b)}\left[I_jC_{in,j} - [I_jC_{in,j} - C_{res,j}(Q_j+b)]\left(\frac{S_{j+1}}{S_j}\right)^{-(Q_j+b)/b}\right] \qquad (6.5)$$

If the reservoir volume is constant during period j,

$$C_{res,j+1} = \frac{1}{Q_j}\left[I_jC_{in,j} - [I_jC_{in,j} - C_{res,j}Q_j] \exp(-\frac{Q_j}{S_j}) \right] \qquad (6.6)$$

The average salinity of spill during period j.

$$C_{o,j} = \frac{I_jC_{in,j}}{Q_j} + \frac{S_j}{Q_j^2}[I_jC_{in,j} - C_{res,j}Q_j] \left\{\exp(-\frac{Q_j}{S_j}) - 1 \right\} \qquad (6.7)$$

Where,

Q_j = total outflow (total of release and spill) during period j, and
b = change of the reservoir storage during period j.

State transformation equation

Based on the principle of continuity of the reservoir,

$$S_{j+1} = S_j + I_j - R_j - E_j - O_j \tag{6.8}$$

E_j is the evaporation during period j in MCM. The other variables are as defined above.

Recursive equation

The DP recursive equation is formulated as,

$$F^*_{j+1}(S_{j+1}) = \underset{R_j}{\text{Min}} \left\{ SQD_j + F^*_j(S_j) \right\} \tag{6.9}$$

Where,

$F^*_{j+1}(S_{j+1})$ is the minimum accumulated value of the objective function from stage 0 to stage j+1, when the state at stage j+1 is S_{j+1}, and

$$SQD_j = \left[W_1(C_{rel,j} - C_{trg,j})^2 + W_2(C_{res,j+1} - \hat{C}_{trg,j})^2 \right]$$

6.2 Optimization Model 2 : Controlling both Inflows and Discharges

The operation of a reservoir is carried out by manipulating the releases when the quantity of water released is of interest. The quality of water available from a reservoir also could be improved by managing releases. Yet, the improvements obtainable in quality by managing only the releases could be considerably enhanced by controlling the inflows to the reservoir. That is by diverting (or by-passing) the poor quality inflows before entering the reservoir. Imberger (1981) suggested by-passing of inflows of high salinity as an effective management strategy in substantially reducing the reservoir salinities.

An optimization model was developed for the optimal operation of a reservoir by controlling both inflows and discharges. The improvement of the quality of water supplied from the reservoir is an important parameter besides satisfying the quantity demand. The water resources system is as shown in Figure 6.2. Provisions to divert part of the inflow whenever necessary has been introduced in this system. Complete mixing is assumed to be occurring in the reservoir throughout the year. The reservoir is operated on a monthly basis. Further, the rate of inflow, outflow, diversion and spill for the reservoir are constant during each time period. The forward algorithm of dynamic programming is used in the optimization procedure. The general scheme of IDP procedure presented in Chapter 5.1.1 is used in the formulation of the model.

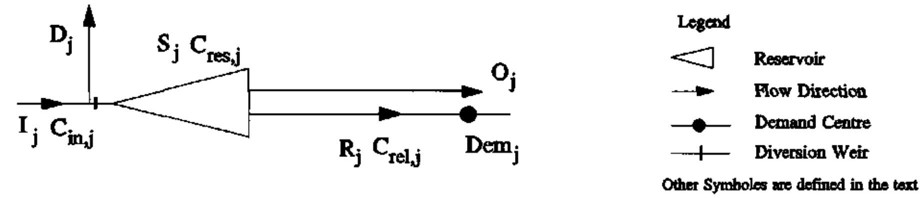

Figure 6.2 System Configuration : Optimization Model 2

The objective function is the same as that in Optimization Model 1 (Eq.6.1). The reservoir storage is the state variable while the release and the diversion are the decision variables. The minimization is subjected to the storage volume and release constraints presented under Optimization Model 1 (Eq.6.2 and Eq.6.3). The diversion from the inflow is constrained by an allowable limit.

$$0 \leq D_j \leq D_{max} \qquad ; \; j=1,2,...,N \tag{6.10}$$

Where,

D_{max} = maximum allowable diversion from inflow in a month in MCM, and

D_j = total diversion made during the period j in MCM.

Diversion during a certain month is always less than or equal to the inflow in that month.

$$0 \leq D_j \leq I_j \qquad ; \; j=1,2,...,N \tag{6.11}$$

Conservation of salt

The constraint that represents the conservation of salt in the reservoir is,

$$S_{j+1}C_{res,j+1} = S_jC_{res,j} + (I_j - D_j)C_{in,j} - R_jC_{rel,j} - C_{o,j}O_j \tag{6.12}$$

The Eq.6.5 through Eq.6.7 are used to assess the salinity in the reservoir at the end of period j and the salinity of spill during period j.

State transformation equation

Based on the principle of continuity of the reservoir,

$$S_{j+1} = S_j + I_j - D_j - R_j - E_j - O_j \tag{6.13}$$

Recursive Equation

The DP recursive equation is same as Eq.6.9 presented under Optimization Model 1.

6.3 Simulation Model : Completely Mixed Reservoir

A simulation model was formulated to simulate the reservoir operation according to a pre-specified release pattern described below. The reservoir is assumed to be completely mixed throughout the year. The Eq.(6.4) through Eq.(6.8) are used in the regulation of the reservoir in this simulation model. Further, the simulation procedure considers the constraints for reservoir storages and releases as given in Eq.(6.2) and Eq.(6.3) respectively. This model furnishes end of month reservoir salinities and monthly average release salinities. The two optimization models will be compared with the results obtained from this simulation model.

In the release pattern adopted in the simulation model, the primary operation criterion is to make mandatory releases (downstream demands) only. However, if this criterion is strictly followed it is inevitable that the reservoir storage reaches maximum volume before the end of the period in certain months. If this happens then the excess volume of water has to spill. In such instances the above policy to release only the demand is over-ruled. The excess volume of water is released through the outlet subjected to the maximum allowable release. If it exceeds maximum limit, the additional volume spills. The monthly demand is not totally satisfied only if there is no enough water in the reservoir. However, in such cases the water available in the reservoir is supplied at least to partly satisfy the demand. This operation pattern is designated as "Standard Release Policy" in this report.

6.4 Model of Salinity in a Reservoir

For a reservoir that is completely mixed, the continuity equation (salt balance equation) is,

$$\frac{d(SC)}{dt} = IC_{in} - QC \qquad (6.14)$$

Where,

C	=	instantaneous salinity in the reservoir at time t
S	=	instantaneous volume of storage in the reservoir at time t
I	=	rate of total inflow
C_{in}	=	average salinity of total inflow
Q	=	rate of total outflow including irrigation supply and spill

i.e.,

$$S\frac{dC}{dt} + C\frac{dS}{dt} = IC_{in} - QC \qquad (6.15)$$

If the rates of inflow and outflow are assumed to be constant, then

$$\frac{dS}{dt} = b \qquad (6.16)$$

and

$$S = a + bt \qquad (6.17)$$

Where, a and b are constants

Therefore, substituting Eq.(6.16) and Eq.(6.17) into Eq.(6.15) gives:

$$(a + bt)\frac{dC}{dt} + Cb = IC_{in} - QC \qquad (6.18)$$

By rearranging

$$\frac{dC}{dt} = \frac{IC_{in} - QC - bC}{a + bt} = \frac{IC_{in} - C(Q + b)}{a + bt}$$

Rearranging and integrating the above equation from time t_j to t_{j+1};
The salinity in the reservoir changes from $C_{res,j}$ to $C_{res,j+1}$ while the storage changes from S_j to S_{j+1}.

$$\int_{C_{res,j}}^{C_{res,j+1}} \frac{dC}{IC_{in} - C(Q + b)} = \int_{t_j}^{t_{j+1}} \frac{dt}{(a + bt)}$$

$$\frac{1}{(Q + b)} \int_{C_{res,j}}^{C_{res,j+1}} \frac{dC}{[IC_{in}/(Q + b) - C]} = \frac{1}{b} \int_{t_j}^{t_{j+1}} \frac{dt}{(a/b + t)}$$

$$\int_{C_{res,j}}^{C_{res,j+1}} \frac{dC}{(IC_{in}/(Q + b) - C)} = \frac{Q + b}{b} \int_{t_j}^{t_{j+1}} \frac{dt}{(a/b + t)}$$

$$- \ln\left[\frac{IC_{in}}{(Q + b)} - C\right] \Bigg|_{C_{res,j}}^{C_{res,j+1}} = \frac{(Q + b)}{b} \ln\left(\frac{a}{b} + t\right) \Bigg|_{t_j}^{t_{j+1}}$$

$$\ln\left[\frac{IC_{in}/(Q + b) - C_{res,j+1}}{IC_{in}/(Q + b) - C_{res,j}}\right] = - \frac{Q+b}{b} \ln\left[\frac{a/b + t_{j+1}}{a/b + t_j}\right]$$

$$\frac{IC_{in} - C_{res,j+1}(Q + b)}{IC_{in} - C_{res,j}(Q + b)} = \left(\frac{a + bt_{j+1}}{a + bt_j}\right)^{-(Q+b)/b} = \left(\frac{S_{j+1}}{S_j}\right)^{-(Q+b)/b}$$

$$IC_{in} - C_{res,j+1}(Q + b) = [IC_{in} - C_{res,j}(Q + b)] \left(\frac{S_{j+1}}{S_j}\right)^{-(Q+b)/b}$$

At the end of the time period the salinity in the reservoir,

$$C_{res,j+1} = \frac{1}{(Q + b)} \left[IC_{in} - [IC_{in} - C_{res,j}(Q + b)] \left(\frac{S_{j+1}}{S_j}\right)^{-(Q+b)/b} \right]$$

Special case where the volume of the reservoir is not changing (i.e., b = 0):

The continuity equation - Eq.(6.14)

$$\frac{d(SC)}{dt} = IC_{in} - QC$$

i.e.,

$$S\frac{dC}{dt} + C\frac{dS}{dt} = IC_{in} - QC$$

If the storage is constant,

$$S = A \ (= a \ \text{constant}) \rightarrow \frac{dS}{dt} = 0$$

$$A\frac{dC}{dt} = IC_{in} - QC \tag{6.19}$$

By rearranging,

$$\frac{dC}{(IC_{in}/Q - C)} = \frac{Q}{A}dt$$

Integrating the above equation from time t_j to t_{j+1} with the change in salinity from $C_{res,j}$ to $C_{res,j+1}$.

$$\int_{C_{res,j}}^{C_{res,j+1}} \frac{dC}{(IC_{in}/Q - C)} = \frac{Q}{A}\int_{t_j}^{t_{j+1}} dt$$

$$-\ln\left(IC_{in}/Q - C\right)\Big|_{C_{res,j}}^{C_{res,j+1}} = \frac{Q}{A}(t_{j+1} - t_j)$$

If $t_{j+1} - t_j = \Delta t$, then:

$$\ln\left(\frac{IC_{in} - C_{res,j+1}Q}{IC_{in} - C_{res,j}Q}\right) = -\frac{Q\Delta t}{A}$$

$$\left(\frac{IC_{in} - C_{res,j+1}Q}{IC_{in} - C_{res,j}Q}\right) = \exp\left(-\frac{Q\Delta t}{A}\right)$$

$$IC_{in} - C_{res,j+1}Q = [\ IC_{in} - C_{res,j}Q\ ]\ \exp\left(-\frac{Q\Delta t}{S_j}\right)$$

At the end of the time period the salinity in the reservoir,

$$C_{res,j+1} = \frac{1}{Q}\left[IC_{in} - [\ IC_{in} - C_{res,j}Q\ ]\ \exp\left(-\frac{Q\Delta t}{S_j}\right)\right] \tag{6.20}$$

Spilled salt load

During spill there is a constant volume of water in the reservoir (ignoring the effect of surcharge). Therefore, Eq.(6.20) can be used to determine the spilled salt load and hence, the average salinity of the spilled water.

Let

L_s = spilled salt load during the time period

O_s = volume of spill per unit time during the time period (assumed constant)

C_o = average salinity of spill during the time period

Then

$$L_s = \int_{t_j}^{t_{j+1}} O_s C dt \tag{6.21}$$

$$= \int_{t_j}^{t_{j+1}} (O_s/Q)\left[IC_{in} - [IC_{in} - C_{res,j}Q]\ \exp\left(-\frac{Q\Delta t}{S_j}\right)\right] dt$$

$$L_s = \frac{O_s}{Q} IC_{in}\Delta t + \frac{O_s S_j}{Q^2}[IC_{in} - C_{res,j}Q]\left[\exp\left(-\frac{Q\Delta t}{S_j}\right) - 1\right]$$

but $C_o = L_s/(O_s\Delta t)$

$$C_o = \frac{IC_{in}}{Q} + \frac{S_j}{Q^2\Delta t}[IC_{in} - C_{res,j}Q]\left[\exp\left(-\frac{Q\Delta t}{S_j}\right) - 1\right] \tag{6.22}$$

6.5 Analysis and Results

The discharge and salinity of the Shapur river at the dam site (Jarreh reservoir) are shown for the period 1975-1989 in Figure 6.3. It shows that the salinity of the river is strongly influenced by long term variations in stream flow in addition to the seasonal variations. For example, the high annual inflows of 1982 (discharge 1127 MCM, 2.12 times the median) averaged 1500 ppm whereas the inflows of 1984, a dry year (discharge 280 MCM, 0.54 times median) averaged 2180 ppm in salinity. On an occasional basis, the flood flows (winter period) are generally less saline. Low flows (summer period), however, are in part due to groundwater flows and remain highly saline. For the recorded period the salinity of the inflowing water varies between 750-4200 ppm.

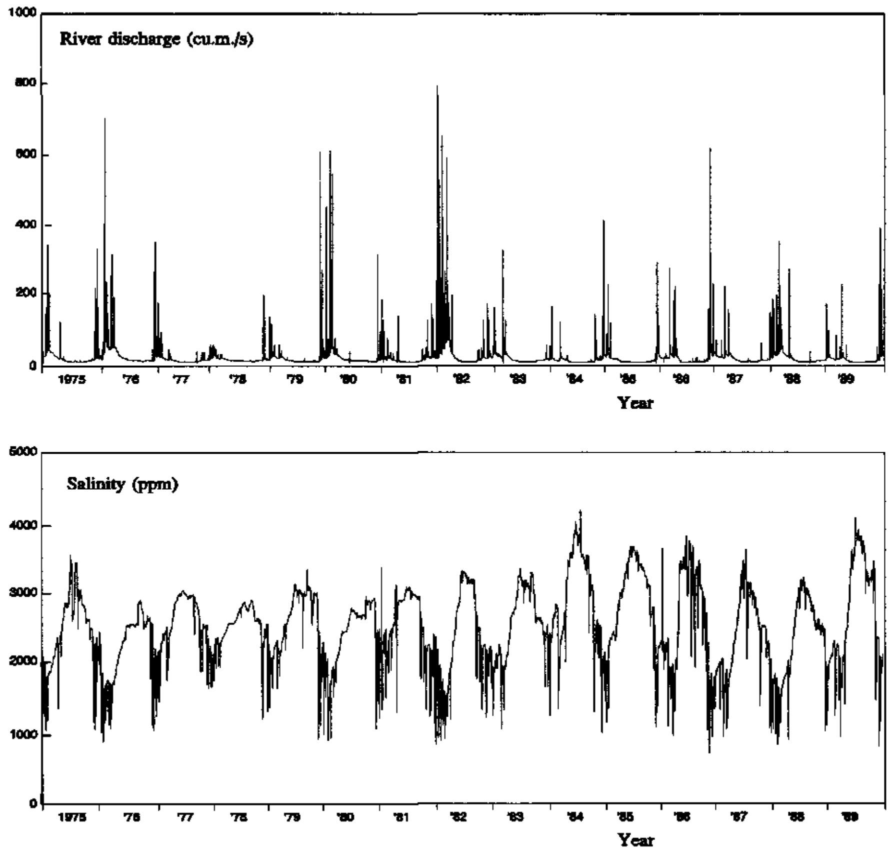

Figure 6.3 River Discharges and Salinities : 1975-1989

Shapur river is characterized by the high variability of both the discharges and the salinity. In wet years when the river flows are high, the average salinity of inflow is low and the reservoir is flushed out so that the quality of the impounded water improves. On the other hand, a dry year causes a considerable deterioration of quality, and especially a series of consecutive dry years will deteriorate the quality considerably. This analysis was carried out to study the long term optimum operation of the Jarreh reservoir assuming the reservoir is completely mixed throughout the entire volume throughout the year. Improving the quality of water both in the reservoir and supplied to the downstream are of interest besides satisfying the quantity demand.

6.5.1 Optimization Model 1 : Controlling Discharges Only

The Jarreh reservoir is assumed to be having a total storage capacity of 470 MCM and a dead storage capacity of 75 MCM, respectively. The allowable release through the reservoir is limited to 150 MCM in a month. The target release and reservoir salinities are set to 1000 ppm. The release and reservoir salinities were always higher than this value. The monthly irrigation demands are given in Table 3.2. The period considered in a single optimization is 15 years, the total number of stages being 180 (12 months x 15 years). Data for 15 years are available.

6.5.1.1 Comparison of Components in the Objective Function

The objective function used in the model (see Eq.6.1) has two parts. They are;

a. to minimize the deviation of release salinity from a target; and,

b. to minimize the deviation of reservoir salinity from a target.

Initially, the impact of these two components has on the final aim of reducing the release salinity was examined. This was carried out by giving different weightages for the two components as given below.

i. $W_1 = 1.0$, $W_2 = 0.0$ - Only release salinity is considered.

ii. $W_1 = 0.5$, $W_2 = 0.5$ - Both release salinity and reservoir salinity are considered with equal importance.

iii. $W_1 = 0.0$, $W_2 = 1.0$ - Only reservoir salinity is considered.

The results are compared in Table 6.1. The monthly average release salinities for the above three cases are shown in Figure 6.4.

Table 6.1 Comparison of Different Objective Functions

Weightages		O.F. Value $/10^6$	Total Release (MCM)	Total Spill (MCM)	Monthly Average Salinity(ppm)	
W_1	W_2				Reservoir	Release
1.0	0.0	134.5	8043	89	1832	1828
0.5	0.5	132.2	8090	47	1820	1815
0.0	1.0	133.4	8089	46	1821	1816

According to Table 6.1 and Figure 6.4 the differences observed among the above mentioned three different objective functions are almost negligible. This shows that the improvements obtained in the quality of the release water, by considering the quality of the release or quality of the reservoir or both, in the objective function, are almost similar. In this model the improvements in the quality of release water are attempted through the manipulation of releases only. Finally, the second alternative that gives equal weightages to the two components was selected to be used in the study.

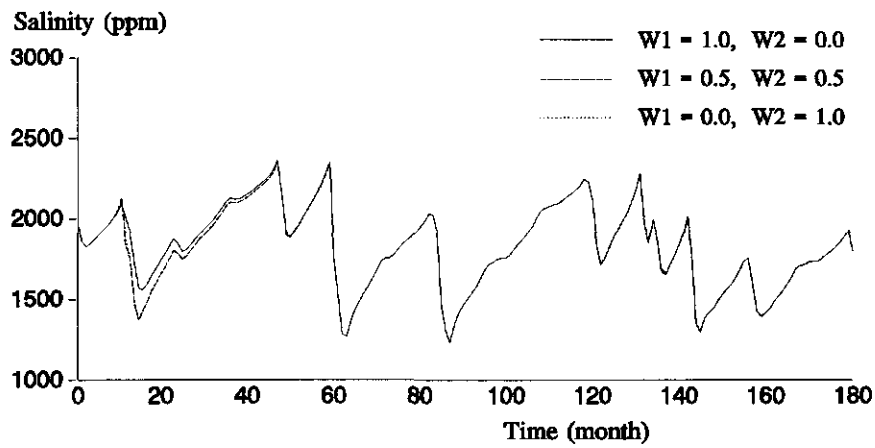

Figure 6.4 Monthly Average Release Salinity - Comparison of Alternative Objective Functions

6.5.1.2 Comparison of IDP Based Optimum Operation with "Standard Release Policy"

The purpose of this chapter is to compare the IDP optimum operation with the simple operation of releasing only the downstream quantity demand. For that the release salinities obtained from the Optimization Model 1 was compared with that obtained from a reservoir operation simulation model. This simulation model assumes complete mixing of water is occurring in the reservoir throughout the year (presented in Chapter 6.3). The operating rule designated as the "Standard Release Policy" in Chapter 6.3 was adopted in this simulation. The results of the comparison are presented in Table 6.2. The end of month reservoir salinities and monthly average release salinities for these two cases are compared in Figure 6.5 and Figure 6.6 respectively. These figures indicate that the IDP based optimum operation is superior to simulation throughout the total period of 15 years.

Table 6.2 indicates that the IDP optimum operation results in an improved operation pattern. This is the best release pattern for improving the quality of water when only the outflow could be manipulated. Because the optimization model was run with perfect knowledge of inflows. The spill has been reduced in the IDP based optimization compared with the simulation. This reduced spill has been used to flush the reservoir whenever possible, thereby improving the quality of water in both the reservoir and the releases. The increase in release (that includes scour/flush volume) indicates this.

Table 6.2 Comparison of IDP Optimum Operation with Simulation

Operation	O.F. Value /10^6	Total Release (includes Scour) (MCM)	Total Spill (MCM)	Monthly average Salinity(ppm)	
				Reservoir	Release
Model 1	132.2	8090	47	1820	1815
Simulation (Std.Rel.Policy)	166.2	7263	729	1939	1939

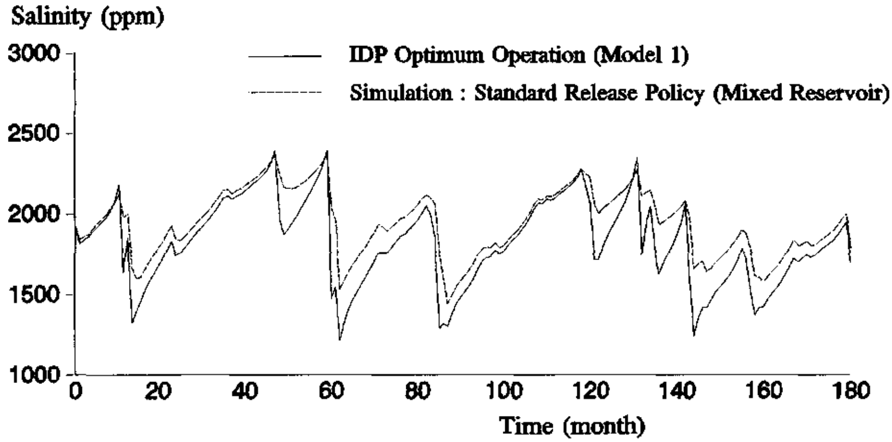

Figure 6.5 Reservoir Salinity - Comparison of IDP Optimum Operation with Standard Release Policy

The average monthly inflows, average monthly releases (obtained from the IDP model) and the demands are given in Table 6.3. The additional releases represent the amount of water released beyond the compulsory downstream demand. This volume of water is used for flushing (or scouring) the reservoir. Table 6.3 indicates that the flushing of the reservoir occurs mainly in autumn and early winter (Sep. - Dec.) when quality of water in the reservoir is poor (Sep.- Nov.). This is followed by the improvement of the quality of water in the reservoir significantly by the high inflows of good quality in winter and early spring (Dec. - Mar.). Although flushing continues in winter till early spring, the quantity is lesser compared with that in autumn.

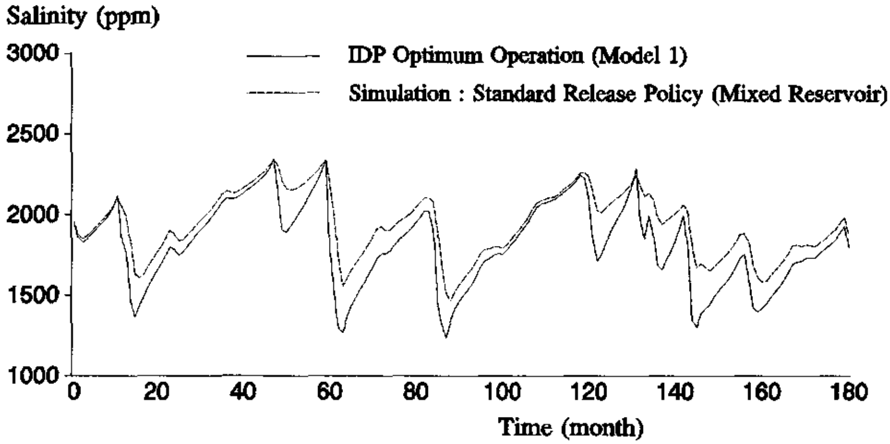

Figure 6.6 Monthly Average Release Salinity - Comparison of IDP Optimum Operation with Standard Release Policy

Table 6.3 Releases of the IDP Optimization

Month	Average Monthly Inflow (MCM)	Average Monthly Release (MCM)	Demand (MCM)	Average of Additional Releases (MCM)
January	90.75	50.21	17.50	32.71
February	105.41	37.42	23.00	14.42
March	91.23	52.72	34.00	18.72
April	57.44	32.51	26.50	6.01
May	25.77	23.55	19.50	4.05
June	13.33	22.22	22.00	0.77
July	9.76	26.55	26.50	0.05
August	10.55	30.42	30.00	0.42
September	10.85	46.36	27.00	19.36
October	17.28	63.23	22.00	41.23
November	30.26	89.11	10.50	78.11
December	97.63	64.52	12.00	52.52

6.5.1.3 Effect of the Inclusion of Quality Considerations in Optimization

Apparently the concentration of salinity in the releases obtained from the IDP model are lower than that obtained from the 'Standard Release Policy' (releasing only the demands). However, it is of interest to compare the release salinity obtained from the IDP model with the release salinity obtained from an optimization model that considers only the downstream quantity requirement. This comparison is designed to examine the effectiveness of the inclusion of quality considerations into the optimization model. For this a model based on IDP technique, but considering only the downstream quantity demand was formulated. At this step the optimization algorithm presented in Chapter 6.1 was used with few modifications. In this model quality of water is not taken into account. The objective function is to minimize the squared deviation of release from the demand over the total period. i.e.,

$$O.F. = \text{Minimize} \sum_{j=1}^{N} (R_j - Dem_j)^2 \tag{6.23}$$

Optimization was carried out with the same set of inflow data (15 years; from 1974 to 1989). The model has the same storage volume constraints (Eq.6.2) as in Optimization Model 1. But release is only limited by the maximum allowable amount in Eq.6.3. State transformation equation is same as in Optimization Model 1 (Eq.6.8). The results are presented in Table 6.4. Figure 6.7 shows the concentration of salinity in the releases. These results indicate that the inclusion of quality considerations in the optimization as effective if the reservoir is to be operated for the improvement of quality besides merely satisfying the quantity demand.

Table 6.4 Comparison of the Two Optimizations : Effect of Inclusion of Quality

IDP Model (Objective Function)	Total Release (includes scour) (MCM)	Total Spill (MCM)	Average Salinity (ppm)	
			Reservoir	Release
Quantity only	7438	684	1915	1913
Quantity and Quality	8090	47	1820	1815

Figure 6.8 shows the releases from the reservoir during the total period of 15 years. If quality is included in the model dramatic changes in operating policy are indicated. These involve increased releases in autumn and early winter (to flush the reservoir) and reduced releases in the summer.

The releases obtained from the IDP model that considers only the quantity requirement show that the releases obtained from that model are high in winter when the inflows are high. This operation improves the quality of water compared with the simulation in which only the demands were released. Compare the average reservoir salinity of 1915 ppm obtained from the IDP model (Quantity only) with 1939 ppm obtained from the simulation model (releasing demands only). Loh and Hewer (1977) reported a similar result for the Wellington reservoir in Western Australia. That is, major streamflows often greater than the reservoir capacity effectively flushes the reservoir and reduces the salinity considerably. The streamflows observed in winter are high.

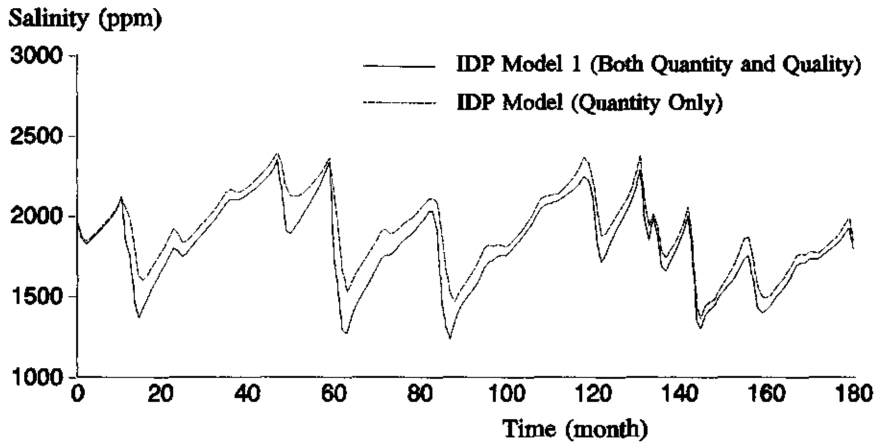

Figure 6.7 Monthly Average Release Salinity - Effect of Including Quality Considerations in the Optimization Model

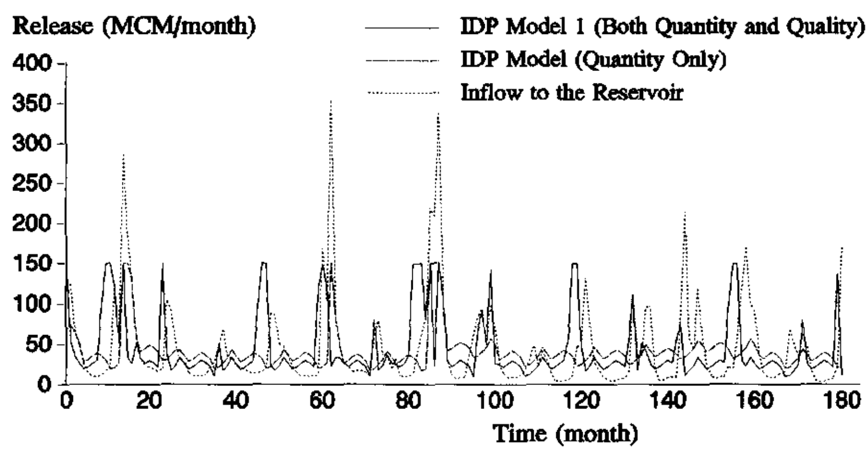

Figure 6.8 Release from the Reservoir - Effect of Including Quality Considerations in the Optimization Model

Nevertheless, if the reservoir is flushed immediately before the high inflow period (i.e., during the time in which the reservoir water quality has been deteriorated by the summer inflows of poor quality) even better improvements in the quality of water in releases could be obtained. By this operation pattern, the average reservoir salinity is further reduced to 1820 ppm. The optimum operation pattern recommended by the IDP model that considers quality besides quantity is to flush the reservoir mainly in autumn. That is immediately before the expected winter high inflows.

6.5.2 Optimization Model 2 : Controlling both Inflows and Discharges

The only controls available over the behaviour of a reservoir are the releases of water from the reservoir and the possible diversion of some of the inflow. The Optimization Model 2 uses/controls both inflows and outflows in the operation of a reservoir for the improvement of the quality of water supplied. It was run employing the same set of data used in the model presented in the Chapter 6.5.1. All the other parameters used in this model are same as in the previous one. The downstream quantity demand was treated as a constraint to be satisfied always.

6.5.2.1 Effect of Allowable Maximum Diversion

The important feature in this model is the ability to divert inflows (or by-pass inflows) in addition to the manipulation of the releases. However, it may be necessary to limit the maximum quantity of water that could be diverted in a month due to practical limitations such as capacity of diversion structures, canals etc. Therefore, it is of interest to study the influence of the diversion limit has on the final aim of improving the quality of the water supplied. For this the model was run for several allowable diversion limits and the results obtained are presented in Table 6.5.

Table 6.5 Effect of Allowable Maximum Diversion

Allowable Diversion MCM/mon	O.F Value $/10^6$	Total Release (MCM)	Total Spill (MCM)	Diversion		Mean Salinity (ppm)	
				Volume (MCM)	Salt load 10^6 kg	Reservoir	Release
10	97.7	6793	47	1315	3356	1706	1703
20	79.8	5929	47	2189	5302	1638	1636
30	74.0	5506	47	2617	6134	1611	1608
40	71.0	5348	47	2780	6442	1595	1593
50	69.0	5226	47	2899	6670	1590	1586
60	68.0	5166	47	2972	6807	1578	1576
70	67.5	5141	47	2997	6847	1576	1574
80	67.4	5132	47	3006	6853	1575	1573

The release salinity and reservoir salinity were observed to be improving with the increase of the allowable diversion limit. With the increase of the allowable diversion limit, the total volume of water diverted and the total salt load diverted have been increased. Associated with that the total amount of release has been decreased. This implies the high influence of the diversion of poor quality inflows has on the improvement of the quality in the reservoir and consequently in the releases.

But the improvements appeared to be negligible above a certain limit, as shown in Figure 6.9. For the Jarreh reservoir increasing the allowable diversion limit above 40 MCM/month is not influential in reducing the concentrations of release or reservoir salinity significantly.

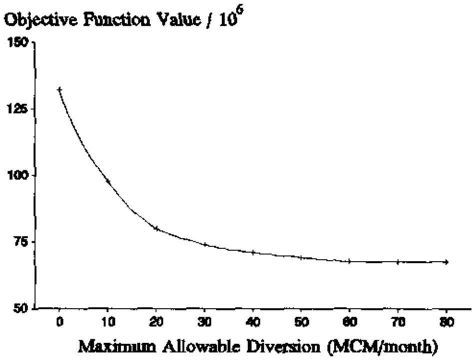

Figure 6.9 Objective Function Value for Different Allowable Diversion Limits

Figure 6.10 displays the time series of the diversions for a few selected different diversion limits. When the allowable diversion limit is 80 MCM/month, the maximum diversion observed was 79.5 MCM/month. Further increase in the allowable diversion limit would not be effective in reducing the release salinity for this set of data. However, from these observations it is apparent that the limitation on the allowable diversion affects the reductions in the reservoir and release salinities.

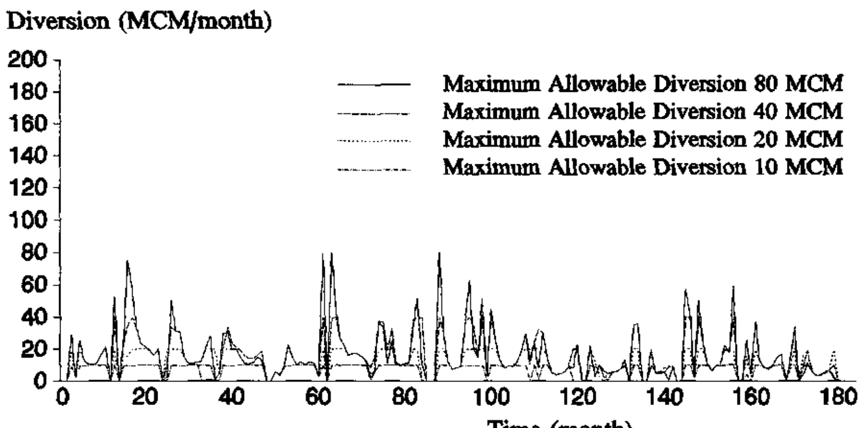

Figure 6.10 Diversion from Inflow - Effect of Different Diversion Limits in Optimization Model 2

The average monthly release salinities for the four different diversion limits are compared in Figure 6.11. They conclusively indicate that by increasing the limit on the allowable diversion amount, the salinity in the releases could be reduced. However, the improvements observed in the reduction of salinity in releases beyond the diversion limit of 40 MCM/month is not significant. The releases and reservoir volumes for these operations are shown in Figure 6.12 and Figure 6.13 respectively. Figure 6.12 indicates that most of the time optimum releases from the reservoir are the same in all the cases. But the number of times the reservoir is flushed (cleansed) by larger winter flows is more when the diversion limit is low compared with the occurrence of that when the diversion limit is high. The model attempts to improve the quality of water by flushing the reservoir more, when the diversion is more restricted. However, this is less effective than diverting poor quality inflows. Figure 6.13 reveals that the number of times the reservoir volume has reached the minimum level is independent of the limit on allowable diversion amount.

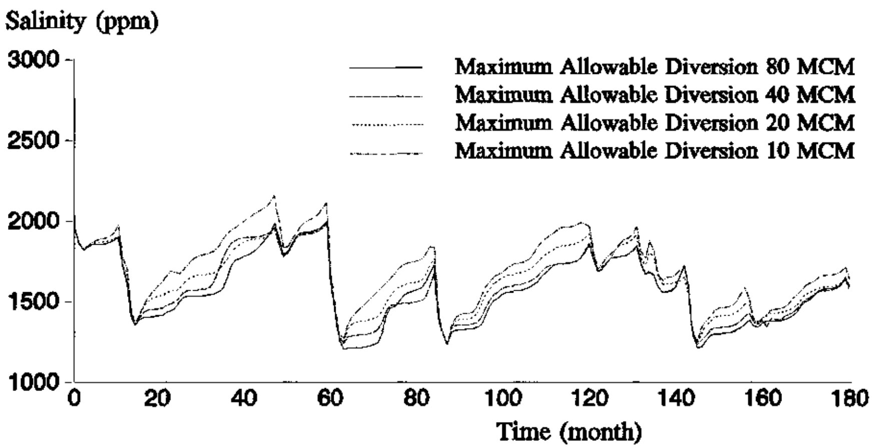

Figure 6.11 Monthly Average Release Salinity - Effect of Different Diversion Limits in Optimization Model 2

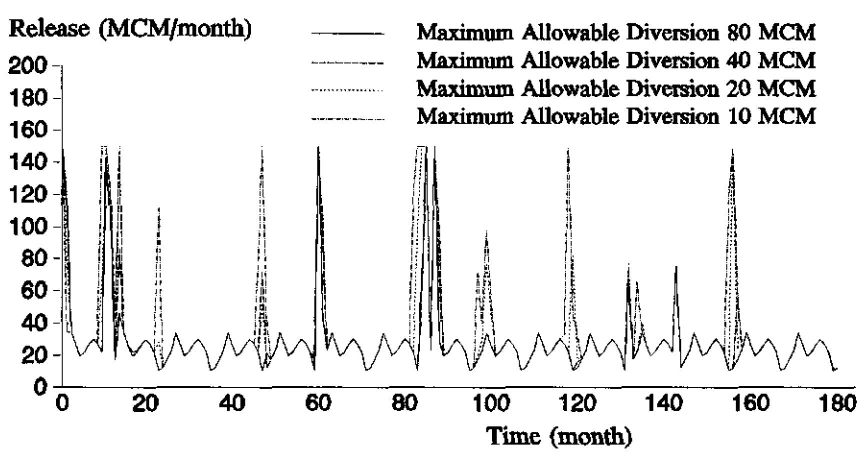

Figure 6.12 Average Monthly Releases for Different Diversion Limits

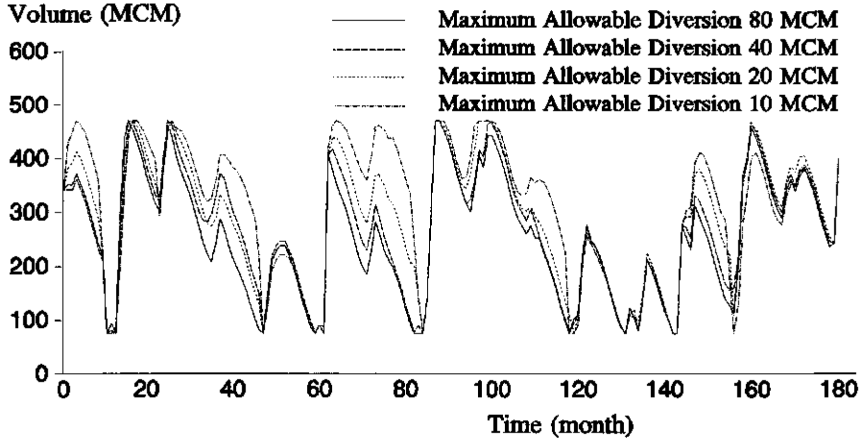

Figure 6.13 Reservoir Storage Volume for Different Diversion Limits

6.5.2.2 Correlation Between Diversion and Inflow

The correlation between the diversion and inflow in the case of maximum allowable limit of 80 MCM was computed. The correlation coefficients between diversion and inflow volume and those between diversion and inflow salinity were evaluated on monthly basis and the results are presented in Table 6.6.

Table 6.6 Correlations of Diversion with Inflow and Inflow Salinity

Month	Correlation Coefficient	
	With Inflow	With Inflow Salinity
January	0.127422	0.107046
February	0.453836	0.510899
March	0.067644	0.141584
April	0.279314	0.074667
May	0.942757	0.471539
June	0.978782	0.785512
July	0.944724	0.790878
August	0.943020	0.645447
September	0.730809	0.368789
October	0.991691	0.856404
November	0.159597	0.041866
December	0.223750	0.172546

From May to October the correlation between diversions and inflow is considerably high. Almost all inflows are diverted during this period of the year. That is the summer period and the first half of the autumn period. Generally inflow is low and salinity is high during this period. This suggests the possibility for the development of a policy for the diversions to be made during this period of 6 months based on linear regression technique.

However, the lack of strong correlation between the decision variable and the independent variables during the remaining six months represent a significant drawback to the use of implicit stochastic optimization approach in the derivation of operating policies for all the months in a year.

6.5.3 Comparison of the Two Optimization Models

The monthly average release salinity distributions obtained from the two optimization models and the operation simulation with 'Standard Release Policy' are compared in Figure 6.14. In the Optimization Model 2 the allowable diversion was limited to 80 MCM/month.

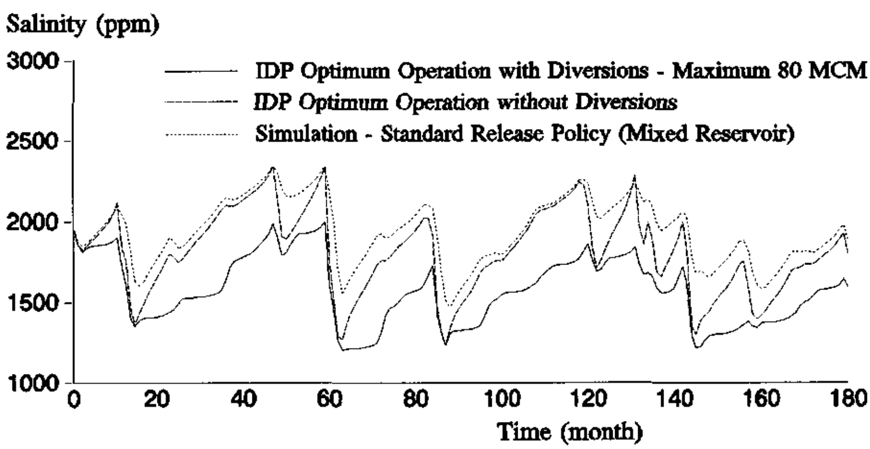

Figure 6.14 Monthly Average Release Salinity - Comparison of Models

Figure 6.14 displays the influence of the diversion of poor quality inflows has on the final aim of reducing the salinity concentration in releases. The release salinities obtained from the IDP optimum operation with diversions are observed to be the lowest throughout the total period. Further, Figure 6.15 compares the cumulative distributions of release salinities for the above three reservoir operations. From this it is clear that about 40% of the time the release salinity is greater than 2000 ppm for the operation according to the "Standard Release Policy". For IDP optimum operation without diversions it is only 25%. When the diversions are considered release salinity is always less than 2000 ppm. Also it can be stated that for about 50% of the time the release salinity is below 1567 ppm when diversions are made, compared with the salinities of 1827 ppm and 1942 ppm for the other two operations.

The above results suggest that the diversion of part of inflows before entering the reservoir as the best management option for reducing the salinity level in the releases. The diverted water is of much higher salinity than any that could be scoured. In Optimization Model 2 the downstream quantity demand is treated as a constraint. Therefore, downstream demand is supplied throughout the total period without failures.

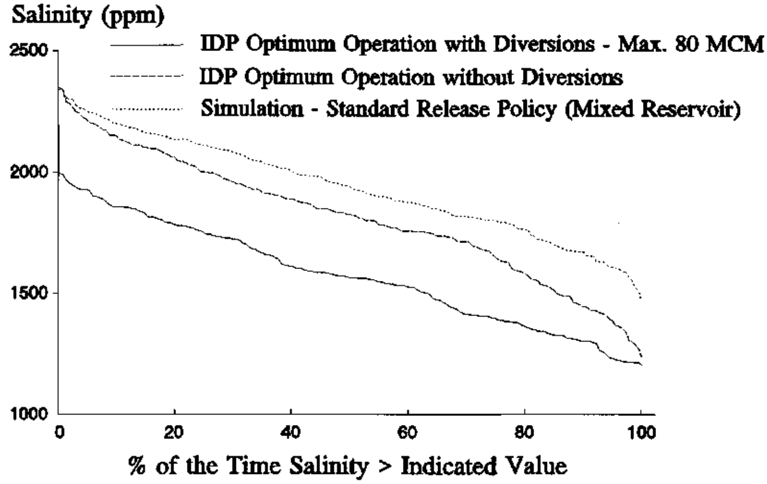

Figure 6.15 Cumulative Distribution of Release Salinity - Comparison of the Models

6.5.4 Comparison of Optimum Diversions with Cut-off Diversions

Shiati (1991) showed that by-passing inflows having salinity concentrations above a prespecified (cut-off) level were effective in reducing release salinity in the Jarreh reservoir. This operation alternative was compared with the optimum operation obtained from Optimization Model 2. For that, the reservoir operation was simulated with diverting inflows having salinity concentration above several cut-off levels. "Standard Release Policy" was adopted in the operation of the reservoir. The different cut-off levels used and the results obtained are presented in Table 6.7.

The comparison of monthly average release salinities for the different operation alternatives are shown in Figure 6.16. The improvements are increasing with the reduction of the cut-off level, which is associated with more diversions. However, this is an insecure measure as far as satisfying downstream quantity requirement is concerned.

According to Table 6.7 total quantity of diversions made in Optimization Model 2 with maximum diversion constrained to 10 MCM/month is close to that in the simulation with cut-off at 2500 ppm. But the mean reservoir and release salinities obtained from Model 2 are observed to be less. Further, about 32% of the time the diversions were more than 10 MCM/month in the simulation with cut-off level at 2500 ppm. Monthly diversions for these two operations are shown in Figure 6.17. In certain months diversion quantity even

Table 6.7 Comparison of Optimum Diversions with Cut-off Level Diversions

Alternative	O.F. Value 10^6	Total Release (MCM)	Total Spill (MCM)	Total Diversion (MCM)	Mean Salinity (ppm)	
					Reservoir	Release
Cut-off at 3000 ppm	147.7	7000	703	297	1884	1884
Cut-off at 2800 ppm	135.0	6740	702	564	1846	1847
Cut-off at 2500 ppm	107.2	6166	689	1194	1756	1756
Model 2 - Max. Diversion 10 MCM/month	97.7	6793	47	1315	1706	1703
Model 2 - Max. Diversion 80 MCM/month	67.4	5132	47	3006	1575	1573

rose upto 22 MCM/month. This requires larger diversion structures and canals etc. Therefore, it can be concluded that IDP based (Model 2) optimum operation with allowable diversion limited to 10 MCM/month is superior to diverting inflows having salinity concentration above cut-off level of 2500 ppm.

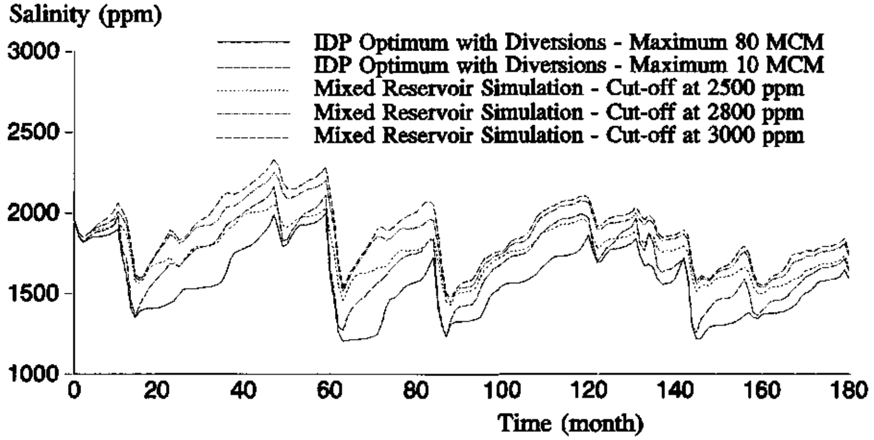

Figure 6.16 Monthly Average Release Salinity - Comparison of Cut-off Level with Optimization Model 2

The improvements obtained from Model 2 with allowable diversion limited to 80 MCM/month is apparently the best. Eventhough the total amount of diversions is more in this operation it does not have the risk of violating the satisfaction of downstream quantity demand. Because downstream quantity demand is treated as a constraint in the optimization model. The scrutiny of the results indicated that most of the diversions are in the summer during which the inflows are of poor quality. Flushing the reservoir was observed to be in winter when the inflows are substantial.

The substantially large drops in release salinity (e.g., around months 12, 60, 84, 144 etc.) are due to very high inflows to the reservoir. These high inflows are of good quality and they improve the quality of water in the reservoir significantly.

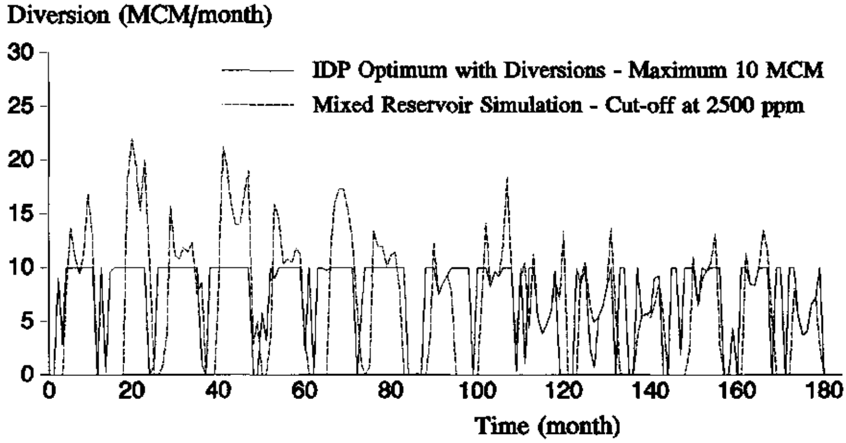

Figure 6.17 Diversions from Inflows - Comparison of Cut-off Level with Optimization Model 2

Figure 6.18 clearly indicates that the optimum operation obtained from Optimization Model 2 (maximum diversion 10 MCM/month) is better than the operation with cut-off level 2500 ppm about 80% of the time.

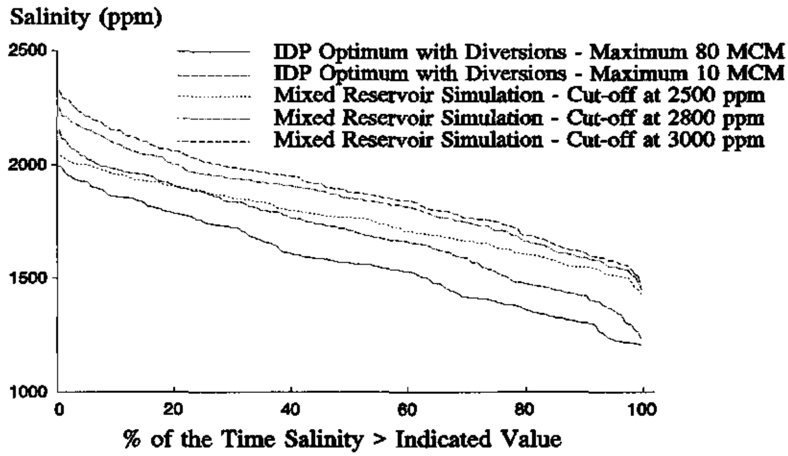

Figure 6.18 Cumulative Distribution of Release Salinity - Comparison of Cut-off Level with Optimization Model 2

6.5.5 Complete Mixing and DYRESM Simulation

The assumption of complete mixing of water in the reservoir throughout the year is a simplification compared with the real behaviour of reservoirs that undergo stratification and mixing cycles in a year. Therefore, it is interesting to examine the validity of this simplification as it has been used in this section. For that, the reservoir operation was initially simulated employing the simulation model that assumes complete mixing in the reservoir. The operation rule (Standard Release Policy) described in Chapter 6.3 was used at this step. Subsequently, the reservoir operation was simulated using the one-dimensional reservoir simulation model DYRESM that takes stratification into consideration. In the simulation with DYRESM the releases were made through the bottom outlet throughout the total period. It was assumed that releases upto 150 MCM/month could be made through the outlet. The same time series of releases (Standard Release Policy) was used in the two simulations to make the comparison consistent.

The reservoir salinities obtained from the simulation employing DYRESM (i.e., with releasing through bottom outlet) show very little deviations from those from the mixed reservoir simulation (with one outlet) as presented in Figure 6.19.

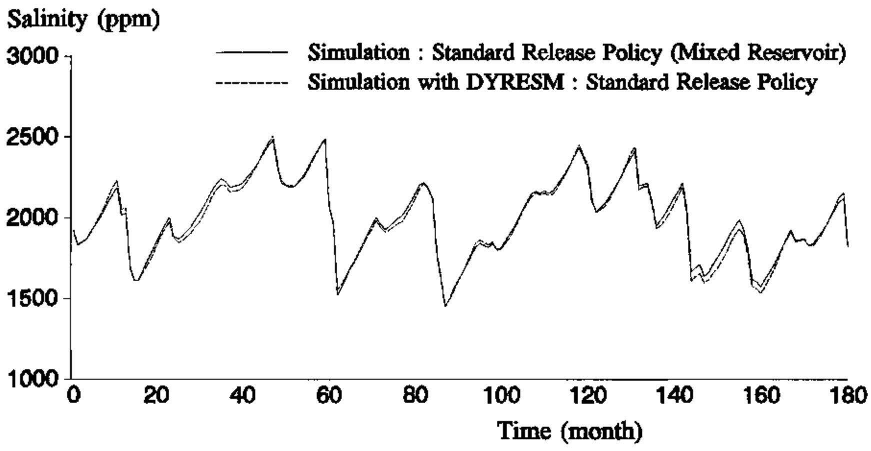

Figure 6.19 Reservoir Salinity - Effect of Stratification

During summer warm water of high salinity mixes with the top layers of the stratified reservoir. This results in a higher salinity concentration at the top layers of the stratified reservoir compared with the lower part. Therefore, the salinity of the water released from the bottom outlet of the stratified reservoir is lower than that from the fully mixed reservoir in summer. Figure 6.20 indicates this clearly. However, in winter during which the reservoir gets completely mixed the release salinities are almost the same in both cases. The degree to which the reservoir is not completely mixed in nature is reflected in these results.

The above results imply the possibility of utilizing the assumption of fully mixing in the reservoir in deriving operational policies for the Jarreh reservoir. Foruria *et al.* (1985), stated that the concentration of dissolved solids in the outflow can be modelled by assuming an instantaneously completely mixed reservoir when the detention time is greater than one year for that reservoir. However, the detention time, which is defined as reservoir volume divided by inflow rate is close to 1 year (470 MCM/560 MCM/yr = 0.84 yr) for the Jarreh reservoir. Note that the detention time is based on the assumption that the entire volume of the reservoir is available for dilution and flow.

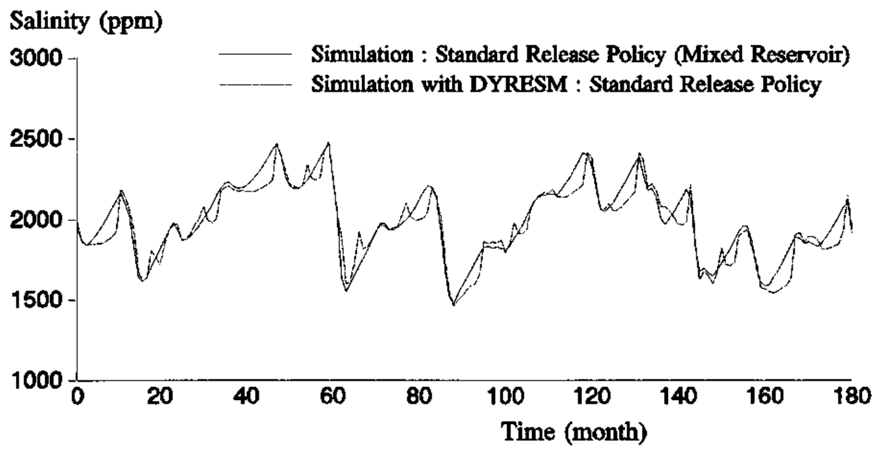

Figure 6.20 Monthly Average Release Salinity - Effect of Stratification

6.5.6 DYRESM Simulation with IDP Optimum Results

The operation policies obtained from a stratified reservoir by using its water is completely mixed throughout the year may be useful in managing it. Therefore, the impact of the results obtained from the IDP optimization models for a fully mixed reservoir has on a stratified reservoir was studied in this section. For this the reservoir operation was simulated employing the stratification model DYRESM with the releases obtained from the two IDP optimization models. The resulting reservoir and release salinities were compared with those obtained from the simulation with DYRESM (Standard Release Policy) discussed before. In the above three simulations water was withdrawn through the bottom outlet of the stratified reservoir.

The reservoir salinities and release salinities are observed to be improved when the operation patterns obtained from IDP optimizations (with the assumption of fully mixing in the reservoir) are used as shown in Figure 6.21 and Figure 6.22. It is observed that the highest improvements are obtained when the diversions from the inflows are allowed. The above results indicate the possibility for deriving operation policies for a reservoir even with the simplification of fully mixing is occurring in the reservoir. This enables to avoid the large amount of computational efforts required when the reservoir stratification is considered in the operating policy derivation.

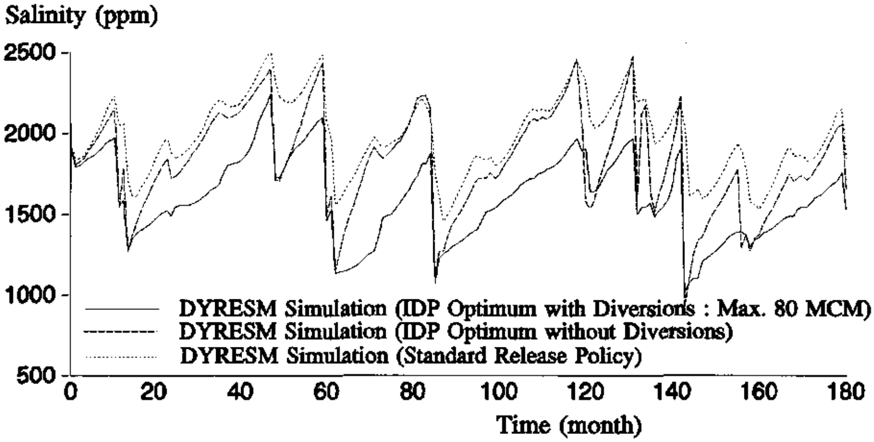

Figure 6.21 Reservoir Salinity - Effect of IDP Optimization on a Stratified Reservoir

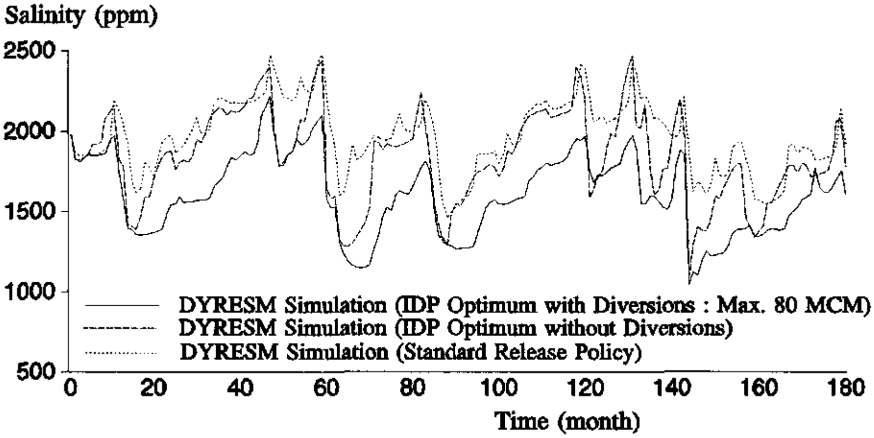

Figure 6.22 Monthly Average Release Salinity - Effect of IDP Optimization on a Stratified Reservoir

6.5.7 Comparison of IDP and SDP Based Policies

The operation of the reservoir with the operation policy defined by the SDP model presented in Chapter 4.2.2 was compared with the IDP optimum operation. The IDP Model 1 is used in this comparison. The SDP model does not consider quality during its optimization procedure. If the release obtained from the SDP based policy is less than the demand in a certain month, then the SDP policy is over-ruled and demand is released during that month (provided water is available). If volume of water available in the reservoir is less than the demand, the available amount is released at least partly fulfilling the demand. In IDP operation as the demand has been introduced as a constraint this problem does not arise. Figure 6.23 shows the monthly average releases for these two operations. In both operations the releases were made through the bottom outlet throughout the whole period. As Figure 6.23 reveals during winter IDP releases are higher than the SDP releases. But during the remainder period, including summer, the SDP defined releases are higher.

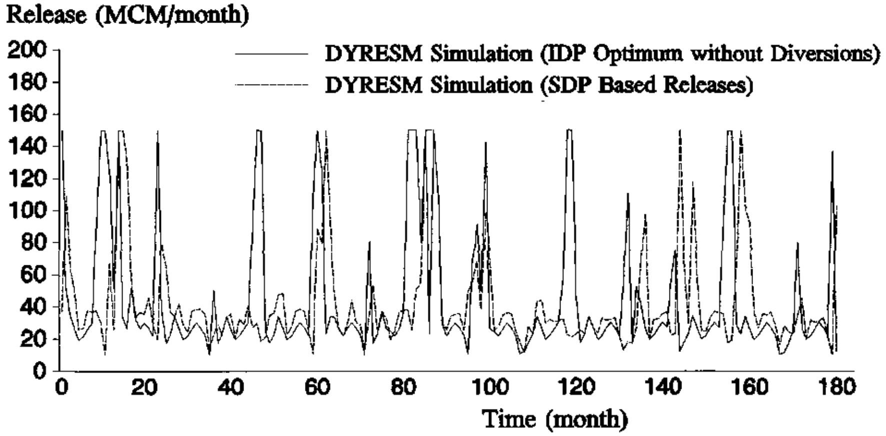

Figure 6.23 Monthly Average Releases - Comparison of IDP and SDP Releases

Figure 6.24 and Figure 6.25 show the reservoir salinity and release salinity for the period of 15 years. Figure 6.25 shows that the release salinity obtained from SDP releases are inferior to that obtained from standard release policy in several occasions. These were observed during the years of dry spells. The releases that are larger than demand during summer causes loss of water of better quality compared with the inflows to be followed during the dry period in the same year. Note that the SDP optimization considers quantity requirement only. Therefore, the scouring or removal of water as scouring at the wrong time may be detrimental for the reservoir operation.

The release salinities and reservoir salinities obtained from the IDP Model 1 (which considers quality also) are always superior to those from the other two operations.

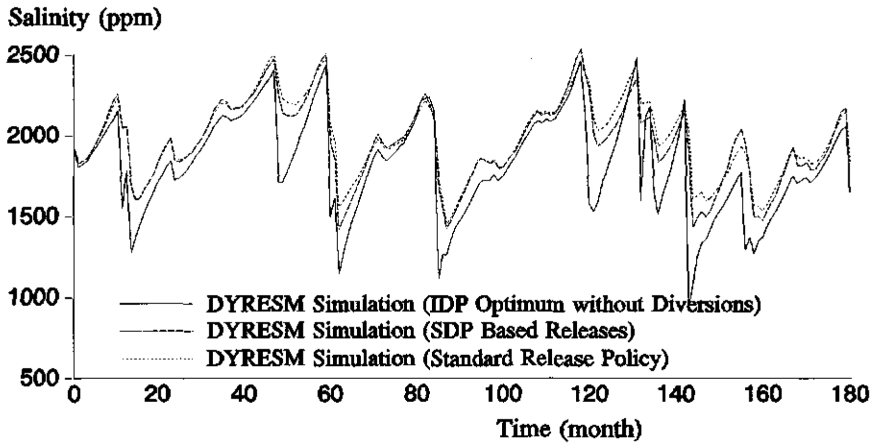

Figure 6.24 Reservoir Salinity - Comparison of SDP Releases with IDP Optimum

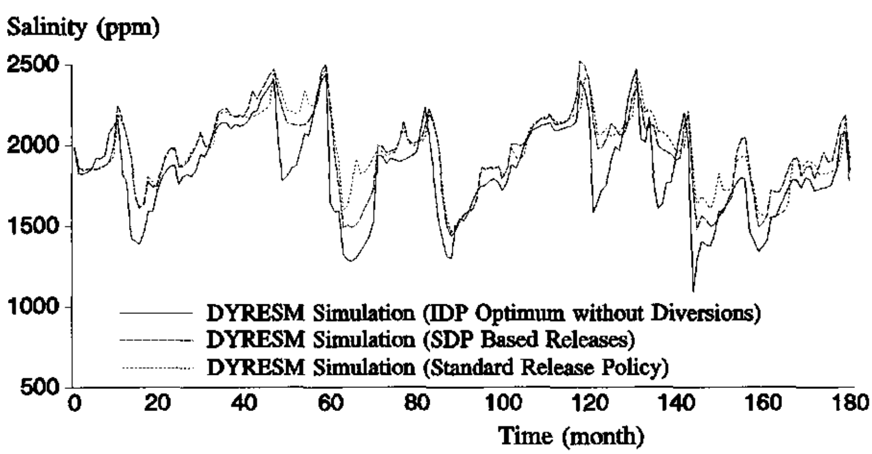

Figure 6.25 Monthly Average Release Salinity - Comparison of SDP Releases with IDP Optimum

6.5.8 Operation Based on Optimization-Simulation Methodology

In the previous chapter the IDP based releases were drawn through the bottom outlet throughout the period. However, the Jarreh reservoir is stratified during a few months in a year with the associated variation of quality of water with depth. Therefore, water of better quality could be obtained by withdrawing water from different elevations. Besides, when the IDP defined releases exceed the downstream demand the excess could be used to scour the reservoir more efficiently. That is by withdrawing the excess water to waste from the most suitable (of highest salinity) elevation.

The Optimization-Simulation methodology presented in Chapter 4 was used to determine the release and scour volumes and the outlets (different elevations) for releasing them. In the application of the methodology, the total discharges were constrained (A_j's in Eq.4.8) to the IDP defined release (obtained from completely mixed reservoir with one outlet) for the particular month. The five years 1982 through 1986 were used in the analysis. The resulted optimum operation pattern for three years (1982-1984) is presented in Table 6.8. At this step, the reservoir was assumed to have outlets at three different elevations. The total available discharges (total of release and scour) through top, middle and bottom outlet were assumed to be 60 MCM, 60 MCM and 30 MCM, respectively. Figure 6.26 compares the release salinities obtained from this operation and from the SDP based optimum operation presented in Chapter 4.3.4. The optimum release pattern obtained based on the IDP optimum releases is observed to be superior to that obtained based on the SDP optimum releases.

Figure 6.27 and Figure 6.28 show the temperature and salinity distributions in the reservoir during these three years when IDP based releases are adopted. The releases and scours are made through outlets at three elevations. During 1983 and 1984 the destratification effect of the IDP policy appears very clearly. In the wet year (1982) stratification is strong in summer. In the dry year the reservoir is weakly stratified, although more strongly than in the previous year (median year -1983). In these two years the salinity gradients with the depth have reduced markedly. Clearly the dynamics of the reservoir are strongly dependent on the management policy instituted (compare with Figure 4.27 through Figure 4.34). Therefore, with the manipulation of withdrawal rates from different outlets, quite fine control of the reservoir dynamics could be achieved, with the corresponding control of both storage and withdrawal quality.

Table 6.8 Optimum Releases and Scours : IDP Model Based Releases and Scour Volumes

Year	Month	Release Volume (MCM)			Scour Volume (MCM)		
		Top	Middle	Bottom	Top	Middle	Bottom
1982	Jan	0.0	18.1	0.0	0.0	41.8	30.0
	Feb	23.0	0.0	0.0	0.0	60.0	30.0
	Mar	34.0	0.0	0.0	25.9	60.0	23.9
	Apr	0.0	0.0	26.5	40.9	40.6	0.0
	May	0.0	7.9	11.6	9.4	0.0	0.0
	Jun	0.0	0.0	22.0	0.0	0.0	0.0
	Jul	0.0	0.0	26.5	0.0	0.0	0.0
	Aug	0.0	0.0	30.0	0.0	0.0	0.0
	Sep	0.0	0.0	27.0	0.0	0.0	0.0
	Oct	0.0	0.0	22.0	0.0	0.0	0.0
	Nov	0.0	10.5	0.0	0.0	0.0	0.0
	Dec	12.0	0.0	0.0	34.3	0.0	18.6
1983	Jan	0.0	17.5	0.0	52.5	0.0	20.9
	Feb	0.0	23.0	0.0	27.0	0.0	0.0
	Mar	19.3	14.7	0.0	40.7	45.3	19.0
	Apr	0.0	0.0	26.5	0.0	0.0	0.0
	May	0.0	0.0	19.5	0.0	2.6	2.4
	Jun	0.0	0.0	22.0	0.0	0.0	0.0
	Jul	0.0	0.0	26.5	0.0	0.0	0.0
	Aug	0.0	0.0	30.0	0.0	0.0	0.0
	Sep	0.0	0.0	27.0	0.0	0.0	0.0
	Oct	11.0	11.0	0.0	0.0	0.0	0.0
	Nov	0.0	10.5	0.0	0.0	0.0	0.0
	Dec	12.0	0.0	0.0	0.0	0.0	0.0
1984	Jan	8.8	8.8	0.0	0.0	0.0	0.0
	Feb	11.5	11.5	0.0	0.0	0.0	0.0
	Mar	34.0	0.0	0.0	0.0	0.0	0.0
	Apr	26.5	0.0	0.0	0.0	0.0	0.0
	May	0.0	19.5	0.0	0.0	0.0	0.0
	Jun	0.0	0.0	22.0	0.0	0.0	0.0
	Jul	0.0	0.0	26.5	0.0	0.0	0.0
	Aug	0.0	0.0	30.0	0.0	0.0	0.0
	Sep	0.0	0.0	27.0	0.0	0.0	0.0
	Oct	0.0	0.0	22.0	0.0	0.0	0.0
	Nov	0.0	10.5	0.0	0.0	49.5	30.0
	Dec	0.0	12.0	0.0	0.0	39.9	18.0

When determining operation policies for the reservoir using SDP, quality was not considered, whereas in IDP the quality was considered. Incorporation of IDP based (mixed reservoir) releases into Stepwise Optimization-Simulation procedure presented in Chapter 4 seems to be more effective than incorporating SDP based policies as adopted in Chapter 4.2.

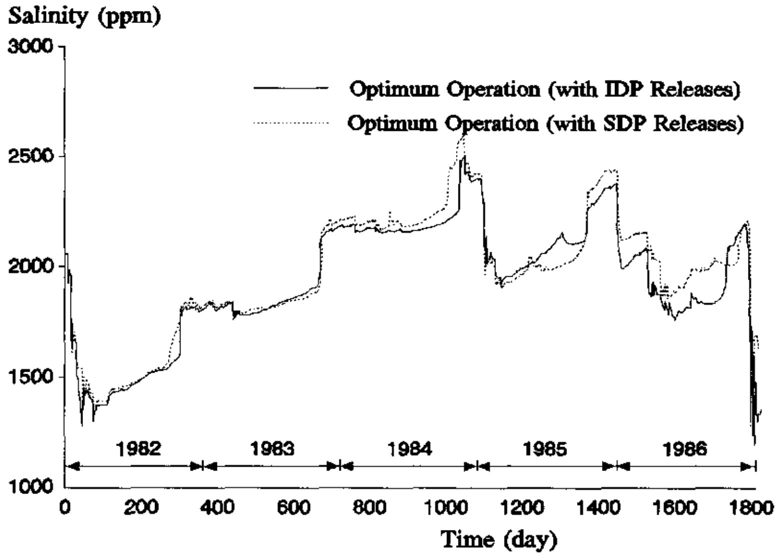

Figure 6.26 Release Salinity - Comparison of IDP and SDP Releases : 1982-1986

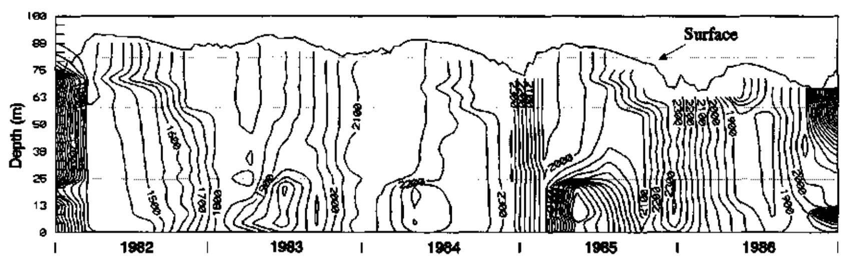

Figure 6.27 Salinity Distribution in the Reservoir - Optimum Operation with IDP Releases

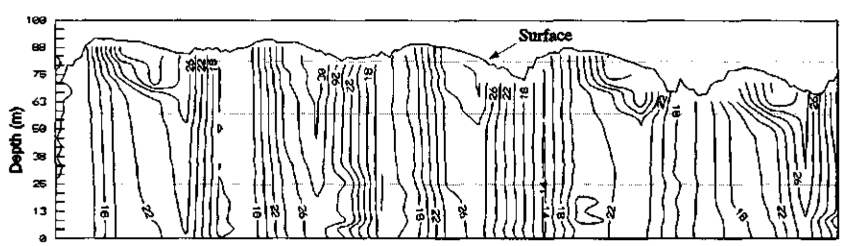

Figure 6.28 Temperature Distribution in the Reservoir - Optimum Operation with IDP Releases

6.5.9 Effect of Active Storage Volume

The aim of this analysis is to study the effect of the active storage volume on the final objective of reducing the salinity in the releases from the reservoir.

6.5.9.1 Effect of Storage Volume : Controlling Discharges Only

Initially, the improvements achievable by manipulating only the releases were studied using the Optimization Model 1. The dead storage volume was varied in steps and the model was run for each case. The results are summarized in Table 6.9.

Table 6.9 Effect of Active Storage Volume : Optimization Model 1

Full Storage (MCM)	470	470	470	470	470
Dead Storage (MCM)	150	100	75	50	25
Active Storage (MCM)	320	370	395	420	445
O. F. Value/10^6	139.3	135.1	132.2	132.3	131.3
Total Release (MCM)	8119	8130	8090	8121	8140
Total Spill (MCM)	0	0	47	22	11
Reservoir Salinity (ppm)	1845	1829	1820	1816	1811
Release Salinity (ppm)	1843	1825	1815	1810	1804

Increasing the active storage volume of the reservoir is effective in reducing the salinity in the reservoir and in the releases. The scrutiny of the results (reservoir releases and volume) showed that the releases from the reservoir are increased during winter (when the inflow is large) with the increase of the reservoir active storage capacity. When the storage capacity of the reservoir is large, it enables the release of more water from the reservoir. This increased releases (or flushing) consequently improves the quality of water in the reservoir.

However, by enlarging the active storage volume by about 40% (from 320 MCM to 445 MCM) the average salinity in the releases could be reduced from 1843 ppm to 1804 ppm only. When this is compared with the average release salinity of 1703 ppm achieved by diverting inflows with the maximum limited to even a very low value of 10 MCM/month (for the reservoir active storage capacity of 395 MCM), the manipulation of inflows seems to be the most effective means in improving the quality of water for the Jarreh reservoir.

6.5.9.2 Effect of Storage Volume : Controlling Both Inflows and Discharges

Then the influence of the active storage volume of the reservoir has on improving the salinity in the releases when the inflow to the reservoir also could be manipulated was studied. For this evaluation the Optimization Model 2 was used and it was run for several different storage volumes as shown in Table 6.10. The results obtained are also shown in the same table.

Table 6.10 Effect of Active Storage Volume : Optimization Model 2

Full Storage (MCM)	470	470	470	470	470
Dead Storage (MCM)	150	100	75	50	25
Active Storage (MCM)	320	370	395	420	445
Allowable Diversion = 10 MCM/month					
O. F. Value/10^6	104.2	100.1	97.7	97.0	95.2
Total Release (MCM)	6800	6785	6793	6830	6821
Total Spill (MCM)	70	70	47	25	42
Total Diversion (MCM)	1263	1290	1315	1306	1308
Reservoir Salinity (ppm)	1732	1716	1706	1703	1697
Release Salinity (ppm)	1731	1714	1703	1699	1690
Allowable Diversion = 40 MCM/month					
O. F. Value/10^6	79.2	72.2	71.0	69.3	64.4
Total Release (MCM)	5521	5337	5348	5331	5184
Total Spill (MCM)	74	72	47	35	41
Total Diversion (MCM)	2557	2758	2780	2814	2967
Reservoir Salinity (ppm)	1632	1603	1595	1588	1570
Release Salinity (ppm)	1631	1600	1593	1584	1564
Allowable Diversion = 80 MCM/month					
O. F. Value/10^6	79.2	70.8	67.4	64.9	64.0
Total Release (MCM)	5425	5146	5132	5071	5085
Total Spill (MCM)	73	71	47	29	44
Total Diversion (MCM)	2659	2958	3006	3096	3081
Reservoir Salinity (ppm)	1628	1590	1575	1564	1559
Release Salinity (ppm)	1625	1588	1573	1560	1553

The objective function value improves with the increase of the active storage capacity of the reservoir. The improvement of the objective function value reflects the reduction in the reservoir salinity and the release salinity. This was observed for all the three cases (of different allowable diversion limits) analyzed.

Changes in total quantity of diversion, release and spill from the reservoir were observed when the active storage capacity of the reservoir is changed. The monthly releases from the reservoir and the monthly diversions from the inflows when the diversions are limited to 80 MCM/month are displayed in Figure 6.29 and Figure 6.30, respectively.

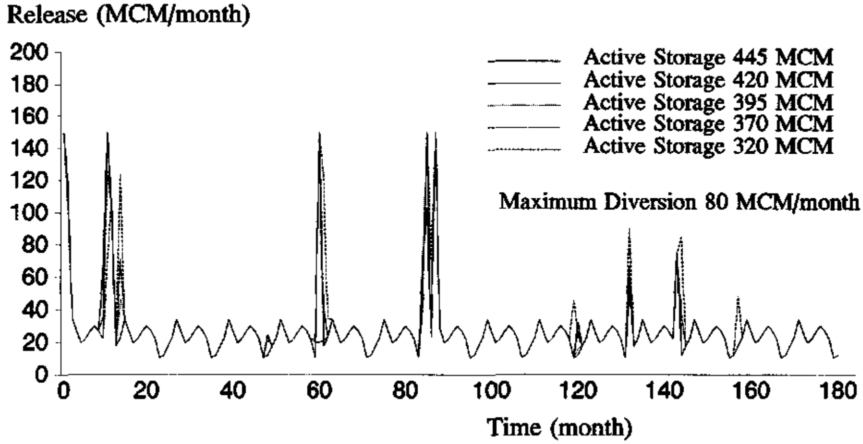

Figure 6.29 Releases from the Reservoir - Effect of Storage Capacity

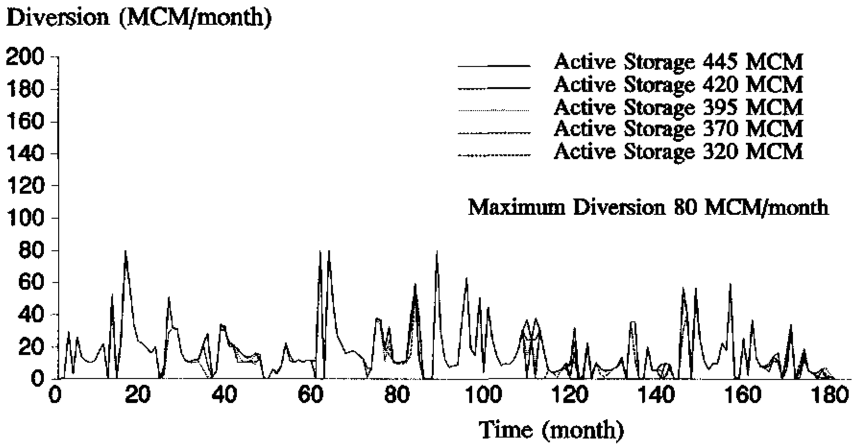

Figure 6.30 Diversions from Inflow - Effect of Storage Capacity

The releases were noticed to be changed only in a few occasions during the total period of operation. Those were during the periods of very high inflows. The diversions are observed to be changing more frequently compared with the releases. When the reservoir storage volume is large its ability to supply water to satisfy the quantity demand is high. Therefore, it is possible to divert more water of poor quality when the reservoir volume is large. This consequently improves the quality of water supplied from the reservoir. Figure 6.31 shows the variation of the reservoir storage volume for different storage capacities in these operations. It shows the obvious fact that the variation of the reservoir storage is large when the active storage capacity is high.

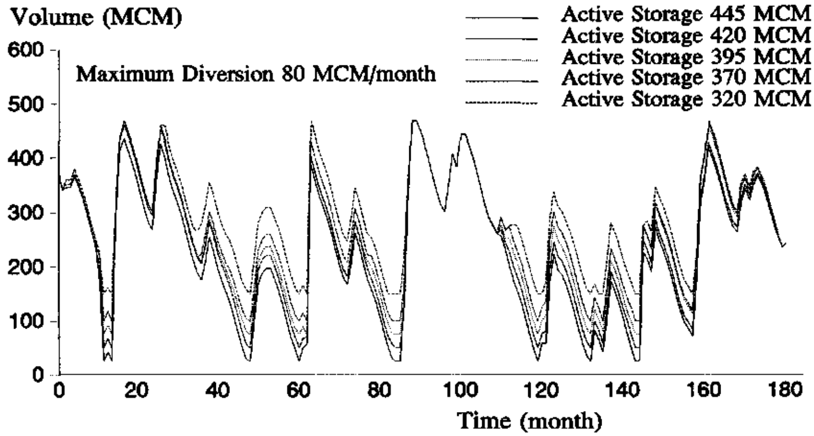

Figure 6.31 Reservoir Storage Volume - Effect of Storage Volume

The release salinities obtained when the storage capacity is changed while limiting the maximum diversion to 80 MCM/month are shown in Figure 6.32. Even though, improvements are obtained by increasing the active storage capacity those are not appreciably high. For an enlargement of the active storage capacity by 40% (diversion limited to 80 MCM/month) the average release salinity has been reduced from 1625 ppm to 1553 ppm only.

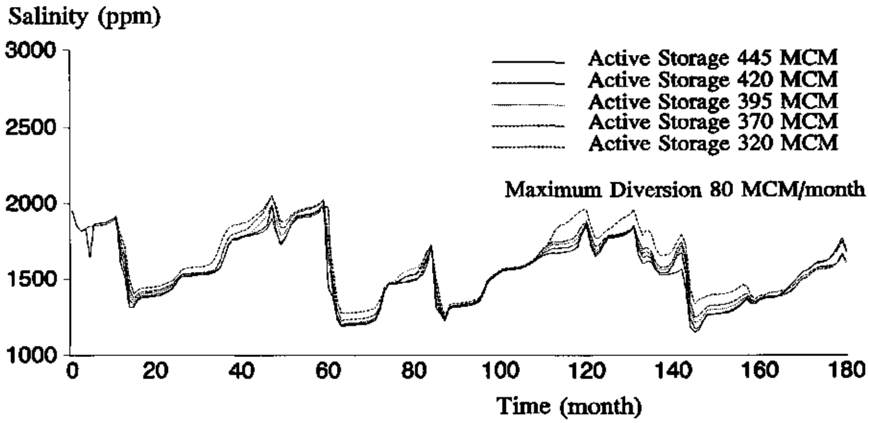

Figure 6.32 Monthly Average Release Salinity - Effect of Storage Capacity

7 Multiobjective Considerations in Satisfying Quantity and Quality Requirements

Supplying water of good quality for irrigation is the aim in the operation of the reservoir under consideration. Quality of water supplied from a reservoir could be improved by diverting (by-passing) the poor quality inflows as shown in Chapter 6. By diverting more water of poor quality, more improvements in the quality of the water supplied could be obtained. But this might affect the satisfaction of the downstream quantity demand. Hence, the objectives of satisfying downstream quantity demand and improving quality of water (by diverting inflows of poor quality) are two conflicting objectives. Therefore, the operation of a reservoir for quality control by diverting poor quality inflows could be studied under the multiobjective analysis framework.

7.1 Set of Nondominated Solutions

In single-objective problems the goal of solution is the identification of the optimal solution: the feasible solution that gives the best value of the objective function. This notion of optimality is not applicable for multiobjective problems, because a solution that maximizes one objective will not, in general, maximize any of the other objectives.

Optimality plays an important role in the solution of single-objective problems. It allows the analyst and decision maker (DM) to restrict their attention to a single solution or a very small subset of solutions from among the much larger set of feasible solutions. A concept called "non-dominance" or "non-inferiority" serves a similar but less limiting purpose for multiobjective problems. A feasible solution to a multiobjective programming problem is nondominated if there exists no other feasible solution that will yield an improvement in one objective without causing a degradation in at least one other objective.

There are several techniques available to generate nondominated solutions for a multiobjective problem. A generating method considers a vector of an objective function and uses this vector to identify and generate the subset of nondominated solutions in the initial feasible region. These methods deal strictly with the physical realities of the problem (i.e., the set of constraints) and make no attempt to consider the preferences of a DM. The desired outcome, then, is the identification of the set of nondominated solutions to help the DM gain an insight to the physical realities of the problem at hand.

To generate the nondominated solution set the simple technique called "Weighting Method" is selected in this study. This method transforms the multiobjective problem into a single objective programming format. Then, by parametric variation of the parameters used to effect transformations, the set of nondominated solution is generated. This method is applicable when the objective function and/or constraints are nonlinear, also. The weighting method for multiobjective problem is well described by Cohon (1978), and Goicoechea *et al.* (1982).

7.1.1 The Weighting Method

In this method weights are assigned to the various objective functions to combine these into a single objective function. Then the weights are parametrically varied to generate the nondominated set.

Mathematically, the weighting method can be stated as follows;

$$\max F(x) = W_1F_1(x) + W_2F_2(x) + \dots\dots + W_pF_p(x) \qquad (7.1)$$

subject to $x \in X$

which can be thought of as an operational form of the formulation

$$\text{max-dominate } F(x) = [\, F_1(x), F_2(x), \dots\dots, F_p(x) \,] \qquad (7.2)$$

subject to $x \in X$

Here a multiobjective problem has been transformed into a single optimization problem for which solution methods exist. The coefficient W_i operating on the ith objective function $F_i(x)$ is called a weight and can be interpreted as 'the relative weight or worth' of that objective when compared with the other objectives.

If the weights of the various objectives are interpreted as representing the relative preferences of some DM, then the solution to Eq.7.1 is equal to the best compromise solution. That is the optimal solution relative to a particular preference structure. Moreover, the optimal solution to Eq.7.1 is a nondominated solution provided all the weights are positive.

7.1.2 Problem Formulation

In a previous chapter (Chapter 6.5.1.1) it was shown that the differences between the two objectives of improving the reservoir salinity and improving release salinity are almost negligible. Therefore, in this study only the quality of water in the reservoir is considered as far as the quality improvement is concerned. The reservoir is assumed to be completely mixed throughout the year. Both inflows and releases could be controlled in the improvement of the quality of water supplied from the reservoir. The reservoir is operated on a monthly basis. The rate of inflow, outflow, diversion, and spill are constant during each time step.

The optimization algorithm developed based on IDP technique in Chapter 6.2 is used with a few alterations. They are the modifications in the objective function and the constraint on releases. The system configuration is as in Figure 6.2 (see Chapter 6.2).

The optimization problem has two objectives. They are, to minimize the squared deviation of the release from demand over the total period (F_1) and to minimize the squared deviation of the reservoir salinity from a target level over the total period (F_2). i.e.,

$$\text{O.F.} = \text{Minimize} \ [\ F_1, \ \ F_2 \ ] \tag{7.3}$$

Where the two objectives F_1 and F_2 are,

a. minimizing squared deviation of the release from demand over the total period,

$$F_1 = \text{Min} \sum_{j=1}^{N} (R_j - Dem_j)^2 \qquad \text{and,}$$

b. minimizing squared deviation of the reservoir salinity from a pre-specified target level over the total period,

$$F_2 = \text{Min} \sum_{j=1}^{N} (C_{res,j+1} - \hat{C}_{trg,j})^2 .$$

Note that the two objective functions F_1 and F_2 have different dimensions. By the use of weights to the objectives the problem could be converted to a problem having a single objective function as shown below. This objective function is used in the IDP based optimization algorithm.

$$\text{O.F.} = \text{Min} \sum_{j=1}^{N} \left[W_1 \ (R_j - Dem_j)^2 + W_2 \ (C_{res,j+1} - \hat{C}_{trg,j})^2 \right] \tag{7.4}$$

Where, $C_{res,j+1}$, $\hat{C}_{trg,j}$, R_j, W_1 and W_2 are as defined in Eq.6.1. Dem_j is the downstream irrigation demand (MCM). The W_i's have different dimensions.

The reservoir storage is the state variable while the release and the diversion are the decision variables. The minimization is subjected to constraints in storage volume, release and conservation of salt.

Storage volume constraint

The storage volume at the beginning of the first period and at the end of the last period are fixed. For all the other periods it belongs to the set of admissible storage volume.

$$S_{min} \le S_{j+1} \le S_{max} \qquad ; \qquad j=1,2,...,N-1 \tag{7.5}$$

Where, S_{j+1}, S_{min} and S_{max} are as defined in Eq.6.2.

Release constraint

The maximum release from the reservoir is limited only by the allowable release through the outlet.

$$0 \le R_j \le R_{max} \qquad ; \qquad j=1,2,...,N \tag{7.6}$$

Where, R_j and R_{max} are as defined in Eq.6.3.

Diversion constraint

The diversion from the inflows is constrained by an allowable limit.

$$0 \le D_j \le D_{max} \qquad ; \qquad j=1,2,...,N \tag{7.7}$$

Diversion during a certain month is always less than or equal to the inflow in that month.

$$0 \le D_j \le I_j \qquad ; \qquad j=1,2,...,N \tag{7.8}$$

Where, D_j and D_{max} are as defined in Eq.6.10 and I_j is defined in Eq.6.4.

Conservation of salt

The constraint that represent the conservation of salt in the reservoir is,

$$S_{j+1}C_{res,j+1} = S_jC_{res,j} + (I_j - D_j)C_{in,j} - R_jC_{rel,j} - C_{o,j}O_j \tag{7.9}$$

Where, $C_{in,j}$ and O_j are as defined in Eq.6.4 and $C_{rel,j}$ is defined in Eq.6.1. Other variables are as described before.

The equations (Eq.6.5 through Eq.6.7) are used to assess the salinity in the reservoir at the end of the period j.

State transformation equation

Based on the principle of continuity of the reservoir,

$$S_{j+1} = S_j + I_j - D_j - R_j - E_j - O_j \tag{7.10}$$

Where, E_j is as defined in Eq.6.8. Other variables are as defined before.

Recursive Equation

The DP recursive equation is formulated as,

$$F^*_{j+1}(S_{j+1}) = \underset{R_j, D_j}{\text{Min}} \left\{ SQD_j + F^*_j(S_j) \right\} \tag{6.9}$$

Where,

$F^*_{j+1}(S_{j+1})$ is the minimum accumulated value of the objective function from stage 0 to stage j+1, when the state at stage j+1 is S_{j+1}, and

$$SQD_j = \left| W_1(R_j - Dem_j)^2 + W_2(C_{res,j+1} - \hat{C}_{trg,j})^2 \right|$$

7.2 Analysis and Results

7.2.1 Nondominated solution : The Weighting Method

The quality of water supplied from a reservoir could be improved by manipulating only the discharges as shown in Chapter 6.5.1. But the improvements obtainable from this are marginal. Improvements in the quality of water supplied could be considerably enhanced by controlling inflows to the reservoir. Chapter 6.5.2 indicated this fact. In that analysis the downstream demand was treated as a constraint. If the downstream quantity demand constraint is relaxed the quality of water supplied could be improved further. That is by diverting (by-passing) more inflows of poor quality before entering the reservoir. But this might lead to violations in satisfying the downstream quantity demand. Imberger (1981) studied the influence a by-pass strategy has on the reduction of salinity in a reservoir. His results showed a dramatic reduction in salinity, but at the expense of a reduction in irrigation supply. Additionally, the operation ended with a partially full reservoir. The operation strategy adopted in that study was to by-pass inflows having salinity above a pre-specified level. Based on the results he stated that a wise balance between reduction in irrigation and by-passing highly saline water could lead to very marked reduction in average reservoir salinity.

Thus the two criteria, diverting more inflows of poor quality (to supply water of better quality from the reservoir) and satisfying downstream quantity demand are conflicting objectives. In this study trade-offs between these two objectives are sought to assist the decision making process.

The total reservoir storage and the dead storage are assumed to be 470 MCM and 75 MCM respectively. The allowable monthly release from the reservoir is 150 MCM. The monthly irrigation demands are given in Table 3.2. The maximum volume of water that could be diverted from inflow is constrained to 150 MCM in a month.

The two conflicting objectives are,

a. to satisfy the downstream quantity demand, and
b. to improve the quality of the water in the reservoir (quality of water released is highly correlated to the quality of water in the reservoir).

The optimization model developed based on the IDP technique is used to obtain the sequence of optimum decisions. The nondominated solution set was generated by giving different weightages to the two components in the objective function (Eq.7.4). The total period of 15 years (from 1974 to 1989) for which observed data are available was analyzed. The different weightages given and the results obtained are presented in Table 7.1. The diversions and the releases are the total volumes observed during the period of 15 years. The salinities given in the table are the averages of the monthly values over the period of 15 years.

The generated nondominated solution set is shown in Figure 7.1. The two axes are the standardized objective function achievement (within the range of 0 - 1) values as defined below. Ideal point is (0,0).

$$Z1 = \left(\frac{F_1 - F_{1,min}}{F_{1,max} - F_{1,min}}\right) \tag{7.11}$$

$$Z2 = \left(\frac{F_2 - F_{2,min}}{F_{2,max} - F_{2,min}}\right) \tag{7.12}$$

Where,

F_1 = Squared deviation of the release from demand over the total period (ref. Chapter 7.1.2),

F_2 = Squared deviation of the reservoir salinity from a target over the total period (ref. Chapter 7.1.2),

$F_{1,max}$ = Observed maximum value of F_1; (89646 : Table 7.1),

$F_{1,min}$ = Observed minimum value of F_1; (0 : Table 7.1),

$F_{2,max}$ = Observed maximum value of F_2; (79353000 : Table 7.1), and

$F_{2,min}$ = Observed minimum value of F_2; (38198000 : Table 7.1).

Table 7.1 Results of the Optimizations : Nondominated Solutions

Weightages		Objective Function		Total Release (MCM)	Total Diversion (MCM)	Mean Salinity (ppm)	
W_1	W_2	F_1	$F_2/10^3$			Reservoir	Release
**		0	79353	5422	2735	1626	1626
700	1	385	66447	5030	3124	1578	1578
600	1	474	66075	4996	3158	1576	1576
500	1	918	64501	4893	3262	1570	1570
400	1	1119	64049	4846	3309	1568	1568
300	1	1562	63737	4923	3229	1567	1568
200	1	2136	62135	4677	3473	1561	1561
100	1	4686	58471	4502	3643	1545	1545
80	1	5089	56695	4302	3845	1536	1537
60	1	5901	56541	4377	3760	1536	1537
40	1	10675	51554	4090	4048	1512	1513
30	1	18026	48151	3931	4160	1495	1494
25	1	24198	47007	3976	4126	1489	1491
20	1	27850	45237	3756	4356	1478	1479
15	1	30071	44621	3727	4365	1475	1475
10	1	47923	41415	3461	4650	1456	1459
5	1	55490	41247	3416	4689	1455	1456
0	1	89646	38198	2735	5372	1434	1435

** - releases are constrained by the downstream demands (demand fully satisfied)

In the above table the total diversion in the first row and the total release in the last row are observed to be the same. This occurrence is incidental. The summation of total release and total diversion for different alternatives are noted to be very close to each other. The difference that exists is left in the storage of the reservoir.

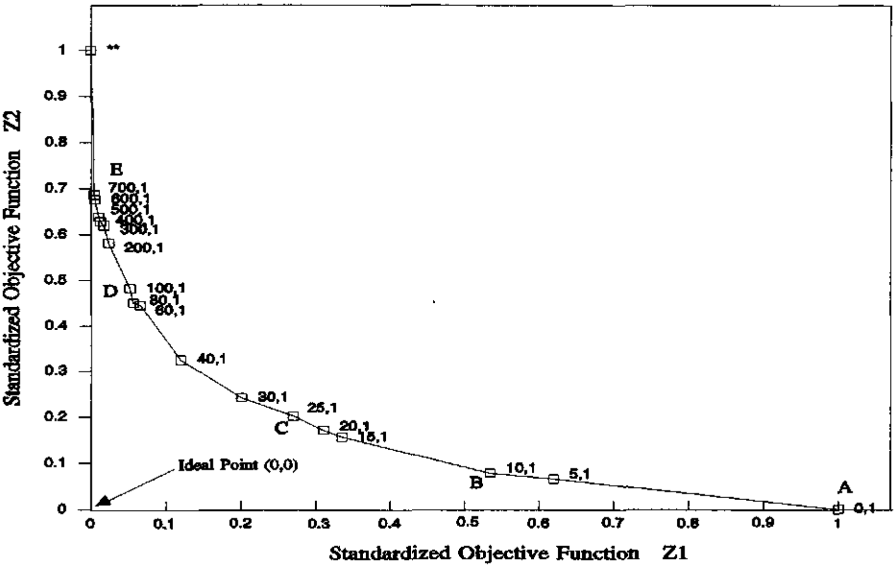

Figure 7.1 Nondominated Solution Set : Weighting Method

Five nondominated solutions were selected for comparison. These selected points, A, B, C, D and E are shown in Figure 7.1. Figure 7.2 compares the reservoir salinities of these five nondominated solutions. The releases and diversions are compared in Figure 7.3 and Figure 7.4 respectively. The reservoir storage volume for the operations corresponding to the above five points are presented in Figure 7.5.

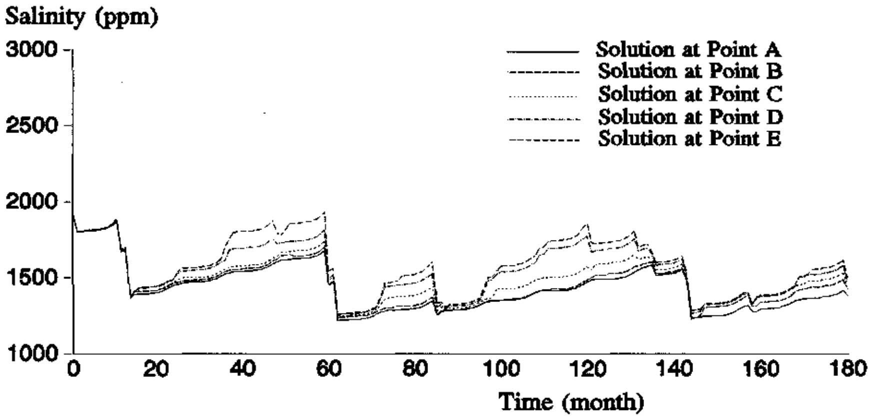

Figure 7.2 Reservoir Salinities - Comparison of Alternative Solutions

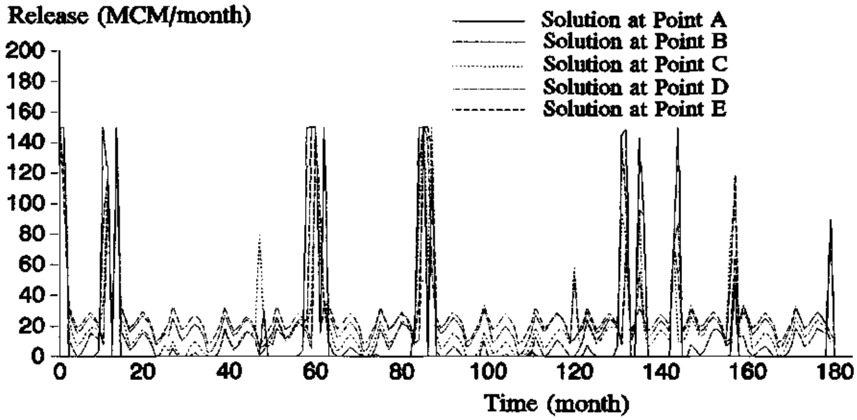

Figure 7.3 Releases from the Reservoir - Comparison of Alternative Solutions

Solution A provides the water of best quality among the solutions obtained. The differences between solutions B and A are trivial as far as the quality of water in the reservoir is concerned. But these two solutions are very unsatisfactory when the satisfaction of quantity demand is taken into account. No water is released for about 82% of the total time for the solution A and about 30% of the total time for the solution B. This factor makes these two solutions unworthy. However, it is noted that the diversions are very large with these two solutions. This implies the influence of the diversion of poor quality inflows has on improving the quality of water supplied from a reservoir.

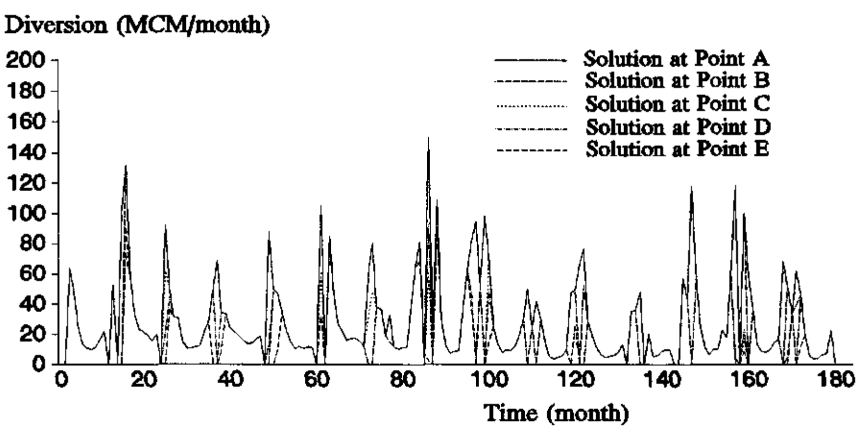

Figure 7.4 Diversions from Inflow - Comparison of Alternative Solutions

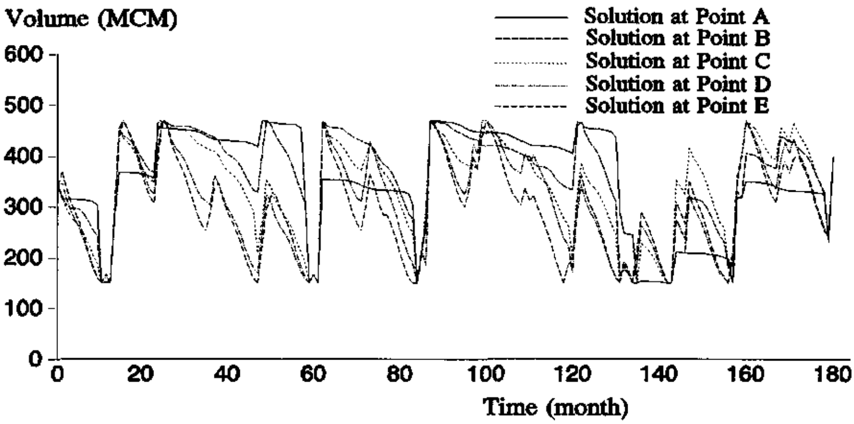

Figure 7.5 Reservoir Volume - Comparison of Alternative Solutions

The solution C, which is ranked next when the quality is considered, is also not a satisfactory solution as far as the quantity of water supplied is concerned. This solution satisfies more than 50% of the monthly demands for about 58% of the total period only. When the improvements in the quality of the water supplied from the reservoir is regarded the solutions D and E are not as attractive as the other three solutions. Nevertheless, the satisfaction of quantity demand is far better with these solutions compared with A, B and C. As Figure 7.6 reveals the solution D supplies more than 50% of the monthly demand for about 95% of the total period. More than 75% of the monthly demands are supplied in solution E throughout the total period.

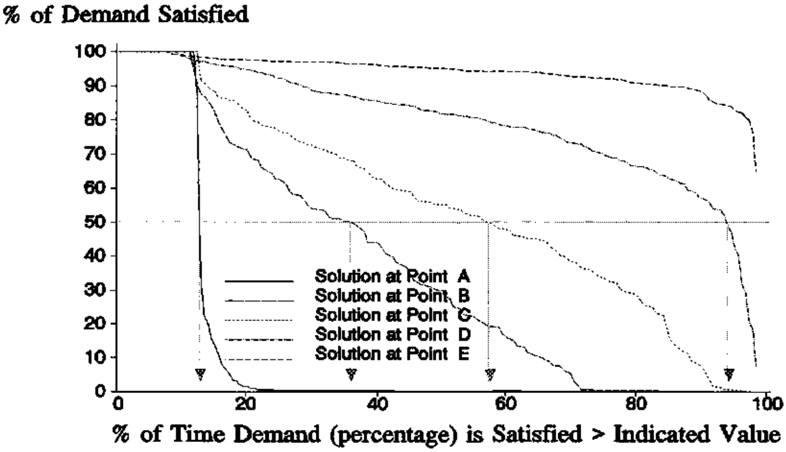

Figure 7.6 Percentage of Demand Satisfied - Comparison of Alternative Solutions

The release salinities obtained from the operations corresponding to point 'D' and 'E' are compared with those obtained from the optimum operations in Chapter 6, in Figure 7.7.

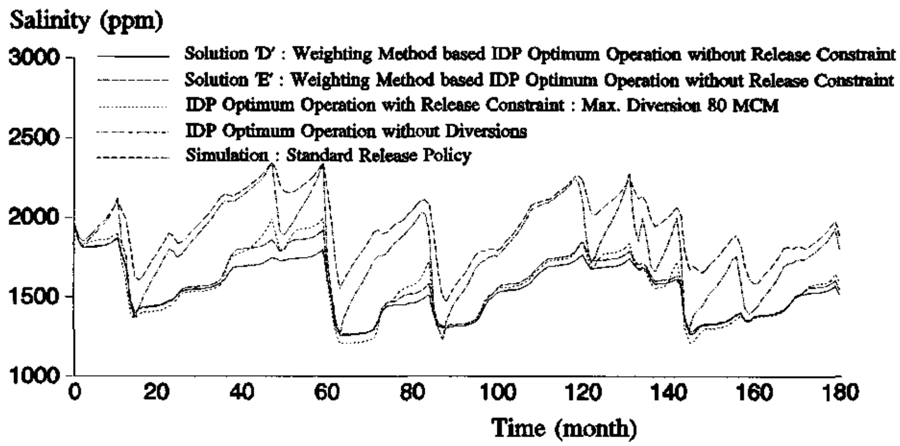

Figure 7.7 Release Salinity - Comparison with Previous Models

As Figure 7.7 displays the operations obtained from the weighting method (multiobjective analysis) are better than the others in the improvement of the quality of water. But these two solutions do not satisfy the quantity demand totally. The quantity reliability that is defined as the quantity supplied for satisfying demand as a factor of the total demand is 0.94 for Solution 'E' and 0.80 for Solution 'D'.

A few sharp drops in the release salinity are observed in Figure 7.7. Those drops are associated with high inflows of low salinity concentration. These high inflows (of low salinity) make the reservoir salinity low. Further, the high releases observed during these periods (occurred during the periods of very high winter inflow) flushes/cleanses the reservoir. This improves the quality in the reservoir and therefore, in the releases significantly.

7.2.2 Effect of Constraining Releases

By-passing inflows of poor quality is an effective management strategy in substantially reducing the reservoir salinity. But it was obtained at the expense of a reduction of the volume of water for irrigation. The releases from the reservoir were not constrained by a minimum limit in the previous chapter (Chapter 7.2.1). Therefore, there were months even without any supply of water for irrigation. It may be preferable if at least a percentage of the demand could be assured throughout the total period of operation. In this chapter the effect of constraining the minimum supply of water for irrigation has on the improvement of the quality has been investigated.

The minimum downstream irrigation release was varied parametrically (as a percentage of the total demands) and the 'trade-off' between diverting and releasing to downstream were studied. The objective function used in the optimization is,

$$O.F. = Min \sum_{j=1}^{N} (C_{res,j+1} - \hat{C}_{trg,j})^2 \qquad (7.13)$$

$$\text{if,} \quad C_{res,j+1} \leq \hat{C}_{trg,j} \quad ; \text{then,} \quad C_{rel,j+1} - \hat{C}_{trg,j} = 0.0$$

Releases were constrained by downstream quantity demands. The optimization model based on IDP technique, presented in Chapter 7.1.2 was used with modifications in objective function and constraint on release. The objective function used is the one shown above (Eq.7.13). The releases were constrained by a lower limit that could be varied. Optimizations were carried out by varying this limit (downstream quantity requirements); always this limit being a percentage of the total demand. The results obtained are summarized in Table 7.2.

The results obtained by limiting the minimum release to a percentage of the demand showed that except a few months, almost always releases were equal to the pre-specified percentage of the demand. These results suggest that the solutions obtained are close to the solution of the following multiobjective objective function,

$$Min \left[W_1 \sum_{j=1}^{N} (R_j - Dem_j)^2 + W_2 \sum_{j=1}^{N} (C_{res,j+1} - \hat{C}_{trg,j})^2 \right] \qquad (7.14)$$

$$\text{if, } R_j > Dem_j \quad ; \quad \text{then} \quad R_j - Dem_j = 0.0$$

$$\text{if, } C_{res,j+1} < \hat{C}_{trg,j} \quad ;\text{then} \quad C_{res,j+1} - \hat{C}_{trg,j} = 0.0$$

solved by the so called "constrained method" by treating the first objective as a constraint. In this method one objective is maximized subjected to lower limit on the other objectives. As there were a few releases greater than the constraint percentage the solution set is not exactly the nondominated set. But it is very close to the nondominated set obtained at the previous chapter as shown in Figure 7.8. The two axes of the graph are the standardized objective function values as defined in Eq.7.11 and Eq.7.12. The percentage of the demand constrained in each optimization are also shown in this figure.

Constraining method has been used to solve multiobjective reservoir operational problems. For example, Mohan and Raipure (1992) reported the application of the constrained technique to analyze the operational alternatives for a large scale river basin in India.

Table 7.2 Results of the Optimizations : Effect of Constraining Releases

Percentage of Demand	F_1	$F_2/10^3$	Total Release (MCM)	Total Diversion (MCM)	Mean Salinity (ppm)	
					Reservoir	Release
100	0	79353	5422	2735	1626	1626
90	904	69264	5099	3057	1586	1588
80	3646	62069	4663	3491	1557	1559
75	5735	58260	4330	3825	1542	1542
70	8246	57339	4408	3714	1537	1539
60	14670	52190	4147	4005	1513	1513
50	22874	47677	3771	4379	1491	1491
40	33143	43943	3407	4740	1471	1472
30	45040	42328	3257	4880	1461	1462
25	51105	41548	3179	4955	1456	1457
20	58452	40996	3143	4984	1453	1426
10	74091	39337	2924	5193	1441	1458
0	89646	38198	2735	5372	1434	1435

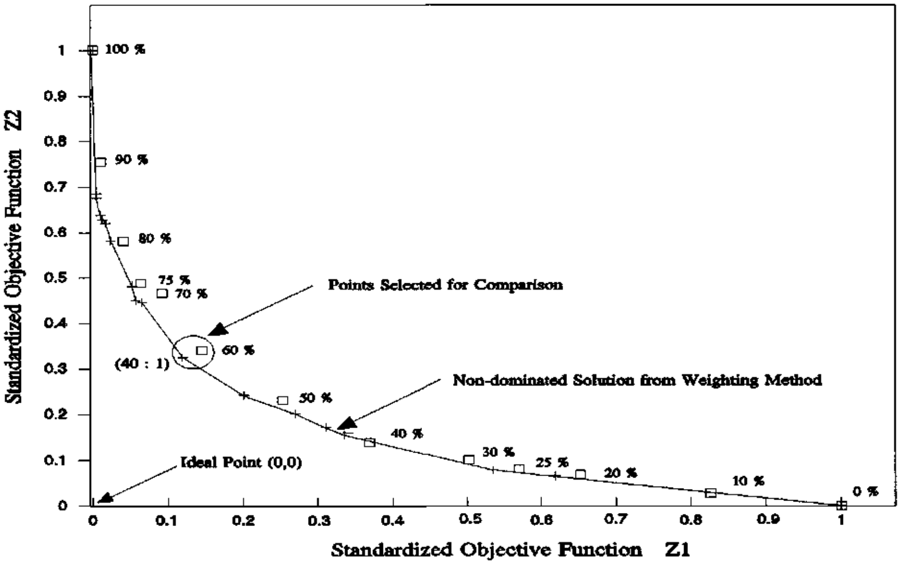

Figure 7.8 Optimum Solutions Obtained by Constraining Releases

The solution obtained by constraining releases to 60% of the downstream quantity demand is very close to that obtained by weighting method with the weightages 40:1 as shown in Figure 7.8. Therefore, those two solutions were selected for comparison.

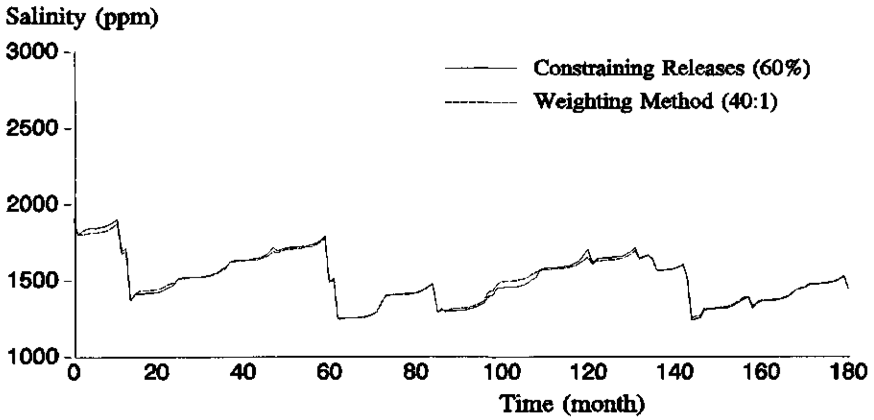

Figure 7.9 Reservoir Salinity - Effect of Constraining Releases

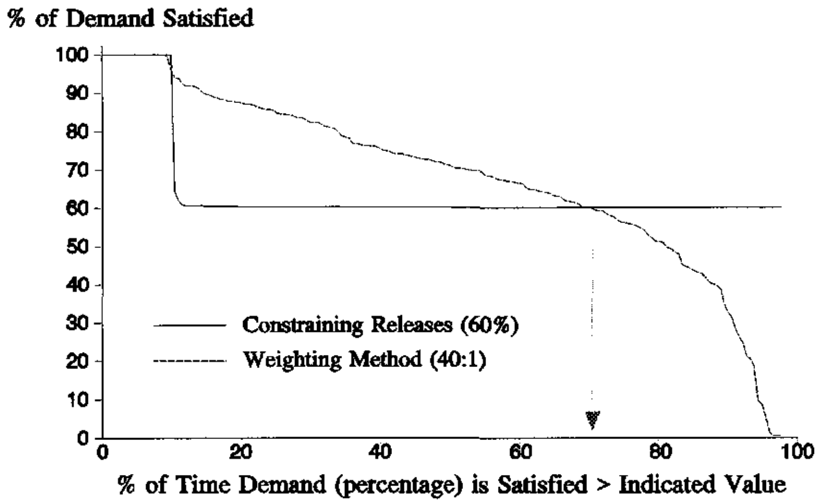

Figure 7.10 Percentage of Demand Satisfied - Effect of Constraining Releases

Figure 7.9 displays the reservoir salinities for these two solutions. They appear to be very similar. Figure 7.10 indicates that the constraint method satisfies more than or equal to 60% of the demand throughout the total period for the selected solution. But the solution from the weighting method (with weightages 40:1) satisfies 60% of the demand, for about 72% of the total time only. During the remainder period supply is less than 60%. However, the overall demand satisfaction is 0.69 with the solution from weighting method compared with 0.64 obtained by constraining releases to 60%. Therefore, the result from the weighting method is better if overall quantity demand satisfaction is concerned.

8 Conclusions and Recommendations

8.1 Conclusions

This study presents several techniques formulated to manage a reservoir when the improvement of the quality of water supply is of interest besides merely satisfying quantity requirements. In the first two techniques (i.e., Stepwise Optimization-Simulation Method and Iterative Optimization-Simulation Method) the natural process of stratification found in reservoirs is incorporated into the process of deriving optimum operating release policies for the reservoir. In the other models the reservoir is assumed to be completely mixed throughout its volume during the whole annual cycle.

The Stepwise Optimization-Simulation Methodology is accomplished through the coupling of a reservoir dynamics simulation model and a mathematical optimization algorithm. In this technique the mathematical model that simulates reservoir dynamics is retained in its original form rather than having to be restructured to fit into an optimization model. The ability to use the sophisticated reservoir dynamics simulation model without any change is an advantage of the approach. The outlet structure of the reservoir has several outlets at different elevations. The methodology specifies the quantity of water to be withdrawn from these outlets for satisfying downstream quantity demand and for scouring the reservoir. The results obtained show improvements in the quality of supply water during strongly stratified periods of the year. During summer the Jarreh reservoir is strongly stratified and therefore, the gradient of salinity concentration with depth is significant. In winter the reservoir water gets completely mixed and this makes the difference of quality of water in the reservoir with depth trivial. Therefore, during this period the improvements obtainable by withdrawing from different elevations are very limited. These observations imply that the use of the methodology only during the stratified periods is effective. However, the overall improvements in the quality of water obtainable by manipulating the releases are observed to be very marginal for the Jarreh reservoir.

The Stepwise Optimization-Simulation methodology proceeds stepwise in time. Anticipation of future uncertainty of inflow is not incorporated into decisions for a current period, so that the sequential decisions can be regarded as myopic. This is a drawback of the approach. Coupling of decisions made by an SDP based optimization model with the above method is shown to be a viable strategy to overcome this disadvantage. Further, the excess amount of water (as defined by the SDP policy) released beyond the downstream quantity demand could be used to scour the reservoir.

However, scouring the reservoir should not be looked upon as always effective. For example, scouring may have detrimental effects if the water withdrawn for scouring during initial period in a year is of lower salinity than the reservoir salinity during the latter part of that year. That is, water of lower salinity is wasted as scouring with the adverse effects later in the year. For the Jarreh reservoir, the scouring carried out during the initial months of the dry year enhanced the improvements in the quality of water supplied towards the end of the stratified period. However, the salinity concentration starts to rise rapidly with winter mixing towards the end of the dry year. The concentration of salinity in the scours during the initial period of that year was lower than the reservoir salinity at the beginning of winter period and it is the reason for the above behaviour.

For the Jarreh reservoir the optimum operation pattern during summer is to release water for irrigation from the lowest outlet (however, this would vary for different reservoirs). The warm saltier inflows in summer enter the top layers of the stratified Jarreh reservoir. This renders the concentration of salinity in top layers high. Therefore, water of less salinity is available from the bottom outlet. Further, the stratification regime (i.e., timing of turnover and onset of stratification, vertical dimensions of layers, duration of stratification, etc.,) in the reservoir is observed to be affected by the operation pattern.

In contrast to the above method, the Iterative Optimization-Simulation method considers a longer period (of several small time steps) during the optimization phase. This approach also uses the concept of representing the stratified reservoir by several small hypothetical reservoirs during the optimization stage. However, in this model communication between adjacent hypothetical reservoirs is made possible. The mathematical model that simulates reservoir dynamics is used in its original form in this method too. In spite of the above mentioned improvements to the model, the results obtained are almost similar to that obtained from the previous one. These observations confirm the fact that the improvements in water quality obtainable by manipulating only the releases from the Jarreh reservoir are not very significant.

The assumption of complete mixing of water throughout the reservoir during the whole annual cycle is a simplification compared with their real behaviour of undergoing stratification and mixing cycles in a year. This study presents two optimization models formulated on the basis of this simplification. The purpose to use this simplification is to reduce the mathematical and computational complexity involved in modelling a stratified reservoir.

The model developed considering the manipulation of only releases showed some improvements in the supply water quality. The flushing of the reservoir during certain periods, according to the optimum operation pattern obtained from this model, contributed towards these improvements. Flushing of the Jarreh reservoir occurs mainly in autumn and early winter, when the quality of water in the reservoir is poor. The subsequent high inflows of low salinity during winter improve the reservoir quality. The comparison of the two optimizations with and without quality consideration showed apparent changes in the operation pattern when the quality considerations are included in the optimization. Accordingly, obvious improvements in the quality of water supply are also observed.

The improvements obtained in the quality of the water supplied are observed to be considerably enhanced when the manipulation of inflows to the reservoir is also possible. The model that considers the ability to divert inflows before entering the reservoir seems very attractive in improving the supply water quality.

A few researchers suggested that diverting inflows above a pre-specified cut-off level of salt concentration as a strategy for controlling salinity in the water supplied from a reservoir. This is a good technique for the improvement of quality. But this policy might affect the satisfaction of downstream quantity demand. The IDP model developed in this study treats the downstream quantity demand as a constraint that is to be satisfied at all times. Therefore, the operation pattern obtained from it satisfies the quantity demand consistently. Additionally, the water quality improvements obtained from this model were observed to be much higher than those obtained from diverting inflows of salinity above a cut-off level, for the same total amount of water diverted.

Interestingly, the operation of the stratified reservoir (simulation with DYRESM) according to the operation policies defined by the IDP models showed considerably large improvements in the quality of water supplied from it. Therefore, the derivation of optimum operation policies for the Jarreh reservoir assuming complete mixing is occurring in it could be regarded as an acceptable simplification. Thus, a vital reduction in the complexity involved in modelling a stratified reservoir can be obtained.

By relaxing the constraint on release towards the downstream quantity demand more inflows could be diverted before entering the reservoir. In this way, quality improvements could be further increased. Apparently this may affect the satisfaction of downstream quantity demand. Therefore, the objectives of satisfying the downstream quantity demand and improving the quality of water by diverting inflows of poor quality are two conflicting objectives. The weighting method was shown to be capable of generating the nondominated solutions for the above problem. Diversion of more inflows results in more improvements in the quality of water supplied. Once the nondominated solution set is known, by examining the trade-off between the water supply quality and the supply quantity a desirable solution could be selected (e.g., using a distance based technique).

Clearly the inflows have a very high impact on the quality of the water in the reservoir, and thereby in the quality of the water supplied from the Jarreh reservoir. Therefore, improvement in the quality achievable by the control of only the releases is less effective. By-passing of poor quality inflows seems to be a very promising management alternative for improving the quality of water supplied from the reservoir.

The results obtained from the study show the validity of the assumption of reservoir's complete mixing for the stratified reservoir without sacrificing accuracy. Therefore, a relatively simple and straightforward methodology based on the non-stratification assumption proves to be suitable in managing a density stratified reservoir at least at the planning stage.

8.2 Recommendations for Further Research

Both Stepwise Optimization-Simulation method and Iterative Optimization-Simulation method proceed in monthly steps. Accordingly, decisions in the operation of the reservoir are taken monthly. An improved operation of the reservoir may be obtained by making decisions at smaller time steps. For instance, a time step of a week may be attempted. This might result in a smoother variation of the release salinity compared with the sudden changes (e.g., sudden rises at the beginning of winter) observed in this study.

In the iterative technique presented, the reservoir was assumed to have outlets at two different elevations only. Increasing the number of outlets to three instead of two may be useful for having more flexibility in the operation. However, this may increase the time required for one optimization-simulation iterative cycle significantly. This is due to the addition of another sub reservoir, which increases the number of state variables in the IDP optimization model from two to three.

Salinity characterized the quality of water in this study. Nevertheless, actual parameters constituting "quality" vary from reservoir to reservoir and may range from conservative tracers such as temperature or salinity to reacting or growing chemical and biological constituents. The methodologies suggested in this study for the management of a reservoir based on the conservative substance "salinity", may be extended to the other above mentioned quality parameters of water. For example, temperature could replace salinity, if it is of interest to reduce the temperature fluctuations in the river downstream of the reservoir during a year. Temperature of water is important for the fish in the river downstream of the reservoir. The reservoir simulation model DYRESM used in this study is capable in predicting both salinity and temperature profiles in a reservoir. Therefore, the same simulation model could be used if salinity has to be replaced by temperature in the methodology presented.

Inclusion of more than one quality parameter of water in the Stepwise Optimization-Simulation model is another aspect worth examining. Several qualities of water could be very easily included in that methodology at the decision making stage. If quality parameters other than salinity and temperature are of interest the reservoir simulation model DYRESM cannot be used. However, any reservoir simulation model that provides the variation of the other quality parameters in a reservoir could replace the model DYRESM in the suggested methodology. When decisions are made based on only one quality parameter it is possible for another quality of water to get deteriorated. Therefore, inclusion of all the important water quality parameters in the model may be important.

An optimization algorithm based on "Feasible Directions Method" has been used in the Stepwise Optimization-Simulation method in this study. It would be interesting to research on the applicability of other optimization techniques to find probably a more efficient one.

The author has studied the applicability of the "Rosenbrook algorithm" (Kuester and Mize, 1973) and found inferior to the technique finally selected to be used in this study.

The model that assumes complete mixing in the reservoir might be improved by replacing it with the combination of two or even more parallel reservoirs, each getting completely mixed separately. Inflow could be inserted to one of these smaller reservoirs comparing the density of inflow with the density of the sub reservoirs and selecting the most suitable one. In this way besides releasing water for beneficial uses, scouring of the reservoir for improving the reservoir water quality could be carried out. However, it should be kept in mind that this increases the number of state variables in the model. Thus the computer storage requirement as well as the processing time would increase significantly.

The optimization models developed assuming complete mixing in this study are deterministic models. Extending the models to incorporate stochasticity of inflows would be a worthwhile direction to continue this research. Stochastic nature of inflows could be handled by two approaches: an implicit or an explicit approach. In the implicit approach, a time series model is used to generate a number of synthetic inflow sequences. The system is optimized for each streamflow sequence and the operating rules are found by multiple regression. During the optimization synthetic data series are considered as deterministic ones. Therefore, the optimization models formulated in Chapter 6 (for mixed reservoir) could be used in the presented form. The explicit approach considers the probability distribution of the inflows rather than specific inflow sequences. This approach generates an operation policy comprising storage targets or release decisions for every possible reservoir storage and inflow states in each month, rather than a mere single schedule of reservoir releases. Efforts to examine the possibility to model the problem based on explicit stochastic dynamic programming technique is useful. Also it may be interesting to investigate the possibility of incorporating the concept of chance constraints in to the model (complete mixing) to include stochasticity.

Ability to manipulate inflows is observed to be very effective in improving the quality of water supplied from the reservoir. This problem was analyzed in the multiobjective analysis context in Chapter 7. In that study reliability criteria (or performance indices) such as quantity based reliability, time based reliability, vulnerability (quantity, time and quality based) etc., could be used to identify the most promising operation pattern among the nondominated solutions.

Application of the developed models to different case studies should be made to stabilize the results obtained in this study. For instance, reservoirs located at hydrologically different areas may be attempted to examine the validity of the results obtained. Applicability of the models to reservoirs of different size and geometry also should be investigated.

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APPENDIX A: Constrained Nonlinear Optimization Technique

A.1 Problem to be Solved

The general nonlinear programming problem to be solved is;

$$\text{Minimize } f(x) \tag{A.1}$$

Subject to,

$$g_i(x) \leq 0 \quad ; \quad i=1,2,...m \tag{A.2}$$

Where x is of dimension n and m is the number of constraints.

All numerical optimization techniques except tabular methods require an initial point x_0 to be specified and proceed by generating a sequence of points x_i, i=1,2,... , which represent improved approximations to the solution.

That is,

$$f(x_{i+1}) \leq f(x_i) \tag{A.3}$$

Such techniques referred to as iterative techniques are conveniently studied with the aid of equation

$$x_{i+1} = x_i + h_i d_i \tag{A.4}$$

Where, d_i is an n-dimensional direction vector and h_i is a distance moved along it. Initially a suitable direction d_i is determined. Once d_i has been chosen, f can be computed at one or more points along this direction, and from these results a suitable value for h_i can be found.

The Iterative techniques fall into two classes.

a. Direct search methods - do not require the explicit evaluation of any partial derivatives of the function, but instead rely solely on values of the objective function f, plus information gained from earlier iterations.

b. Gradient methods - those which select the direction d_i in equation (A.4) using values of the partial derivatives of the objective function f, with respect to the independent variables as well as values of f itself, together with information gained from earlier iterations.

A.2 Method of Feasible Directions

The idea of the feasible direction method introduced by Zoutendijk (1960), which falls into the gradient methods category is to take steps through the feasible region of the form,

$$x_{k+1} = x_k + \alpha_k d_k \tag{A.5}$$

from a feasible point x_k which satisfies all the constraints.

d_k is a direction vector - a feasible and usable one
α_k is a non-negative scalar - this scalar is chosen to minimize the objective function with the restriction that the point x_k and the line segment joining x_k and x_{k+1} are feasible.

Therefore the method comprises of two decisions:
(a) picking a direction d which is feasible and usable, and
(b) deciding how big a step to be taken in the direction d.

In this Method of Feasible Directions, a Linear Programming problem is incorporated into the algorithm at each step to determine the feasible direction, which is closest to the gradient of objective function and hence, to the constraint boundary.

Expanding functions (A.1) and (A.2) in a Taylor series about point x_k and ignoring terms higher than first order,

$$f(x_k + d_k) \approx f(x_k) + (\nabla f(x_k), d_k) \tag{A.6}$$

$$g_i(x_k + d_k) \approx g_i(x_k) + (\nabla g_i(x_k), d_k) \tag{A.7}$$

An improvement in the minimization in $f(x_k)$ will result if,

$$f(x_k + d_k) - f(x_k) \approx (\nabla f(x_k), d_k) < 0 \tag{A.8}$$

If x_k is strictly inside the feasible region $[g_i(x_i) < 0]$, then there exists some step size $\alpha_k > 0$ such that

$$x_{k+1} = x_k + \alpha_k d_k \tag{A.9}$$

is feasible for any set of directions d_k.

On the other hand, if x_k is on the boundary $g_i(x_k) = 0$, then from equation (A.7), x_{k+1} will be feasible for some $\alpha_k > 0$ if,

$$g_i(x_k) + (\nabla g_i(x_k), d_k) < 0 \quad ; \quad i=1,2,...,m \tag{A.10}$$

If equality is permitted in (A.10), then x_{k+1} will lie on the tangent hyper-plane emanating from x_k, which would be a feasible point only if $g_i(x)$ were linear.

In this case (A.10) becomes

$$(\nabla g_i(x_k),d_k) \leq 0 \quad ; \quad i=1,2,...,m \tag{A.11}$$

In order to determine the direction d_k which leads to a feasible point x_{k+1} and also stay as close as possible to the gradient direction for the objective function, a slack variable x_0 is introduced to convert the strict inequalities (A.8) and (A.10) to normal inequalities, and then solve the following linear programming problem at each point.

$$\underset{d_k}{\text{Maximixe}} \quad x_0 \tag{A.12}$$

such that

$$(\nabla f(x_k),d_k) + x_0 \leq 0 \tag{A.13}$$

$$g_i(x_i) + (\nabla g_i(x_k),d_k) + x_0 \leq 0 \quad ; \quad i=1,2,...,m \tag{A.14}$$

When $x_0 = 0$, no further improvement can be made and the constrained optimum has been found. Thus when $x_0 \geq 0$ becomes active, the problem is solved.

Since the elements of d_k are unconstrained in sign, add constraints

$$d_{j,k} \leq b \tag{A.15}$$

for all j in order to avoid unbounded solution.

For the purpose of determining a direction d_k, it is interested in relative values of d_j only. Thus b is taken to be an arbitrary positive constant (such as 1).

A.3 Algorithm

Summarizing the algorithm is now,

a. Evaluate $\nabla f(x_k)$ and $\nabla g_i(x_k)$; i=1,2,....,m
b. Solve the LP problem given by equations (A.12) through (A.15)
c. Stop if $x_0 = 0$
d. Otherwise, determine a step size $\alpha_k > 0$ such that $f(x_k + \alpha_k d_k)$ is minimized over all feasible points.

Wismer and Chattergy (1978) comprehensively explained the Method of Feasible Directions with examples.

APPENDIX B: DYRESM Model

B.1 Model description

The Dynamic Reservoir Simulation Model DYRESM developed by Imberger *et al.* (1978) is a one dimensional numerical model. It is used for the prediction of the distribution of temperature, salinity and density in small to medium lakes, ponds and reservoirs in response to meteorological forcing, inflow and outflow. The model is based on the assumption of one-dimensionality, that is, the variation in the lateral directions are small compared with the variation in the vertical. This assumption is based on the density stratification usually found in lakes and reservoirs, which inhibits vertical motions while lateral and longitudinal variation in density are quickly relaxed by horizontal convection, occurring on time scales faster than vertical advection. The model has been developed concentrating on parameterization of the physical processes rather than numerical solution of the appropriate differential equations. It uses Lagrangian layer scheme, in which the lake is represented by a series of horizontal layers of uniform property but of variable thickness. The position and therefore the thickness of these layers changes as inflow and outflow modify the lake volume.

Even with the assumption of one-dimensionality, the vertical density structure is the result of a complex interaction of a number of processes active in lakes and reservoirs. The DYRESM approach is to utilize parameterization of these individual processes. The development of the DYRESM model is described in detail in the literature (Imberger *et al.*, 1978; Spigel and Imberger, 1980; Imberger and Patterson, 1981; Patterson *et al.*, 1984), including descriptions of the process parameterizations. The processes included in the model are:

* Surface heat, mass and momentum exchanges,
* Surface mixed layer deepening,
* Inflow,
* Outflow,
* Mixing in the hypolimnion.

The outstanding features of DYRESM are; the accuracy by which the various components (salt and temperature) are modelled, its variable time step, its dependence on only physical interpretable calibration factors and its Lagrangian structure. The one-dimensional assumption places certain restrictions on the applicability of the model. Therefore, it is necessary to validate the one-dimensionality criteria (as described in Chapter 4.3.2) for the lake or reservoir for which the model is applied.

DYRESM was developed over the last decade. The development of the model is continuing, Version 6.4 is used for the present study. A brief description of the model is given here.

B.2 DYRESM Model Structure

The model is constructed as a main programme with subroutines, which separately model each of physical processes of inflow, withdrawal, mixed layer dynamics and vertical transport in the hypolimnion (Figure B.1). In addition there are a number of service subroutines, which provide maintenance of the layer system (volumes, position etc.) and provide calculations of physical properties, which are frequently required such as density. The functions of the main programme are therefore of input/output, the calculation of fixed parameters and control over timing of the calls to the various process subroutines.

The model incorporates two time steps; a fixed basic step of one day and a variable sub-daily time step for the mixing algorithm. The length of the sub daily step is determined by the dynamics and ranges between ¼ hr and 12 hrs. This procedure allows small time steps when the dynamics so require; in less critical periods, the time step expands without loss in accuracy.

The main programme inputs the fixed data, physical dimensions, volume and area as a function of depth, physical properties of the inflowing streams, locations of the offtakes, an initial temperature and salinity profile and output control parameters.

The daily loop begins with the input of the inflow, outflow and meteorological data. After some output, the sub-daily loop commences. The heat exchanges through the surface are modeled by HEATR, which simulates the radiation penetrative heating and evaporative, conductive and long wave radiation exchanges at the surface. The updated slab structure is then adjusted for mixed layer deepening by MIXER and for Kelvin-Helmholtz billowing at the interface by KH. The mixed layer dynamics are modelled in four distinct sections; deepening by convective overturn, deepening by stirring, deepening by shear production and mixing at the thermocline by Kelvin-Helmholtz billows. Once the new thermocline depth and thickness have been computed the model then calculates the vertical turbulent diffusion in the hypolimnion by subroutines ENER, DIFCAL and DIFUSE. These subroutines calculate the eddy diffusivity and the net heat and salt transport from the bottom through the hypolimnion into the epilimnion. This sub-daily loop has a time step varying from 15 minutes to 12 hours.

At the end of the diffusion routine, which is carried out in the same time step as the mixed layer dynamics, a new structure for a particular day is obtained. This density structure is then used to route the inflowing water from the various contributing streams into the reservoir. The subroutine INFLOW allows for turbulent entrainment and subsurface intrusions. The outflow is calculated by the model using the structure left after the inflow has been added. The simulation models withdrawal from each submerged offtake and if necessary, flow over the crest. Two idealized outflow structures are modelled. First, a two dimensional flow into a sink, and second, a radial flow into a point sink, both of finite dimensions.

At this stage the predicted temperature and salinity structure is recorded as output. In the present work the model is extended with the calculation of the average salinity of the withdrawal water at the offtakes and overflow, the total mass and salt content, and the average salinity of the reservoir. This routine is repeated for each day of the simulation.

A number of service subroutines, which are called from the various segments of the main program and the dynamics subroutines, complete the structure of DYRESM. These are THICK, which maintains the model layer volumes between specified limits, DENSTY, which calculates the density of water for given temperature and salinity, SATVAP, which evaluates the saturated vapour pressure of air corresponding to a given temperature, and RESINT, which provides an interpolation between depths, volumes and areas from the physical data input.

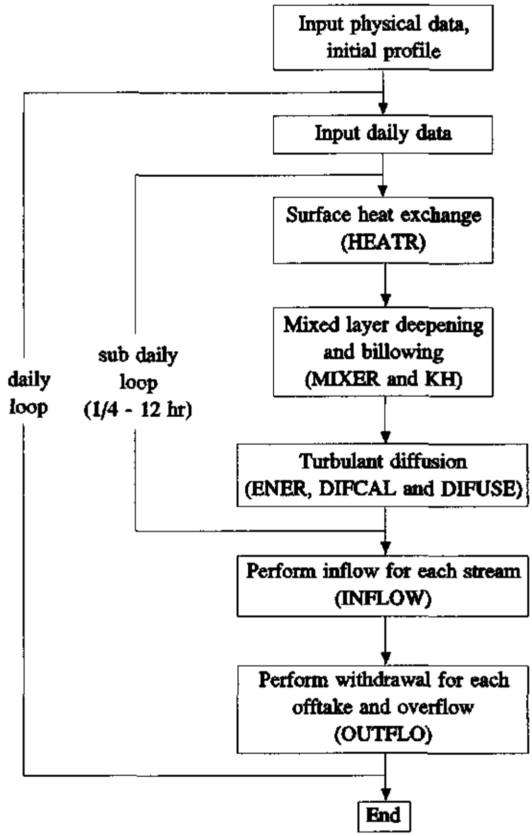

Figure B.1 DYRESM Model Flowchart