A TWO-STATE DETERMINISTIC DYNAMIC PROGRAMMING MODEL FOR OPTIMISING THE JOINT OPERATION OF MANGLA AND TARBELA RESERVOIRS IN PAKISTAN

by

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ABSTRACT

A two-state deterministic DP (Dynamic Programming) model is developed to derive the optimal reservoir operation policy for the Mangla and Tarbela reservoirs in Pakistan. The analysis is carried out with two separate objective functions, (1) maximisation of energy generation while treating the irrigation demands as constraints, and (2) maximisation of combined benefits from energy production and irrigation water supply in monetary terms. Historic data for a period of five years (1985-90) has been used in this research.

The Mangla and Tarbela reservoirs are built on the Jhelum and the Indus Rivers, respectively, in northern Pakistan. Both the reservoirs are multipurpose reservoirs and are operated on a ten-day time step. Water is released from these reservoirs to meet irrigation demands of the agriculture sector as a first priority and generate electricity as a second priority. The maximum live storage capacity of Tarbela reservoir (9.986 MAF) is almost twice as that of Mangla reservoir (5.365 MAF). The current maximum plant output at Tarbela (3500 MW) is more than three times of that at Mangla (1000 MW). Two of the four irrigation regions served by these reservoirs are common to both Mangla and Tarbela, which emphasizes the need to operate the two reservoirs in conjunction with each other in order to maximise benefits from irrigation and energy production.

The optimisation results from the DP model are compared with the actual operation of both the reservoirs during the period 1985-90. The model shows an increase in energy production over actual energy production during the same period. However, the model shows deficits in irrigation water supply in the months of May and June, which are critical from the

point of view of irrigation, when 'maximisation of combined benefits in monetary terms' is used as the objective function. This problem can be overcome by assigning a greater monetary value to benefits from irrigation. The important characteristic of the model, when run using this objective function, is that it maintains a more or less constant discharge through the turbines during most of the one year period of operation which is quite important from the point of view of energy generation. When run using the objective function of 'maximising energy production with constraints on irrigation water supply', the model not only gives higher energy production but also deals adequately with the irrigation demands. The results also show that more water can be released for irrigation from the reservoirs during early Kharif period (Apr-Jun) because both reservoir can fill to their respective maximum conservation levels during the monsoon season (Jul-Sep). This would also help in flood mitigation by providing more storage and reducing flood peaks.

The model can be used, with some modifications, for optimising the real-time operation of Mangla and Tarbela reservoirs. These modifications would involve finer quantisation of the state variables (reservoir levels), determining the limits on minimum discharge outflows necessary to maintain suitable turbine efficiency, criteria to prevent salt water intrusion and meet the requirements of hydro projects downstream of Mangla and Tarbela, and consideration of the losses due to evaporation.

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INTRODUCTION

1.1 BACKGROUND

Pakistan is one of the largest nations of the world that depends on a single river system. The water from the Indus River and its tributaries supports the bulk of the agricultural water supply for its 125 million people. Forty-five percent of the electrical energy of Pakistan is produced by hydroelectric dams on the main stem and tributaries.

The Indus River and many of its tributaries, the Kabul, Jhelum, Chenab, Ravi, and Sutlej, originate in the Karakoram and the Hindukush regions in the north and north eastern borders of Pakistan (see Figure 1.1) descending south towards the Arabian Sea with an annual average volume of 215.25×10^9 m^3 (175 MAF) discharged into the Indus Plains. The Indus main stem and its tributaries form a link between two great natural reservoirs, the snow and glaciers in the mountains and the groundwater contained by the alluvium in the Indus Plains of Punjab and Sindh Provinces of Pakistan.

The climate of the Indus basin varies from subtropical arid and semi-arid in the southern and central lowlands of Punjab and Sindh provinces, to temperate sub-humid/humid and alpine in the mountainous highlands of the north. Annual precipitation ranges between 100 mm and 500 mm in the lowlands to a maximum of 2000 mm (water equivalent) on mountain slopes. Condensation occurs at high altitudes (above 3000 m) where temperatures are colder. The active hydrologic zone lies between Els. 3000 m and 5500 m and snowfall in the mountains accounts for a large portion of the total runoff into the river.

The two major storage dams on the Indus River System, Tarbela on the main stem of the Indus and Mangla on the tributary Jhelum River, have a combined storage capacity less than 16 % of the total flow. A third reservoir, Chashma, provides only regulation. There are long term plans to build additional storage dams on the Indus (Figure 1.2) to capture more water for irrigation and flood control and improve regulation for power generation.

The Indus River and its tributaries provide nearly 90 % of the water utilised for irrigation. Most of the remainder is groundwater which is recharged by various basin streams. The Indus is also main source of domestic and industrial water both at the city and at the village level. It is estimated that at least 80 % of all the water consumption comes from streams, canals, reservoirs and wells recharged by the river or its tributaries. Irrigated land accounts for 85 % of all cereal grain production (mainly rice and wheat), all sugar production and most of the cotton production. Most of these products are utilised both for internal consumption and for export. Rice, cotton, sugar and wheat exports provide the bulk of the foreign trade revenues of the country. The irrigation requirements are divided between two seasons, the *Kharif* (April to September) and the *Rabi* (October to March).

In addition to the irrigation and domestic/industrial water supply, the Indus waters are used for hydroelectric power generation. Since by law, water supply for irrigation for food production is the first priority, water is often released in excess of turbine capacity without generating valuable energy for the country, thus lowering the overall utilisation ratio of the electric turbines.

There are always conflicting demands on releasing or storing water in both key reservoirs, Mangla and Tarbela. There is a continuous competition between agriculture and industry, on releases and saving of water. Both the reservoirs are currently being operated on statistical analysis of historic records and subjective experience of hydrologists, which sometimes leads to shortages of water in dry seasons and excessive spills from reservoirs in the wet seasons. The complexity and extent of the irrigation network (Figure 1.3) and the conflicts between agriculture and industry sectors emphasise the need for developing an efficient method for operating Mangla and Tarbela reservoirs and maximising both energy and irrigation benefits.

1.2 OPTIMISING RESERVOIR SYSTEM OPERATIONS

An operating system is a set of rules for determining the quantities of water to be stored in, or releases from, a reservoir or a system of reservoirs under various conditions in a sequence of time steps. The implicit objective is to minimise costs and maximise benefits of operation. The operation plan for a reservoir system may prescribe the utilisation of water resources on a long or a short term basis or real-time operation in the form of a daily schedule of releases. The development of a reservoir system operation plan requires the following information:

- The inflows to the reservoir; obtained either from a forecasting model or from historical records.
- Demands; irrigation, power generation, water supply, recreation, flood control.
- Storage characteristics of the reservoir.

The main difficulty in reservoir operation stems from the uncertainty of inflows to the reservoir. The streamflows are uncertain, since they are dependent on the hydrology of the region which is a stochastic phenomenon.

Typically, an operational strategy is determined using a model. This model can be very simple, relying on a few empirical equations and rule curves; or in its most sophisticated form it can be a very complex risk-based optimisation model using optimisation techniques in combination with stochastic inputs and a set of sophisticated sub-models. Numerous modeling and analysis methods have been developed for evaluating multipurpose reservoir system operations. System analysis models are commonly categorised in two groups (Wurbs, 1991) ; Descriptive and Prescriptive.

DESCRIPTIVE MODELS:

Descriptive models demonstrate what will happen if specified decisions are made. Simulation models are descriptive. Simulation may be done with generalised software programs, like those of Hydrologic Engineering Center (USACE). Alternatively, to take advantage of the ease-of-use of PC software, simulation may be done with a spreadsheet.

PRESCRIPTIVE MODELS:

Prescriptive models determine what decisions should be made to achieve a specified objective. Optimisation techniques, such as linear programming, dynamic programming, and other non linear programming methods, are generally viewed as being prescriptive. Prescriptive optimisation algorithms systematically and automatically search through all feasible decision policies (set of values for decision variables), to find the decision policy which minimises or maximises a defined objective function. Mathematical programming methods provide useful capabilities to consider an extremely large number of values for decision variables.

Research results and case studies appear to indicate a high potential for information for improving reservoir operation through the use of mathematical programming techniques. However, truly-prescriptive optimisation models have played a relatively minor role compared to simulation models in regard to influencing decision makers in the planning and operation of actual projects. Mathematical programming techniques require that the real system be represented in the proper mathematical format. Reservoir system operation is a complex task involving numerous hydrologic, economic, environmental, institutional, and socio-political considerations. Representing complex project objectives and performance criteria in the required format is a particularly difficult aspect of the modeling process which limits the application of optimisation techniques. Optimisation strategies are often determined by iterative trial-and-error runs of a simulation model. All optimisation models also simulate system performance for alternate decision policies. On the other hand, many complex simulation models contain optimisation algorithms to perform certain functions. Thus , most models, to various degrees, contain elements of both approaches. The most effective strategy for analysing certain reservoir operation problem may involve a combination of optimisation and simulation. Preliminary screening with an optimisation model may be used to develop a manageable range of alternative decision policies for further detailed analysis with a simulation model.

1.3 RESEARCH OBJECTIVES AND THESIS OUTLINE

The design of a Reservoir System Operation Model for the multi-purpose, multi-reservoir system in Pakistan is an extremely complicated task and would require very extensive work. For the purpose of this study, however, the development of an operational model for the Indus River System is kept to a relatively simple level to develop a "feel" for the optimisation process and explore some new approaches. The focus is on the two key reservoirs Mangla and Tarbela. The objective is to apply the Dynamic Programming approach to the Mangla and Tarbela reservoir systems and develop an optimisation model using historic data.

A multi-state D.P.M (Dynamic Programming Model) PK-ROM has been developed for maximising the benefits by optimum operation of these reservoirs for irrigation water supply and energy generation. The course of action in the development of PK-ROM (Pakistan Reservoir Operation Model) has been as follows:

1. Developing a D.P.M for each reservoir i.e., Mangla & Tarbela, using historical data for a period of five years (1985-90).
2. Developing a Two-State D.P.M for Mangla and Tarbela with 'Maximisation of Energy Generation' as the objective function and using deterministic inflows and

irrigation demands (historical data; 19850-90). The irrigation demands being treated as constraints in this case.

3. Modify the Two-State D.P.M by using 'Maximisation of Energy/Irrigation Benefits' as the objective function. In this case, a dollar value is assigned to the amount of energy generated and the volume of water released for irrigation supply.
4. Comparison of results obtained from the above two approaches with the actual operation of the two reservoirs during the same period.
5. Recommending the best approach for real-time (10-day basis) conjunctive operation of Mangla and Tarbela reservoirs for maximisation of both energy and irrigation benefits.

In this way, the outcome of this research contributes to the development of a more refined operational strategy that best meets the needs of both the agriculture and industry sectors.

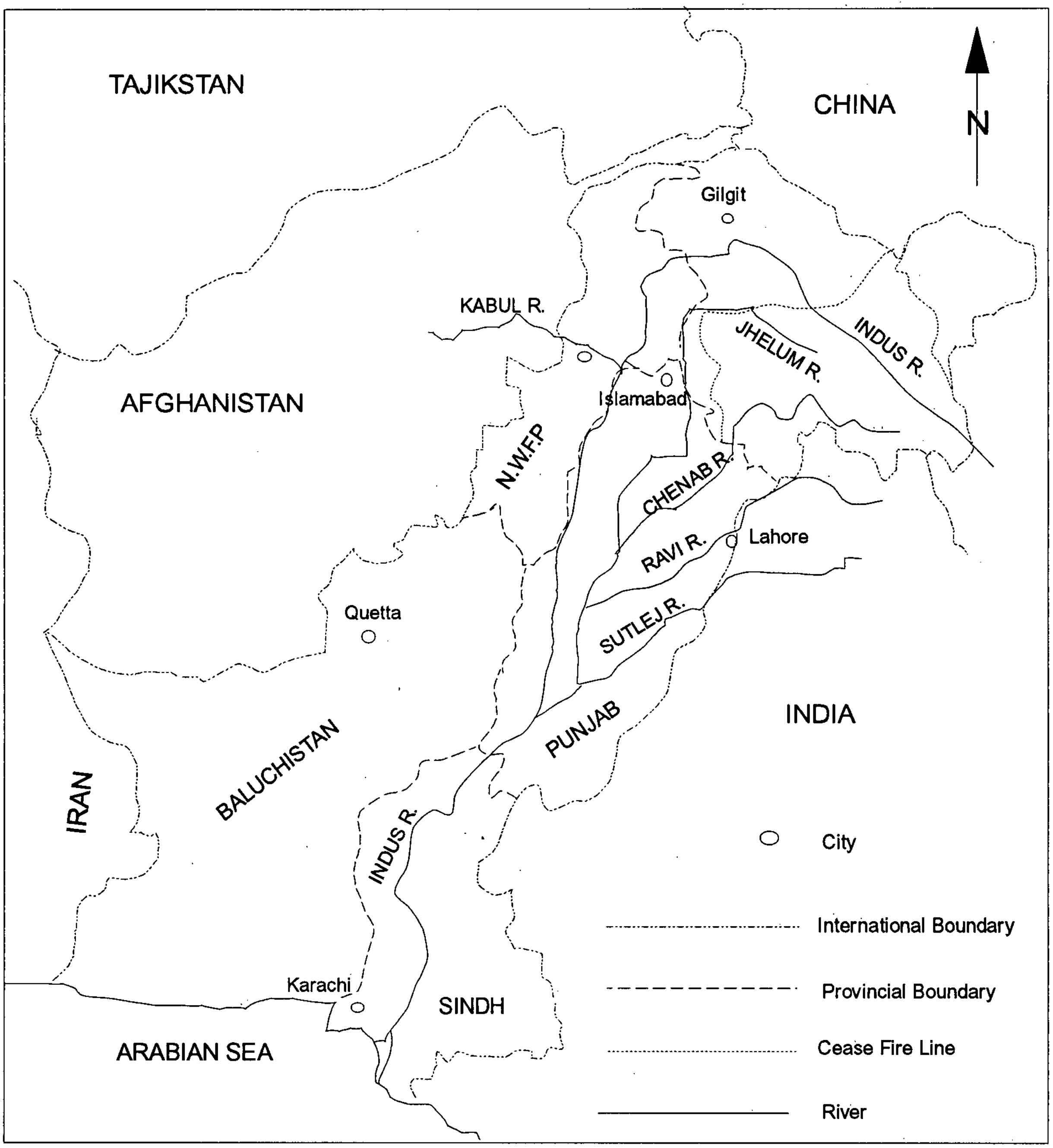

Figure 1.1. The Indus River System, Pakistan

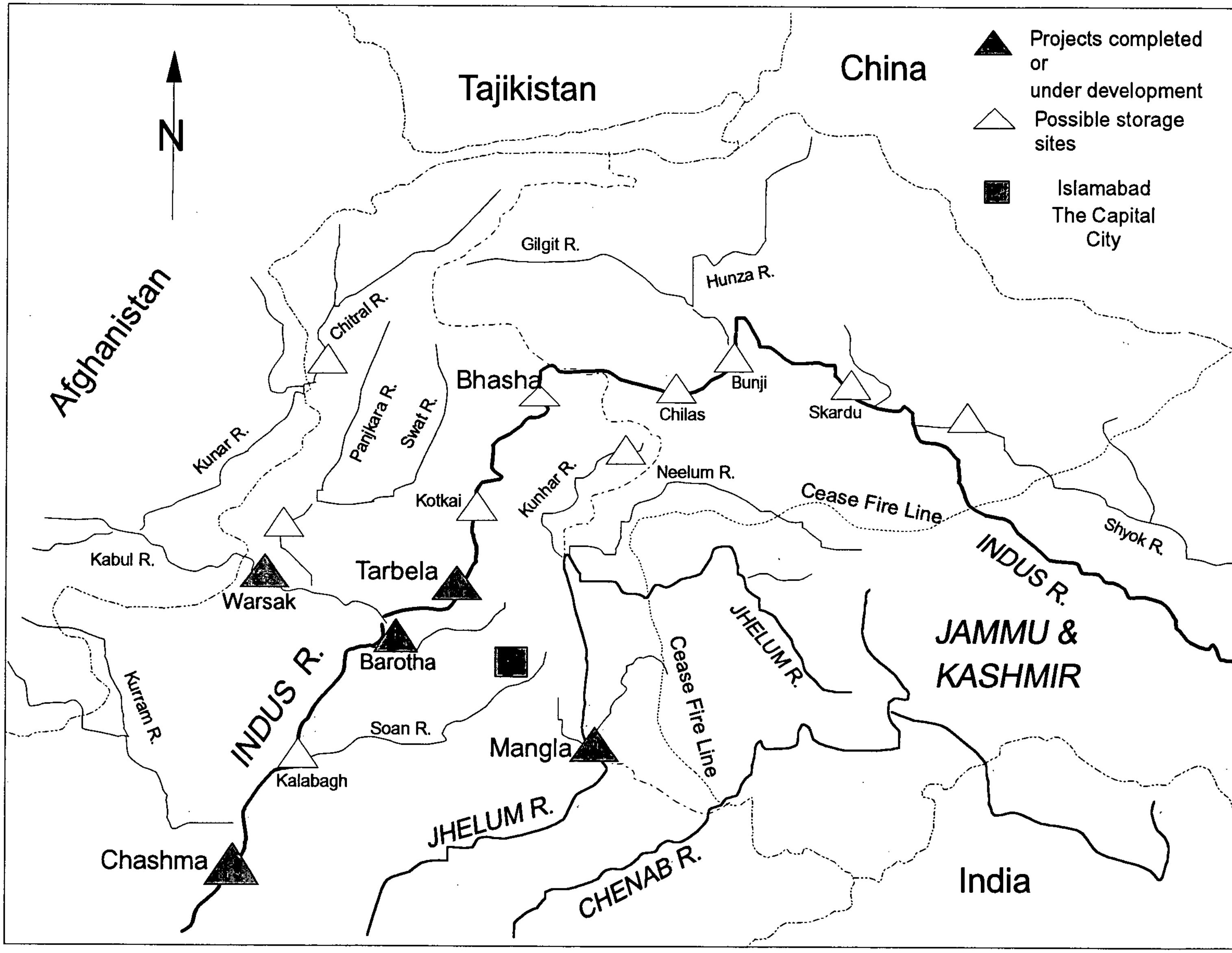

Figure 1.2. Dam sites of the Indus Basin, Pakistan

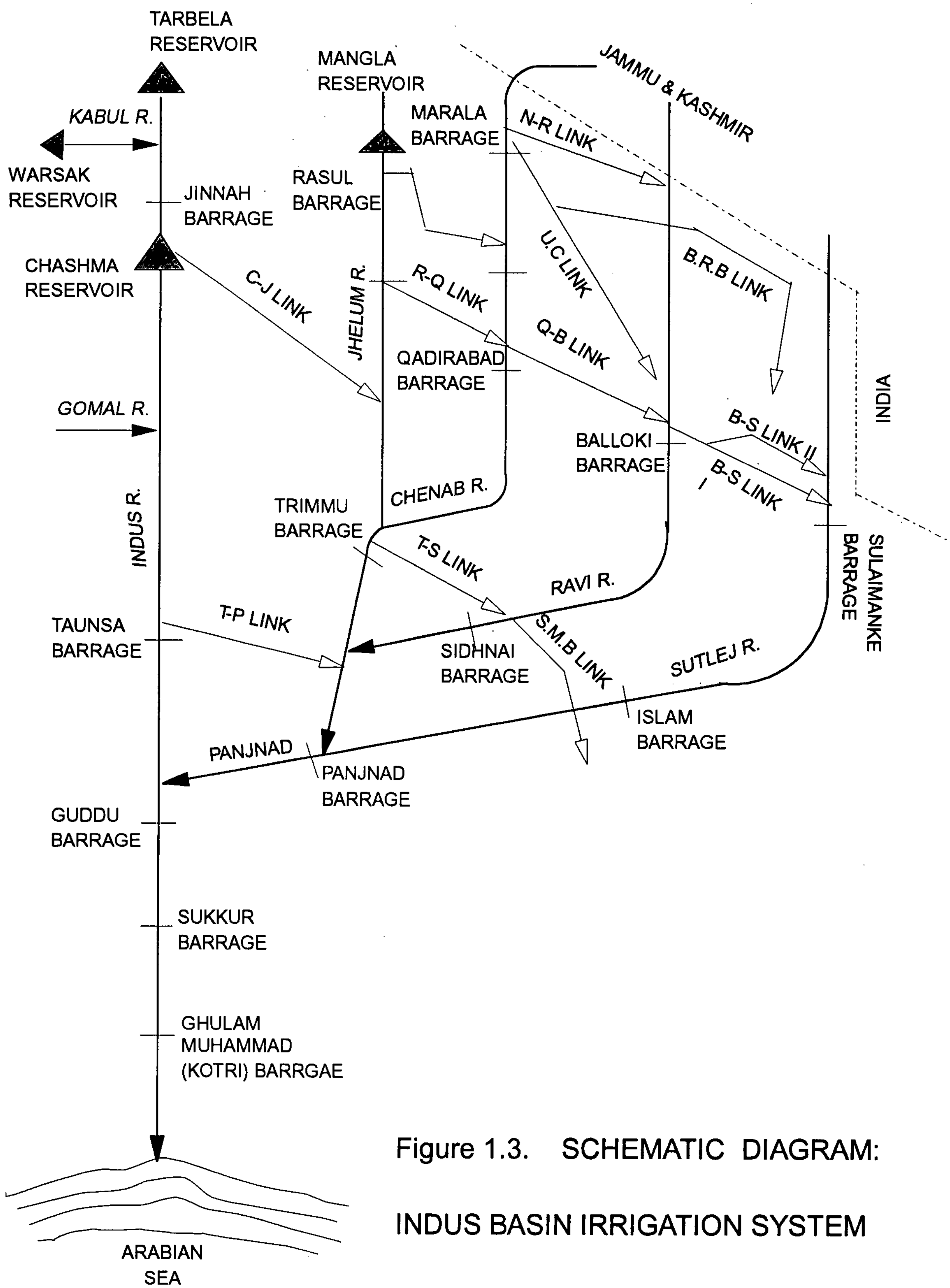

Figure 1.3. SCHEMATIC DIAGRAM:

INDUS BASIN IRRIGATION SYSTEM

THE INDUS RIVER SYSTEM AND ITS MANAGEMENT

2.1 MAJOR RIVERS OF PAKISTAN

According to the *Indus Waters Treaty of 1960*, signed between Pakistan and India under United Nations auspices, the flows of four main rivers are available to Pakistan—the Indus, Kabul, Jhelum, and Chenab. These rivers have a combined average annual discharge of about 174.6×10^9 m^3 (142 MAF). Nearly one-half of this discharge is in the Indus itself and the remainder roughly equally divided between the other three rivers. Since the Tarbela and Mangla reservoirs are built on the Indus (main stem) and Jhelum rivers respectively, the following discussion is focused on these two rivers.

The Indus River rises in Tibet, in a catchment which contains some of the largest glaciers in the world outside the Polar regions. Snow and ice melt from this glacial area of about 22540 square kilometers (14,000 sq. miles) supply about half the total flow of the Indus in the summer season. The importance of this source helps to account for two significant characteristics of the flows in the Indus—their relatively high seasonal concentration and their relatively small fluctuation from year to year (Lieftinck, Sadove, and Creyky; 1969). Of the total mean flow of the Indus at Attock, at the confluence of Indus and Kabul (see Figure 2.1), about 72 percent or $82.41 \times 10^9 m^3$ (67 MAF) occurs in the four months June to September. Annual mean flow in the Indus at Attock is about $114.39 \times 10^9 m^3$ (93 MAF).

The Jhelum is a very different type of river from the Indus—mean annual flows are only about one-third of those in the Indus and they are much more variable from year to year. The river rises in Indian-held Kashmir at a much lower elevation than the source of the Indus and it falls much less rapidly than the Indus after entering Pakistani territory. Snowmelt accounts for some of the flow in the Jhelum but it is much more dependent than the Indus on variable monsoon runoff. As a result, flows in the Jhelum are less concentrated—only about $14.76 \times 10^9 m^3$ (12 MAF) or 53 percent of the total mean flow occurring in the four peak months—but they are more variable from year to year. Annual recorded flows at Mangla range between 65 percent and 135 percent of the mean flow of $28.29 \times 10^9 m^3$ (23 MAF).

The Indus River falls rapidly between the place where it crosses the cease-fire line from the Indian-held Kashmir and Chashma (see Figure 2.1) where it debouches into the plains—nearly 2700 meters (8000 ft.) in 966 Km. (600 miles). Three-quarters of this drop is concentrated in the so-called Indus Gorge, about 483 Km. (300 miles) long, between Skardu and Attock at the confluence of Indus and Kabul rivers (see Figure 2.1). On the other hand, in the 1450 Km. (900 miles) over which the river flows between Chashma and the Arabian Sea, the river drops only about 167 meters (500 ft.) in total. The Jhelum falls about 333 meters (1000 ft.) in 160 Km. (100 miles) before it is joined by the Kunhar River (see Figure 2.1). Between the confluence of the Kunhar and Mangla it drops a further 333 meters (1000 ft.) in slightly more than 160 Km. (100 miles) to an elevation of about 333 meters (1000 ft.) above mean sea level at Mangla.

Besides the distinctions between the Indus and the Jhelum drawn above, there are a number of other differences between the two rivers which are significant from the point of view of power generation. There is an important difference in time when flows start to rise to a summer flood peak and in the length of time that flood flows endure. The hydrographs of both rivers (see Figure 2.2) show a rising stage in the early spring entirely due to snowmelt, the Jhelum being the first to respond at end of January and continuing to rise to its highest level in May, June and July. The Indus, on the other hand, starts to rise later at the end of February and reaches its highest snowmelt peak at the end of June; the Indus continues to rise to a higher glacial melt and monsoon peak early in August.

The Jhelum enters a falling stage at the beginning of August and Indus towards the end of the month; this generally continues, with the exception of rare monsoon rain floods in September, to the end of the year. The winter base-flow discharge on both rivers is largely maintained by bank storage water contained in the valley alluvium and this regeneration makes an important contribution to the available water supplies in the Rabi season (October to March).

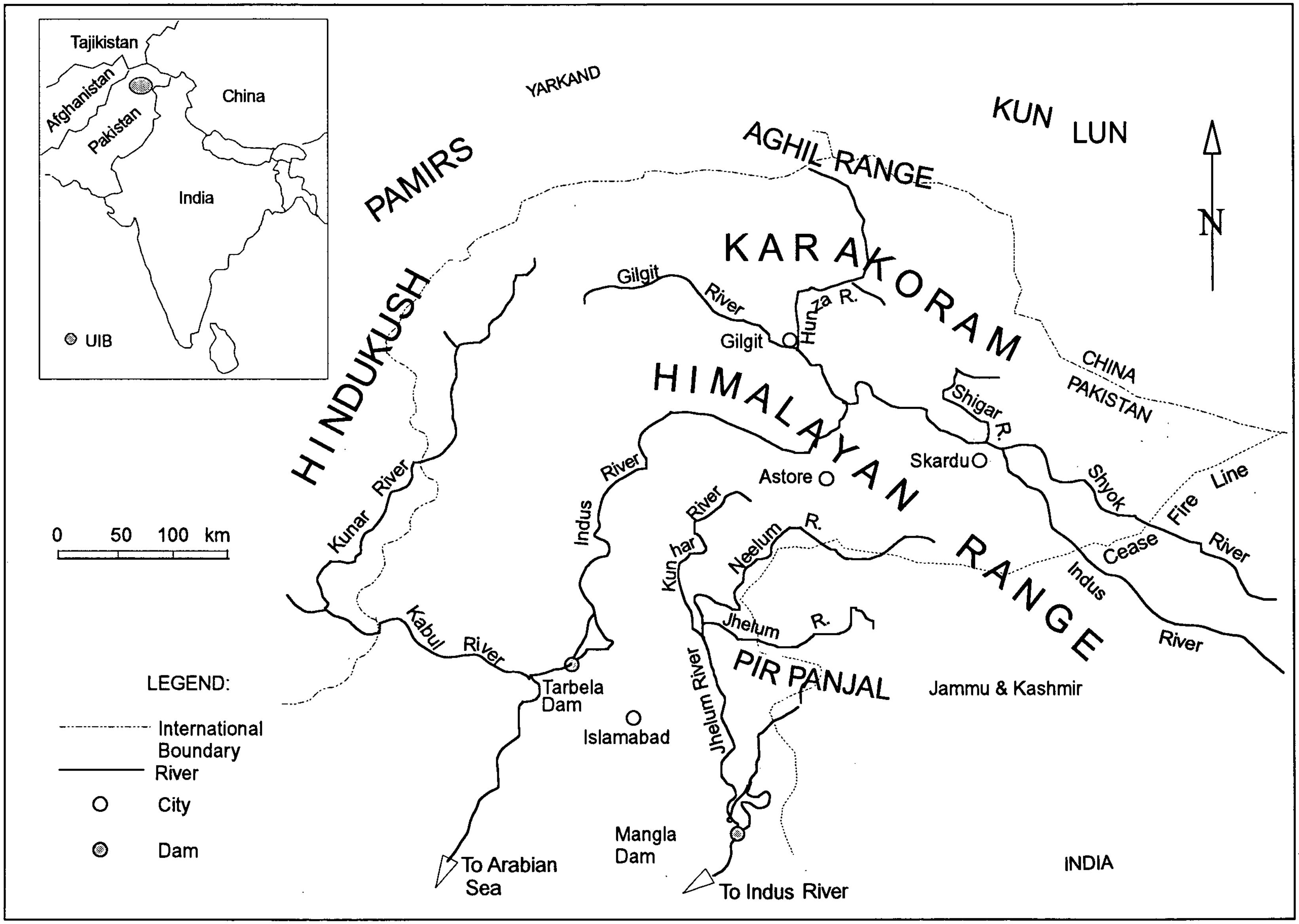

Figure 2.1. Geographical Map of the Karakoram-Himalayan Ranges and The Upper Indus Basin

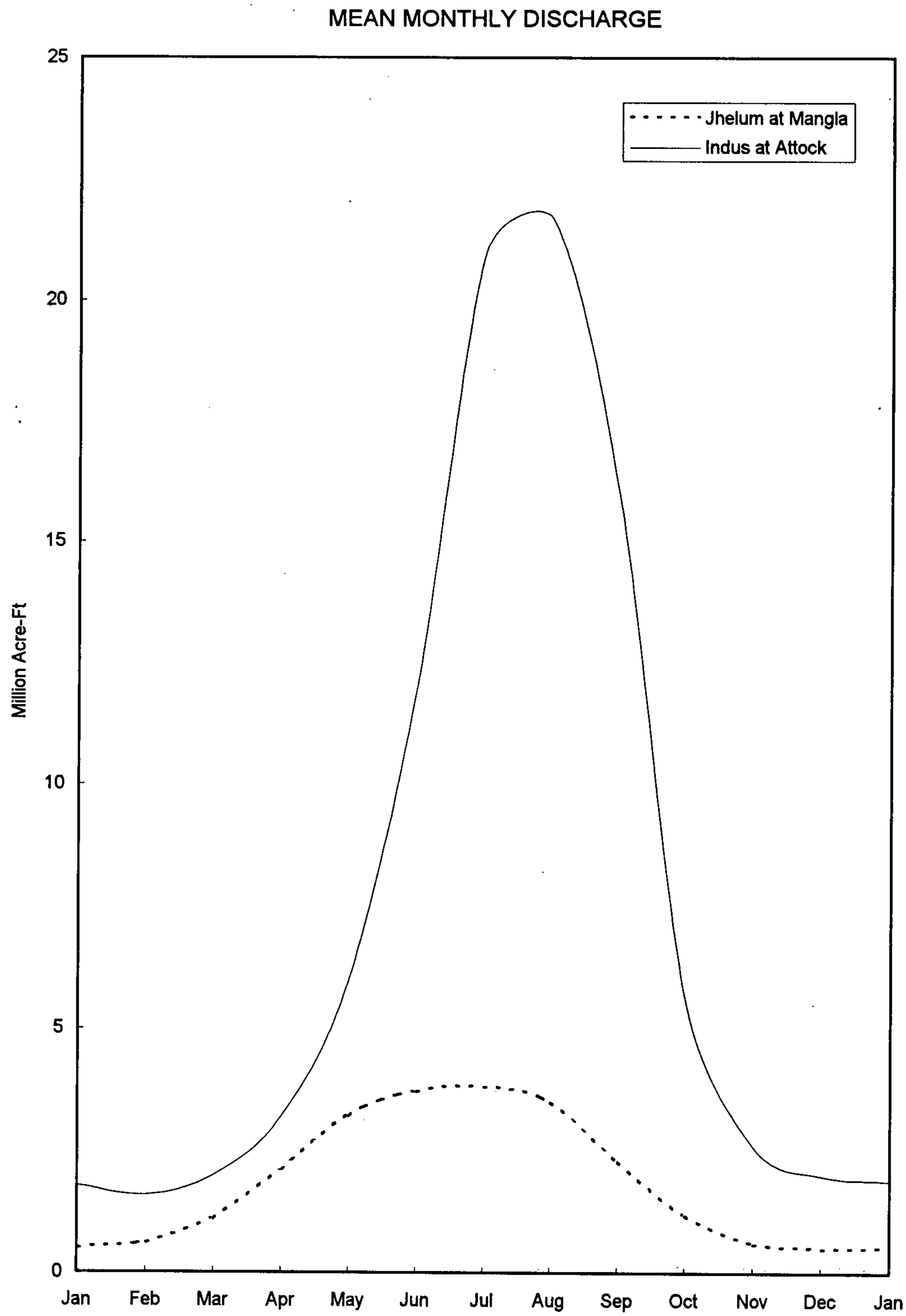

Figure 2.2. Mean Monthly Discharge: Indus, Jhelum

2.2 WATER ALLOCATION PROCEDURES

The procedures for allocation of water involve the following steps on a ten day interval basis:

(1) <u>Estimation of Irrigation Demands</u>

Irrigation demands are determined first at the district level for the following ten day period. These demands are a function of the type of crop, the stage of crop growth and precipitation and temperatures immediately preceding the period under consideration. The demands of the districts (called indents) are then aggregated into divisional and provincial demands for negotiation with other provinces.

(2) <u>Estimation of Inflows and Available Storage</u>

Inflows to the Mangla and Tarbela reservoirs and the Kabul River at its confluence with the Indus River are determined by WAPDA (Water And Power Development Authority) using statistical hydrologic methods. Seasonal inflow estimates are based on historical averages and correlations with the inflows of the previous season. These estimates are then used to produce rule curves for seasonal reservoir operation. Short term inflows (10-day) are based on correlations with measured flows during the immediately preceding period combined with some knowledge of the temperatures in the UIB (Upper Indus Basin). Potential surpluses or shortfalls of water during the season are determined by comparing inflows and comparing available storage with the rule curves. These estimates do not include any consideration of the effects of snow cover depletion and glacial melt.

(3) Determination of any other Operational Demands or Limitations on the System

It is also necessary to be aware of any additional demands, such as from the energy sector. Because Pakistan is short of energy, this sector, represented by the Power Wing of WAPDA, looks for potential surplus flows that can be used to generate additional energy. There are also potential operating problems that must be considered such as outages at Mangla or Tarbela dams. Such outages may mean that it would be more desirable to defer high releases until unit repairs are completed, rather than make releases through the irrigation discharge facilities. Any such temporary constraints must be established prior to negotiating the next 10-day releases. Regardless of the potential operating problems, priority is given to irrigation demands subject to water availability, even if releases must be made through the irrigation release facilities at the expense of generation.

(4) Negotiation

Negotiations to determine storage releases must consider each of the above inputs as well as the percentage of the seasonal allocation (Rabi or Kharif) each province should receive. The percentage seasonal allocations for each province are not followed for each 10-day allocation because of the variation in the crops grown in various provinces. For example, in Punjab the major crops are wheat and rice, whereas in Sindh cotton, rice and sugar-cane are the major crops. Also the growing season starts earlier in Sindh province. These cause variations in the timing of peak irrigation demands which must be factored into short term allocations while still maintaining the agreed seasonal percentage allotments. An additional complicating factor is that some irrigation releases must be made past Chashma Barrage to satisfy downstream irrigation demands in Sindh province. When it appears that there is insufficient inflow and/or storage in the reservoirs to meet all the demands from the provinces and competing sectors, then the provinces and WAPDA try to negotiate the releases that provide the maximum benefit to all. The critical periods are typically in the early Kharif season (April-May) when irrigation demands are high, the reservoirs nearly empty, and the spring melt has yet to commence. The final authority on allocations rests with the Indus River System Authority (IRSA).

2.3 FLOOD CONTROL

Flood control does not enter into the present allocation procedure. It is a byproduct of the storage and control of water for irrigation and power. During flood periods, the emphasis is on flood warning rather than potential flood reduction. There is no prespill or reservoir drawdown in anticipation of major floods. Both Mangla and Tarbela reservoirs contribute to flood control when inflow exceeds downstream releases. Since the two major reservoirs went into service in 1965 and 1974, respectively, there has been only one major flood in the Jhelum River in September 1992 causing colossal damage to life and property downstream of Mangla Reservoir. Other than the flood of September 1992, major flooding has been on the uncontrolled Ravi, Chenab, and Sutlej rivers and has occurred six times in the last 40 years, usually in September.

2.4 IRRIGATION SYSTEM

The irrigation system of Pakistan is one of the largest integrated irrigation networks in the world (Figure 1.3), serving 41.5 million acres of contiguous land. The system draws an average of $130.38 \times 10^9 m^3$ (106 MAF) of surface water each year for irrigation supplemented by an annual groundwater pumpage of some $52.89 \times 10^9 m^3$ (43 MAF). As mentioned earlier in Chapter 1, Pakistan has two annual crops, Kharif (April-September) and Rabi (October-March). The river flows during Kharif are five to six times greater than those in the Rabi season based on the flow records from 1937 to 1991. During the Rabi season, almost all releases from reservoirs and inflows to the Indus are consumed. During almost all the Rabi season, and particularly the latter portion, as well as the early part of Kharif season, farmers rely on reservoir storage for their irrigation needs. Supplementing the gravity fed irrigation system are an increasing number of tube wells. The water supply to the aquifer is made up of lost water from the canals, deep percolation from irrigated fields, plus surface water from seasonal (monsoon) rains.

The entire irrigation system can be divided into four regions (see Figure 2.3) which are as follows:

1. Upper Jhelum - This is the region in the Jhelum, Chenab, Ravi and Sutlej River valleys above the C-J Link Canal that cannot be supplied with irrigation water from the Indus.
2. Lower Jhelum - This is the region in the Jhelum, Chenab, Ravi and Sutlej River valleys below the C-J Link Canal that can be supplied with irrigation water from the Indus.

3. Upper Indus - This is the region along both banks of the Indus River between Tarbela and the confluence of Jhelum and Indus Rivers near Mithankot (Guddu Barrage).
4. Lower Indus - This is the region downstream of the Jhelum and Indus River confluence along both sides of the Indus River to the Arabian Sea.

2.5 ENERGY SECTOR

As irrigation demand has the first priority on water from Tarbela and Mangla reservoirs, the production of energy at these plants occurs, either as a byproduct of irrigation releases or when there is water available that is surplus to irrigation needs. At present there is no strategy or policy that attempts to optimise total benefits from water allocation meeting the demands from power and irrigation sectors. The power sector can only try and optimise the use of any water available beyond the apportionment to the agriculture sector.

2.6 IRRIGATION/POWER CONFLICTS IN WATER ALLOCATION

As mentioned earlier, for the allocation of water from both Mangla and Tarbela reservoirs, the first priority is given to meeting irrigation demands. Even during periods when irrigation allotments are low, conflicts with the irrigation sector may still arise from two sources:

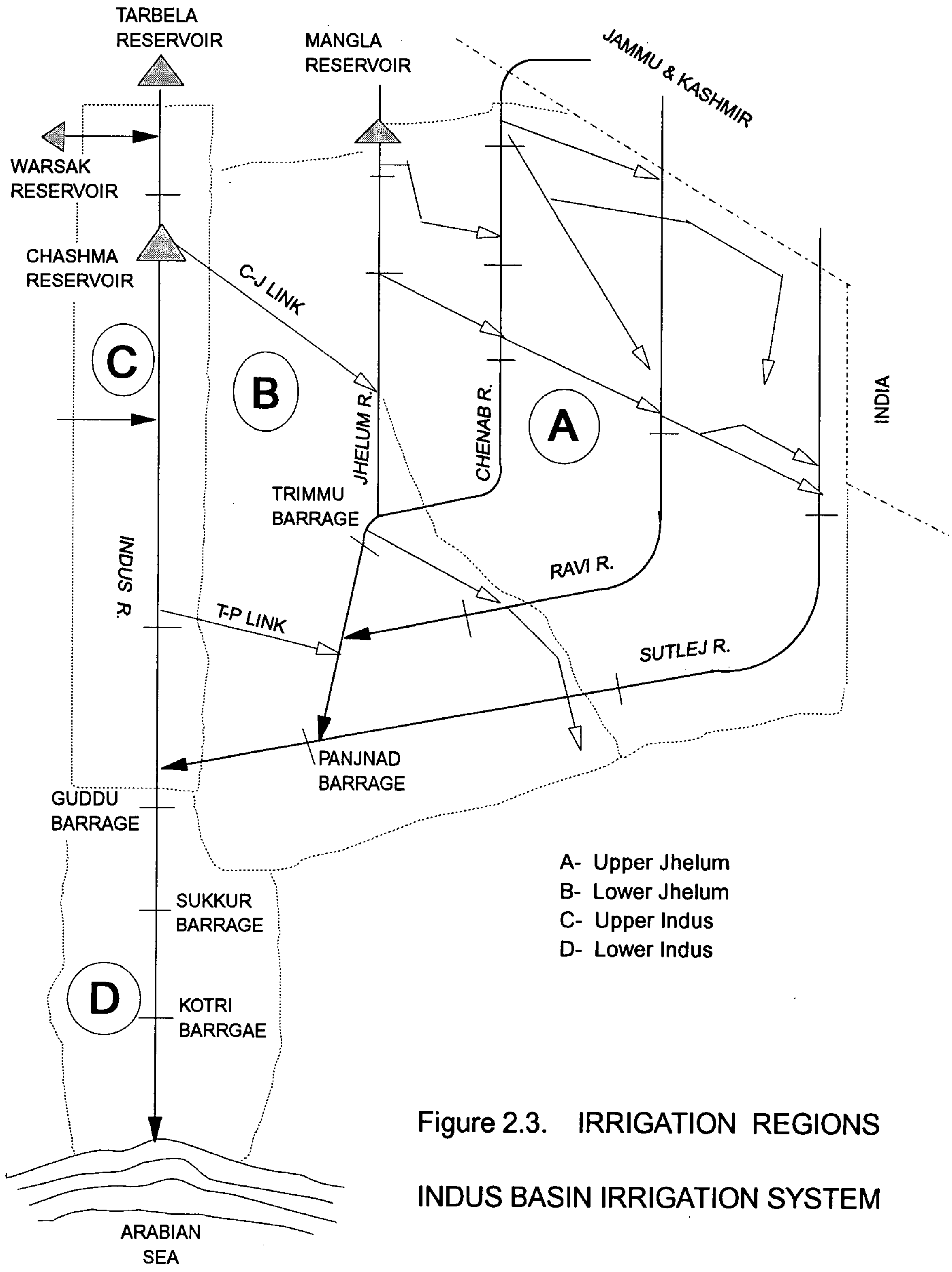

Figure 2.3. IRRIGATION REGIONS

INDUS BASIN IRRIGATION SYSTEM

I. The industrial sector of the economy may be faced with power cutbacks as the capacity of the thermal system is insufficient to meet the power demand of the country.

II. A source of conflict arises within the agricultural sector itself. There are an increasing number of tube wells used to pump water from the aquifer. These tube wells, in turn, require an increasing proportion of the total electrical energy demand. This demand, sometimes, is at its peak when releases from the reservoirs, and hence, hydro power generation, are low.

2.7 FUTURE CHANGES IN ALLOCATION

In the immediate future, there are not likely to be any changes in the priorities for the allocation of water. Pressures from the industrial sector of the economy may, however, lead to requirements for more refined techniques for the estimation and allocation of future flows to ensure that there is minimal wastage of water and maximum energy production under the existing allocation rules. Furthermore, pressures from the industrial sector of the economy may come when projects either proposed or presently under development (Figure 1.2) such as Ghazi-Barotha (1425 MW), Chashma (200 MW), Kalabagh Barrage (200 MW), Taunsa Barrage (200 MW), and Kalabagh Dam (3600 MW) are constructed downstream of Tarbela. As a significant percentage of the flow requirement of these plants would be from Tarbela, any cutback in Tarbela outflows, and hence, energy production would be magnified when compared to the existing conditions. Likewise, the consequences for the industrial sector would be magnified.

When the combination of the economic loss to the industrial sector, plus the people adversely affected by energy cutbacks in this sector, exceeds the economic benefits to the agricultural sector, and the number people benefiting, then the water allocation rules may be modified to give some priority to energy production.

RESERVOIR MANAGEMENT AND DYNAMIC PROGRAMMING

3.1 METHODS OF ANALYSIS

During the last 30 years, one of the most important advances made in the field of water resources engineering is the development and adoption of optimisation techniques for planning, design, and management of complex water resources systems. The analysis of a complex water resources system may involve thousands of decision variables and constraints. Once the objectives and constraints have been determined, most problems lend themselves to solution techniques developed in the field of operations research and management sciences.

Many successful applications of optimisation techniques have been made in reservoir studies, mostly for planning purposes. Extensive literature review of the subject of optimisation of reservoir operations reveals that no general algorithm exists (Yeh, 1985). The choice of methods depends on the characteristics of the reservoir system being considered, on the availability of data, and on the objectives and constraints specified. In general, the available methods can be classified as follows.

1. Linear programming (LP), including chance-constrained LP, stochastic LP, and stochastic programming with recourse.

2. Dynamic programming (DP), including incremental DP (IDP), discrete differential DP (DDDP), incremental DP and successive approximations (IDPSA), stochastic DP, reliability-constrained DP, differential DP (DDP), and the progressive optimality algorithm.
3. Nonlinear programming (NLP).
4. Simulation.

The rest of this chapter deals with the principles of dynamic programming (DP) and application of DP techniques to reservoir management and operations.

3.2 DYNAMIC PROGRAMMING

Dynamic programming, a method formulated largely by R. E. Bellman [1957], is a procedure for optimising a multistage decision process. DP is used extensively in the optimisation of water resource systems and reservoir operation in particular. The popularity and success of this technique can be attributed to the fact that the nonlinear and stochastic features which characterise a large number of water resource systems can be translated into a DP formulation. In addition, it has the advantage of effectively decomposing highly complex optimisation problems with a large number of variables into a series of single subproblems which are solved recursively (Yeh, 1985).

Dynamic programming is based on the "Principle of Optimality" which, according to Bellman, can be stated as:

" An optimal policy has the property that whatever the initial state and initial decision are, the remaining decisions must constitute an optimal policy with regard to the state resulting from the first decision." This principle can be conceptually thought of as follows: Given an optimal trajectory from point A to point C, the portion of the trajectory from any intermediate point B to point C must be the optimal trajectory from B to C (Larson and Casti, 1977).

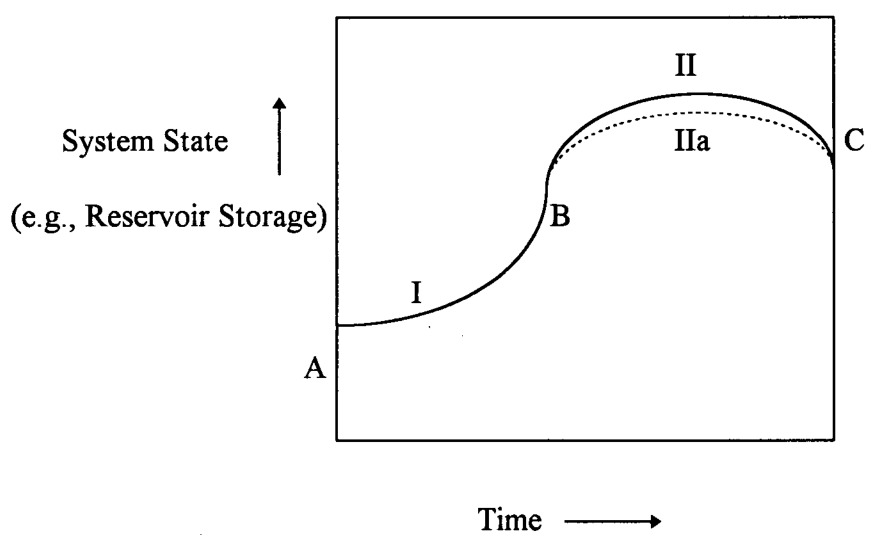

Figure 3.1. Illustration of the Principle of Optimality

In Figure 3.1, if the path I-II is the optimal path from A to C, then according to the principle of optimality path II is the optimal path from B to C. The proof by contradiction for this case is immediate: Assume that some other path, such as IIa, is the optimum path from B to C. Then, path I-IIa has less cost than path I-II. However, this contradicts the fact that I-II is the optimal path from A to C, and hence II must be the optimal path from B to C.

3.3 DP TERMINOLOGY

The dynamic programming terminology is as follows (Caselton, 1995).

Objective

To *Maximise* the sum of benefits or *Minimise* the sum of costs resulting from a decision sequence.

Stages

Each stage is related to a decision in the sequence. Within each stage the full range of circumstances prior to making that decision and the full range of consequences are described. If there are **N** decisions in the sequence then there will be **N** stages and **n** is used to denote a particular stage.

State

A state defines a specific circumstances prior to making a decision and a specific new circumstance as a result of enacting a decision. The total number of discrete state values possible at a stage prior to making a decision is represented by **S** and **s** denotes a particular state or state value.

Decisions

A possible individual decision choice at a stage n and state s is represented by $\mathbf{d_n^s}$. The range or set of decision choices may differ at different stages and states. At a particular stage n and state s the set of decision choices is represented by $\mathbf{D_n^s}$.

Stage Return Function

This specifies how the benefits, costs, etc. are to be calculated. It must depend on the current stage n, state s, and the decision d_n^s. It is represented by $g(d_n^s, s, n)$. There are no other restrictions on this function except that it be evaluatable and single valued.

State Transformation Function

This determines the new state which will result if a particular decision is made at a given stage and state. It must depend only on the stage n, state s, and decision d_n^s so it represented by $t(d_n^s, s, n)$. To simplify the formulation the new state, or state following, is often denoted by s′ so that:

$$s' = t(d_n^s, s, n)$$

Again there are no other restrictions on this function other than it be evaluatable and single valued.

Recursive Equation

This is the equation that provides the recipe to follow each time the Optimal Cumulative Return f(n, s) for any stage n and state s is calculated. This is the result obtained when finding the optimal decision at each and every stage n and state s position in the problem. The recursion equation prescribes $F_n(s)$:

$$F_n(s) = \underset{D_n^s}{\boldsymbol{Max}} \left[g(d_n^s, s, n) + F_{n+1}(t(d_n^s, s, n))\right]$$

If the sum of returns is being minimised then *Max* would be replaced be *Min*.

When there is no special reason for choosing either backward or forward formulation, the backward recurrence is normally used. The procedure of making first a backward and then a forward pass is convenient, especially in problems involving time (such as reservoir operation), as the impact of a decision is assumed as it unfolds naturally with time. In either case, there must be a starting or ending point that does not depend on other stages in order to be able to define the first of the recursive equations (Loucks, 1981). There are other options to deal with the starting/ending point condition. However, in this research the approach as suggested by Loucks has been adopted.

3.4 MULTIPLE-STATE DP

The above formulation implies the existence of just one state variable. Multiple-State DP involves two or more state variables. The introduction of more than one state variable in DP permits the solution of more complicated, but realistic problems. Although the addition of more state variables causes no conceptual difficulties, it does increase the required computational effort. The larger the number of state variables, the more combinations of discrete states that must be examined at each stage. If done on a computer, this added dimensionality requires more computer time and storage capacity. Increasing the number of state variables causes the computational requirements to grow rapidly because of the exponential increase in the total number of discrete state values that have to be considered as the number of state variables increases. This phenomenon is termed as the *Curse of Dimensionality* of multiple-state-variable dynamic programming.

Consider, for example, the annual operation of a single reservoir system on a monthly basis. Let the number of discrete values considered for the state variables, reservoir levels in this case, be equal to 50. Let the number of decision variables i.e., the possible volumes of water to be released from the reservoir, be 10.

Number of stages, N = 12

Number of states, S = 50   Number of decisions variables, D = 10

Then the computational requirements for this single-state DP are:

$$12 \times 50 \times 10 = 6000$$

Now, if a second reservoir is added to the system and its reservoir level represented by a second state variable which is discretised in the same fashion as the first, and its discharge decision possibilities also number 10, then the computational requirements become:

$$12 \times 50 \times 50 \times 10 \times 10 = 3{,}000{,}000$$

The increase is clearly very substantial even in case of the two-state problem.

Therefore, for computational efficiency, DP problems should have no more than three state variables at a time. Beyond this, all methods of solution involve dimensionality reduction, decomposition into subsystems and the use of iterative procedures.

3.5 PROPERTIES OF DYNAMIC PROGRAMMING

The properties of dynamic programming computational procedure can be summed up as follows (Larson and Casti, 1977).

1. In the first place, it is not necessary to make any assumptions about the analytic properties of the stage return function and the state transformation function. These functions are not required to be linear, quadratic, differentiable, continuous or even expressible in terms of well-known functions. All that is required is the existence of a rule for determining values of these functions at quantised values of the state s, the decision d, and the stage n and a procedure for interpolating between quantised values. The procedure can thus accommodate highly nonlinear systems, as well as system equations that implement logical operations and/or experimentally tabulated phenomena.
2. A second desirable property of the dynamic programming procedure is the ease with which it handles constraints. The constraints present only minor difficulties in implementation, and actually serve a useful purpose by decreasing the number of alternative states and/or decisions that must be considered, thus reducing the computational effort.
3. A third desirable property of the procedure is that it is always determines an absolute maximum (or minimum), not a relative maximum (or minimum), or even worse, a stationary point. This property is a result of the fact that all quantised admissible states are considered at each stage and that for each state all quantised admissible decisions are considered. Obviously, the smaller the difference between each discrete value of each state

and decision variable, the greater will be the mathematical accuracy of the solution. Thus, within the accuracy of the quantisation, a true global optimum is always obtained.

4. Still another favourable property of the procedure is its inherent simplicity. The only calculations required are stepping forward with the state transformation equation, looking up and/or interpolating the stage return function from the next stage, and comparing scalar quantities. This simplicity not only makes computer implementation of the procedure quite straightforward, but it also allows workers of diverse technical background to thoroughly understand the method and to feel confident in its application.
5. The procedure also possesses another very important property. This property is related to the fact that solutions are obtained for an entire family of problems, and not just for a single problem. This occurs because optimum benefit/cost and optimum decision are obtained at every admissible quantised state and stage. The importance of this type of solution is that in the case of deviations from the original optimal trajectory as, for example, might occur if an uncontrolled input were applied to the system or if an incorrect decision was inadvertently implemented, a truly optimal decision can be found for the remaining stages.

3.6 DP FORMULATION FOR A SINGLE RESERVOIR

Figure 3.2 shows the various storage zones of a multipurpose reservoir. The *Flood Control Storage* is the uppermost storage zone in the reservoir. It is used primarily during high runoff periods so that the downstream channel capacity will not be exceeded. The

Conservation Storage is the zone where the reservoir will operate most of the time. It may be used to regulate minor floods as well as supply water for various purposes such as hydropower, irrigation, recreation, navigation, and so on. The *Inactive or Dead Storage* is the lowest zone of the reservoir. It is the storage which is used for maintenance of head for power or maintenance of reserve for sedimentation.

For a typical reservoir, there are certain requirements which must be satisfied at all times. First the storage level must not exceed the capacity of the reservoir. Second, the storage level must not be below the minimum allowable level. Third, the *Continuity Equation*

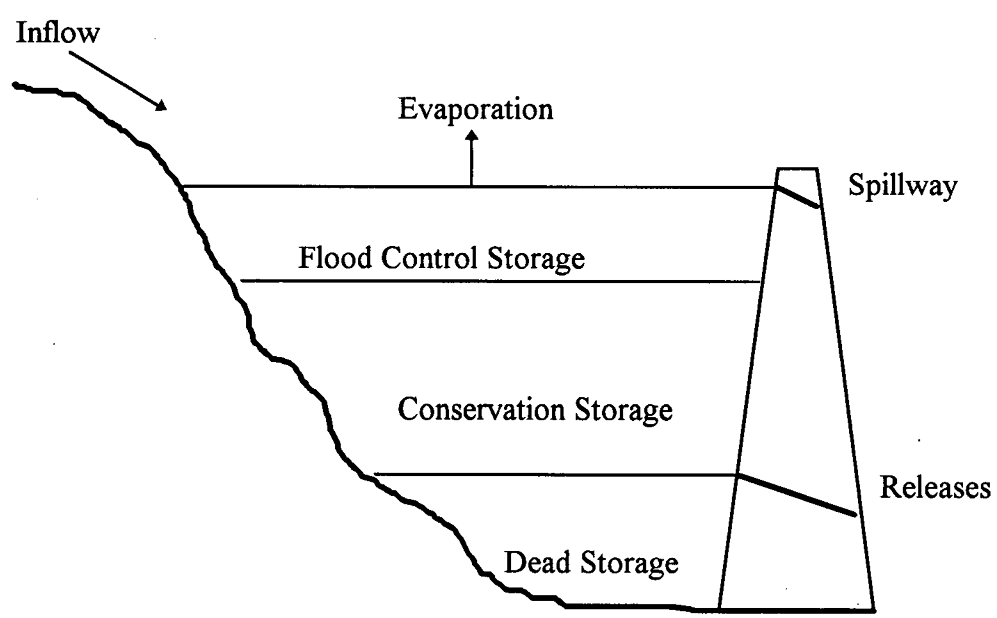

Figure 3.2. Reservoir Storage Zones

which links the storage level, the flows into and out of the reservoir, and the release from the reservoir, must hold during any time period. In addition other constraints such as relationships among various reservoirs in the systems, requirements from various purposes, and other physical characteristics of the system may also have to be included (Changchit, 1993).

Consider a simple example of DP optimisation of a hydroelectric project (Caselton, 1995). Here the objective is to maximise annual energy generation from quarterly (1 quarter = 3 months) operation of a single reservoir using deterministic inflows. For simplicity all inflow and discharge rates have been assumed constant during each quarter. The following information is given.

Natural Inflow Volumes into the Reservoir:

1st Quarter $I_1 = 2$ b.cu.ft. (Billion Cubic Feet)

2nd Quarter $I_2 = 4$ b.cu.ft.

3rd Quarter $I_3 = 0$ b.cu.ft.

4th Quarter $I_4 = 1$ b.cu.ft

Turbine Head vs Stored Volume Relationship:

	Stored Volume	Turbine Head
Full	3 b.cu.ft	30 ft.
3/4	2 b.cu.ft	20 ft.
1/2	1 b.cu.ft	10 ft.
Empty	0 b.cu.ft	0 ft.

Energy Generation:

Energy generated in one quarter = KHQ mkWh (Million kilo Watt hour) where,

K is a coefficient and is arbitrarily chosen here to equal 1/10.

H is average turbine head in ft. for the quarter.

Q is turbine discharge in b.cu.ft. for the quarter.

Operating Constraints:

1. Maximum volume which can be discharged through the turbines is 3 b.cu.ft./quarter.
2. If the volume of water stored in the reservoir exceeds 3 b.cu.ft. then surplus must be discharged down the spillway.
3. Downstream minimum flow must not fall below 1 b.cu.ft./quarter.

Solution by DP

This problem involves a sequence of four discharge decisions, one for each quarter year. Each stage represents a period for which a decision will apply. Thus, there are four stages i.e., N = 4, and the stage numbering will be n = 1 for Jan-Mar, n = 2 for Apr-Jun, n = 3 for Jul-Sep, and n = 4 for Oct-Dec. A state value will correspond with a volume of water in storage at the beginning of a stage. State 3 will represent a full reservoir with 3 b.cu.ft. in storage, state 2 will represent 2 b.cu.ft. in storage, etc.

The turbine discharges can range from zero to 3 b.cu.ft. per quarter. Considering discrete decision alternatives at 1 b.cu.ft. intervals provides four discrete decision options at any state. But the minimum downstream flow constraint reduces this to just three options of 1,2, and 3 b.cu.ft per quarter.

The state transformation function which specifies the state at the end of a stage, after discharging a specified volume commencing a particular quarter with a given stored volume, will be the stored volume at the end of a quarter. The state transformation function for this problem is thus a simple continuity equation:

$$s' = t(d_n^s, s, n) = s + I_n - d_n^s$$

The stage return function specifies the contribution to benefit (or cost) resulting from implementing a decision. This translates here to the electrical energy produced by a specified discharge volume commencing a given quarter with a given stored volume. The stage return function for this problem is based on the energy equation:

Energy generated in a quarter = KHQ

Here, d_n^s corresponds to Q. The average head H is obtained by averaging the turbine heads at the beginning and the end of the stage.

Head at the beginning of stage with state s	=	10 s
Head at the end of stage	=	10 s′
Average head	=	10 (s + s′)/2

Therefore, energy generated is given by

$$g(d_n^s, s, n) = Kd_n^s\, 10(s + s')/2 = d_n^s(s + s')/2$$

Note that substituting the state transformation function for s′ yields:

$$g(d_n^s, s, n) = (2\, s\, d_n^s + In\, d_n^s - (d_n^s)^2)/2$$

And that this expression is not linear in the decision d_n^s.

Finally, the recursive equation can be written as:

$$F_n(s) = \underset{0,1,2,3}{\mathbf{\mathit{Max}}} \; [\, d_n^s(s + s')/2 + F_{n+1}(s')\,]$$

Figure 3.3 (Loucks, 1981), illustrates a typical multistage decision making process in case of a reservoir operation problem.

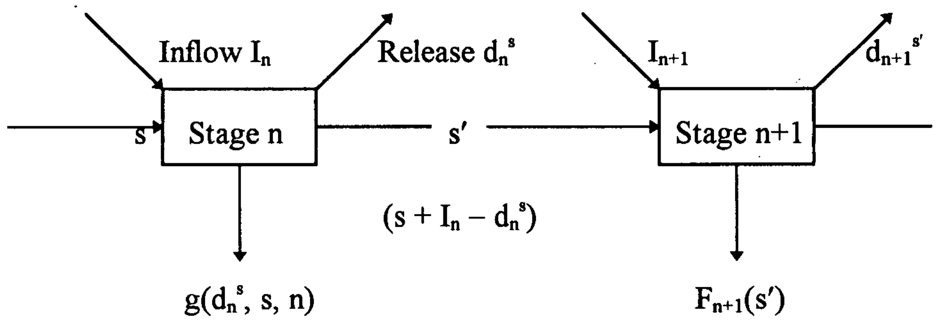

Figure 3.3. Sequential reservoir operation process

The optimisation results of the computer run of this DP example are shown in Figure 3.4. In the figure, d_n^s denotes the optimal discharge for a prescribed stage n and state s. It can be clearly seen that maximum benefits, 20.5 units (mkWh) of energy generation in this case, will be obtained if operation commences with the reservoir full at the beginning of the first quarter. The *Optimal Trajectory,* for the case when reservoir is full at the beginning of the first quarter, is shown by the shaded cells. The energy generated during the first, second, third, and fourth quarters being equal to 6.0, 9.0, 2.5, and 3.0 mkWh, respectively. Optimal operation at other initial storage levels can be traced out from Figure 3.4. For example, begining the year at state 1 i.e., reservoir storage is at one third of the maximum capacity, the total energy generation will be 14.5 mkWh with 1.5, 7.5, 2.5, and 3.0 mkWh of energy generated during the first, second, third, and fourth quarters respectively.

STATE		STAGES 1	2	3	4
3	$F_n(s)$	20.5	14.5	5.5	6.0
Full	d_n^s	2	3	1	3
	s'	3	3	2	1
2	$F_n(s)$	17.0	13.0	2.5	3.0
	d_n^s	1	3	1	2
	s'	3	3	1	1
1	$F_n(s)$	14.5	9.5	0.5	1.0
	d_n^s	1	2	1	1
	s'	2	3	0	1
0	$F_n(s)$	10.0	7.0	-9999	0.0
Empty	d_n^s	1	1	1	1
	s'	1	3	0	0

Figure 3.4. Optimisation results of computer run of the DP formulation

Some times in DP computations a particular state s' will not lie on one of the quantised states at which the $F_{n+1}(s')$ is defined. In fact, it may lie outside of the range of the admissible states. In the latter case the decision is rejected as a candidate for the optimal decision for this state and stage (Larson and Casti, 1977). For example, in Figure 3.4 the computer model has assigned a value of -9999 to the $F_n(s)$ to the state 0 at stage 3. This means that s' falls outside the range of admissible states (0,1,2,3) when the state transformation function is evaluated for each of the decision variables (1,2, and 3), thus making the state 0 at stage 3, an infeasible state.

If a particular next state s′ does fall within the range of allowable states, but not on a quantised value, then it is necessary to use some type of interpolation procedure to compute the benefits at these points. In this research linear interpolation procedure has been adopted to compute the benefits under such circumstances. The justification of the interpolation procedure adopted is that $F_n(s)$, as an accumulated benefit over many stages, is for any value of n, assumed to be a "well behaved" monotone increasing function of state s (Caselton, 1995). This assumption was supported by the numerical results obtained (chapters 4 & 5).

INDEPENDENT RESERVOIR OPERATION

4.1 GENERAL

For optimising the operation of Mangla and Tarbela reservoirs two separate computer models were developed using the Visual Basic language. These models, namely PR1 and PR2 for Tarbela and Mangla reservoirs respectively, were run to maximise the five-year energy generation at Mangla and Tarbela. The irrigation requirements were treated as constraints. With these separate computer models both reservoirs were assumed to be acting independently of each other. Historic data for a period of five years (1985-86 to 1989-90) has been used in this research. The actual recorded reservoir levels on August 1, 1985; 1170.82 El. for Mangla and 1515.55 El. for Tarbela, were adopted as the initial reservoir levels. Both reservoirs were operated on a 10-day time step.

Energy output was simulated on the basis that the total reservoir outflow, up to the full discharge capacity of all turbine units at the available head, was passed through the turbines. Head on the turbine is calculated by averaging the current and previous end-of-10-day reservoir level and subtracting a fixed tail water level. Reservoir water level calculations are based on WAPDA Curve #2 (Stage-Volume Data) for Mangla and WAPDA Curve #8 for

Tarbela (Appendix I). For simplicity, evaporation losses have been neglected and an overall constant turbine/generator efficiency of 85 % has been assumed.

4.2 IRRIGATION DEMANDS

Irrigation demands, in case of both PR1 and PR2 models, have been treated as constraints. Figure 4.1 shows the schematic diagram of the Mangla and Tarbela reservoir system. The maximum energy generation capacities of the two power plants and the four irrigation regions served by the two reservoirs are also shown in the figure. As can be seen in Figure 4.1, Mangla reservoir supplies water to the Upper and Lower Jhelum regions. The Lower Indus region also receives irrigation water from Mangla reservoir that is in excess of the demands of the upper and Lower Jhelum regions. Tarbela reservoir supplies water to the Upper and Lower Indus regions and also to the Lower Jhelum region through the link canals.

In the case of the Single Reservoir Operation DP Models, PR1 and PR2, each of Mangla and Tarbela reservoirs is required to meet a certain percentage of the *Net Irrigation Demand* (NID). The NID is the sum of the irrigation demands of all the four regions that can be met only by discharge outflows from Mangla and Tarbela reservoirs. The NID has been calculated as the difference between the sum of the irrigation demands, determined by the provincial irrigation districts for each irrigation region, and the sum of available flows in the Kabul, Chenab, Ravi, and Sutlej rivers for each 10-day period. Table 4.1 shows the relative percentages of the NID which Mangla and Tarbela are required to meet without violating the constraints on their respective maximum and minimum conservation levels. These proportions are based on the following.

1. Tarbela has almost twice the live storage capacity as Mangla (9.986 MAF Vs 5.365 MAF).
2. The Jhelum River starts to rise at the end of January and continues to rise to its highest level in May, June, and July. It enters a falling stage at the beginning of August with the exception of rare monsoon rain floods in September.
3. The Indus River starts to rise later at the end of February and reaches its highest snowmelt peak in June and continues to rise to a higher glacial melt and monsoon peak early in August. It enters a falling stage towards the end of August.

Table 4.1. Proportions of NID shared by Mangla & Tarbela reservoirs.

	Month	Tarbela	Mangla
1	Jan	50 %	50 %
2	Feb	50 %	50 %
3	Mar	50 %	50 %
4	Apr	60 %	40 %
5	May	70 %	30 %
6	Jun	70 %	30 %
7	Jul	80 %	20 %
8	Aug	80 %	20 %
9	Sep	80 %	20 %
10	Oct	70 %	30 %
11	Nov	70 %	30 %
12	Dec	60 %	40 %

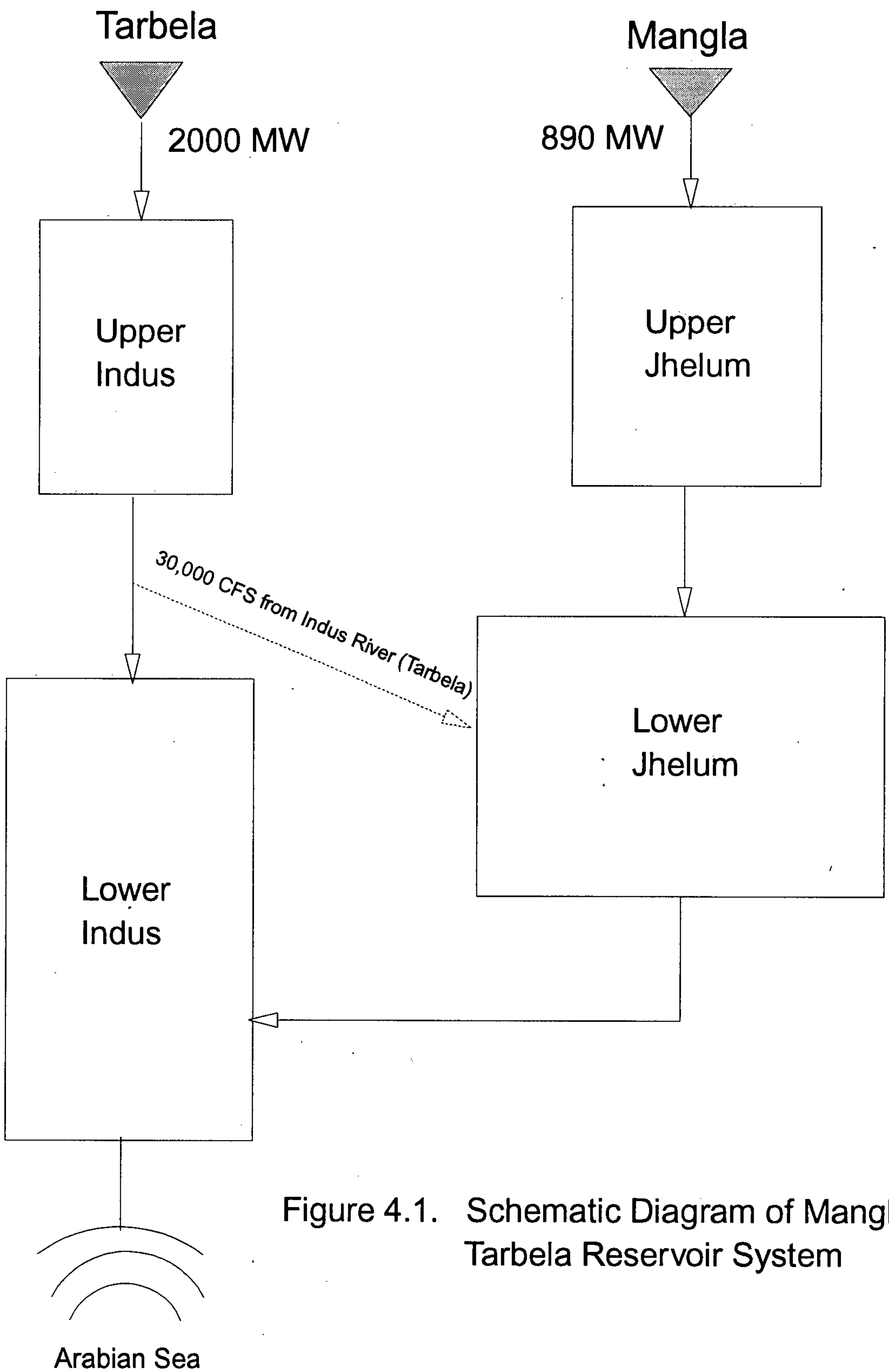

Figure 4.1. Schematic Diagram of Mangla-Tarbela Reservoir System

4. Irrigation demands are high for Lower Jhelum and Lower Indus regions from May to October (early Kharif season). Therefore, Tarbela has a major role to play in these months.
5. On the other hand irrigation demands are at their peak from December to March (Rabi season) for Upper Jhelum region which gets its irrigation water supplies from Mangla reservoir only. Also the main function of Mangla reservoir is to replace the Rabi irrigation supplies which had been available to Pakistan (Lower Jhelum region) but which were allocated to India under the 1960 Indus Waters Treaty.

4.3 MANGLA RESERVOIR

The limits on reservoir water levels for Mangla reservoir are as follows:

Maximum W.L. El. 1202 ft.

Minimum W.L. El. 1062 ft.

The maximum power output from the eight turbine/generator units is 890 MW. A constant tail water level at El. 842 ft. was assumed. The following equations (Parmley, 1991) were used to calculate plant output:

1. $$P_{max} = C1\,(H) - C2 = 4.32\,\left(\frac{S1+S2}{2} - TWL\right) - 461.2 \qquad \text{(MW)}$$

where C1 and C2 are constants

H is head in feet

S1 is reservoir level at start of period (Stage n) in feet

S2 is reservoir level at end of period (Stage n) in feet

TWL is tail water level = El. 842 ft.

If $P_{max} > 890$, then $P_{max} = 890$

2. $$P = \left(\frac{S1+S2}{2} - TWL\right)(Q)(\eta) / 11.8 \qquad \text{(MW)}$$

where 11.8 is factor to convert to MW

Q is reservoir outflow (decision d_n^s) in 1000 CFS

η is plant efficiency (85 %)

If $P > P_{max}$, then $P = P_{max}$

3. $$E = 0.024\,(P)\,(N) \qquad \text{(Million kWh)}$$

where E is the plant output in mkWh

N is the number of days in the period (Stage n)

0.024 is factor to convert to mkWh

The equation of continuity for Mangla reservoir is as follows:

$$V2 = V1 + (I - Q)\,(N)\,1.9835 / 1000 \qquad \text{(Million Acre-Feet)}$$

where V1 is reservoir volume at start of period (Stage n) in MAF

V2 is reservoir volume at end of period (Stage n) in MAF

I is reservoir inflow in 1000 CFS

Q is reservoir outflow (Decision d_n^s) in 1000 CFS

N is number of days in the period (Stage n)

1.9835 is factor to convert to 1000 acre-feet

1000 is factor to convert to MAF

The number of stages is 180 for five-year operation on a 10-day basis. The number of states for Mangla was set to be 15 i.e., 1062 to 1202 at an increment of 10 Ft., and the decision variable (Release from the reservoir) was quantised in uniform increments of 5, so that the set of admissible decisions was:

[5, 10,15,20,25,30,35,40,45,50] , all values in 1000 CFS units.

Thus the number of computations involved in the DP optimisation of five-year operation of Mangla reservoir on a 10-day basis is 27,000. The time of run for the five-year period was about 114 seconds (1.9 min.) on a PC (486-33MHz). Appendix II contains the main module of the Mangla reservoir operation model PR1.

4.4 TARBELA RESERVOIR

The limits on reservoir water levels for Tarbela reservoir are as follows:

Maximum W.L. El. 1550 ft.

Minimum W.L. El. 1310 ft.

The maximum power output from the eight turbine/generator units is 2000 MW. A constant tail water level at El. 1120 ft. was assumed. The following equations (Parmley, 1991) were used to calculate plant output:

1. $$P_{max} = C1\,(H) - C2 = 6.34\,(\frac{S1+S2}{2} - TWL) - 644.5 \qquad (MW)$$

where C1 and C2 are constants

H is head in feet

S1 is reservoir level at start of period (Stage n) in feet

S2 is reservoir level at end of period (Stage n) in feet

TWL is tail water level = El. 1120 ft.

If $P_{max} > 2000$, then $P_{max} = 2000$

2. $$P = (\frac{S1+S2}{2} - TWL)\,(Q)\,(\eta) / 11.8 \qquad \text{(MW)}$$

where 11.8 is factor to convert to MW

Q is reservoir outflow (decision d_n^s) in 1000 CFS

η is plant efficiency (85 %)

If $P > P_{max}$, then $P = P_{max}$

3. $$E = 0.024\,(P)\,(N) \qquad \text{(Million kWh)}$$

where E is the plant output in mkWh

N is the number of days in the period (Stage n)

0.024 is factor to convert to mkWh

The equation of continuity for Tarbela reservoir is as follows:

$$V2 = V1 + (I - Q)\,(N)\,1.9835 / 1000 \qquad \text{(Million Acre-Feet)}$$

where V1 is reservoir volume at start of period (Stage n) in MAF

V2 is reservoir volume at end of period (Stage n) in MAF

I is reservoir inflow in 1000 CFS

Q is reservoir outflow (Decision d_n^s) in 1000 CFS

N is number of days in the period (Stage n)

1.9835 is factor to convert to 1000 Acre-Feet

1000 is factor to convert to MAF

The number of stages is 180 for five-year operation on a 10-day basis. The number of states for Tarbela was set to be 25 i.e., 1310 to 1550 at an increment of 10 Ft., and the decision variable (Release from the reservoir) was quantised in uniform increments of 10, so that the set of admissible decisions was:

[10,20,30,40,50,60,70,80,90,100,110,120,130,140] , all values in 1000 CFS units.

Thus the number of computations involved in the DP optimisation of five-year operation of Tarbela reservoir on a 10-day basis is 63,000. The time of run for the five-year period was about 114 seconds (1.9 min.) on a PC (486-33MHz). Appendix III contains the main module of the Tarbela reservoir operation model PR2.

4.5 OPTIMISATION RESULTS FOR MANGLA & TARBELA

OUTFLOWS: Optimisation results of the computer run of the DP Model for Mangla reservoir do not suggest any drastic changes in the operational strategy from the actual operation of the reservoir during 1985-90. However, the DP model shows lower discharges than actual in the months of October and November in case of Mangla reservoir. The reason being low inflows and low irrigation demands. Figure 4.2 shows the total outflows (through power tunnels and/or spillways) from Mangla reservoir during 1988-89. The corresponding inflows to the reservoir are also shown.

Figure 4.3 shows the total outflows from Tarbela reservoir during 1988-89 and the corresponding inflows to the reservoir. The calculated outflows, in case of Tarbela, are lower than the actual outflows during the months of October through January which is the low inflow season for Tarbela reservoir. However, the irrigation demands seem to have been met as indicated in Figure 4.4. But still these figures do not give a clear picture of the actual supply and demand situation between the two reservoirs and the four irrigation regions unless both reservoir are operated in conjunction with each other for meeting the irrigation demands. Figure 4.5 shows the net irrigation demands; demands that can only be met by releases from Mangla and Tarbela reservoirs, for the four irrigation regions for the year 1988-89. The optimisation results are labelled as "Calculated" in all the figures presented.

RESERVOIR LEVELS: The low discharges from October to November-December for Mangla and from October to January for Tarbela are in an effort by the DP model to keep the reservoir levels higher in order to produce more electrical energy later from December-January onwards. Reservoir levels for both Mangla and Tarbela for the year 1988-89 are shown in Figures 4.6 and 4.7, respectively. The reservoir levels calculated by the DP model seem to match closely with the recorded levels for Mangla during high inflow periods. However, the model starts to draw the levels down by the end of January to a minimum by mid March before they start rising at the end of April. Whereas, in actual operation of Mangla reservoir, the levels are drawn down from mid October onwards to a minimum in mid March before they start rising again in early April.

In case of Tarbela reservoir, the DP model suggests to draw the levels down by the end of February to a minimum in the month of May. In the actual operation of Tarbela, the reservoir levels are drawn down in October-November to a minimum in May before they start rising again in June. The difference in the calculated and actual reservoir levels in case of Tarbela reservoir is much greater than in case of Mangla reservoir. But the difference between the calculated and the actual energy generated at Tarbela reservoir is also greater than the difference between the two for Mangla reservoir.

The minimum discharge outflows calculated were lower than the actual minimum discharge outflows during 1985-90 for both the reservoirs. This is the only factor responsible for higher drawdown levels calculated by the model (more details in chapter 6, section 6.1). The actual recorded discharge outflows at Mangla and Tarbela reservoirs were also used to in the DP model and the resulting reservoir levels were exactly the same as the recorded ones. This verifies the propriety of the continuity equation and the various interpolation subroutines used in the model.

ENERGY GENERATION: The amount of electrical energy calculated by the model for the five-year period of 1985-90 is approximately 8.7% more than the actual energy generated at Tarbela reservoir; 56,725 mkWh calculated by the model against 52,183 mkWh actual generation at Tarbela. Whereas, the model shows an increase of only 3.0% over the actual energy generated; 30,034 mkWh as against 29,170 mkWh, at Mangla reservoir. Figures 4.8 and 4.9 show the amount of electrical energy generated in the year 1988-89 at Mangla and Tarbela reservoirs, respectively. Table 4.2 gives the yearly energy generation, calculated and recorded, for the two reservoirs during the five year period of 1985-90.

The calculated annual energy generation is increased to about 2.76% on average at Mangla whereas at Tarbela reservoir the model calculates an increase of over 12.0% for the period 1985 to 1988. For the 1988-89 the increase is only about 2.5% and in 1989-90 there is a slight decrease in the energy calculated by the DP model at Tarbela reservoir. The DP model has increased the overall energy generation at the two reservoirs, however, the minimum energy generation has decreased to almost of half of the actual energy generated during the months of October and November.

Table 4.2. Energy generation at Mangla & Tarbela 1985-90

Year	Mangla mkWh		Tarbela mkWh		Total Energy mkWh		% Increase in Total Eng.
	Cal	Rec	Cal	Rec	Cal	Rec	
1985-86	5367	5340	10951	9515	16318	14855	9.85
1986-87	6519	6153	11204	9613	17723	15766	12.41
1987-88	6319	6142	12346	11001	18665	17143	8.88
1988-89	5704	5516	11566	11279	17270	16795	2.83
1989-90	6125	6019	10659	10775	16784	16794	-0.06
Total 5-Yr	30034	29170	56726	52183	86760	81353	6.65

At Mangla the minimum 10-Day energy generation recorded over the five-year period 1985-90 is 60 mkWh. The minimum energy generation as calculated by the model is 30 MKWH and occurs seven times once in October 1985, twice in November (1985), once in December 1985, and once in January 1985 and 1989. Similarly, the minimum 10-Day energy generation recorded at Tarbela is 80 mkWh during the five-year period while the model calculates a minimum of 70 mkWh twice in November 1985 once in January 1986 and 1988, and twice in January 1989. The model also shows a considerable increase in energy production during the period December-April at Mangla and January-May at Tarbela.

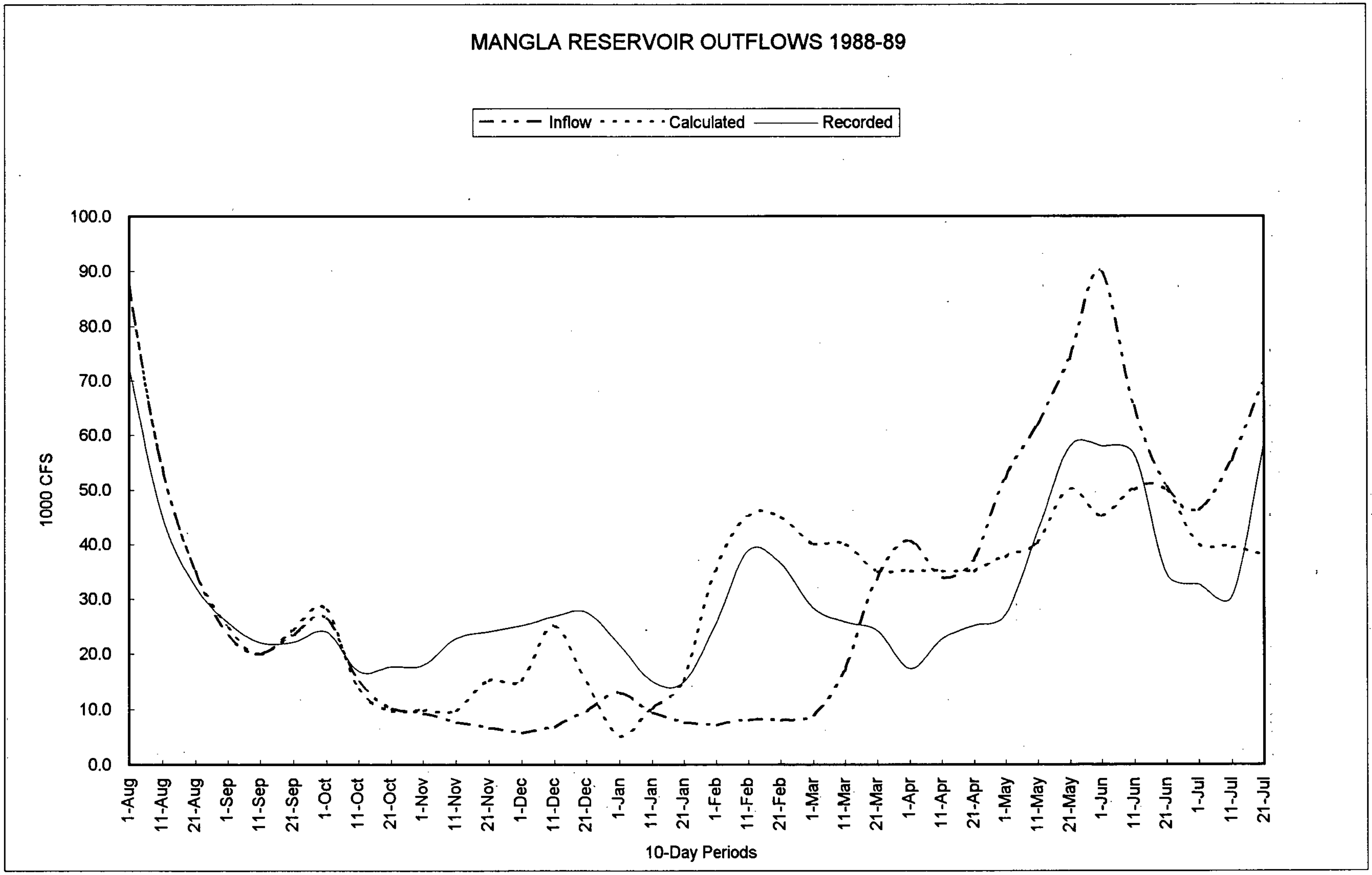

Figure 4.2. Discharge outflows from Mangla reservoir 1988-89

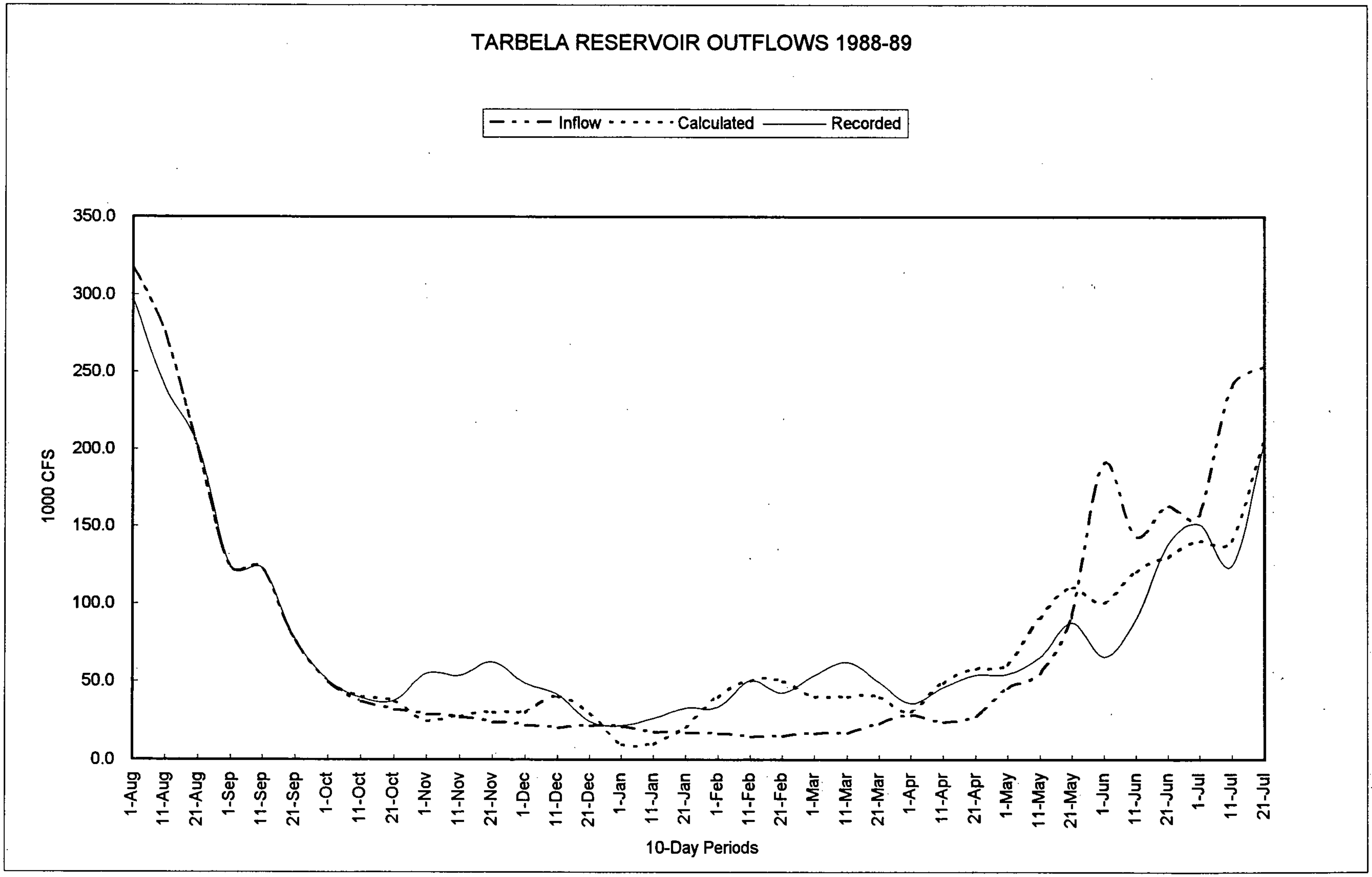

Figure 4.3. Discharge outflows from Tarbela reservoir 1988-89

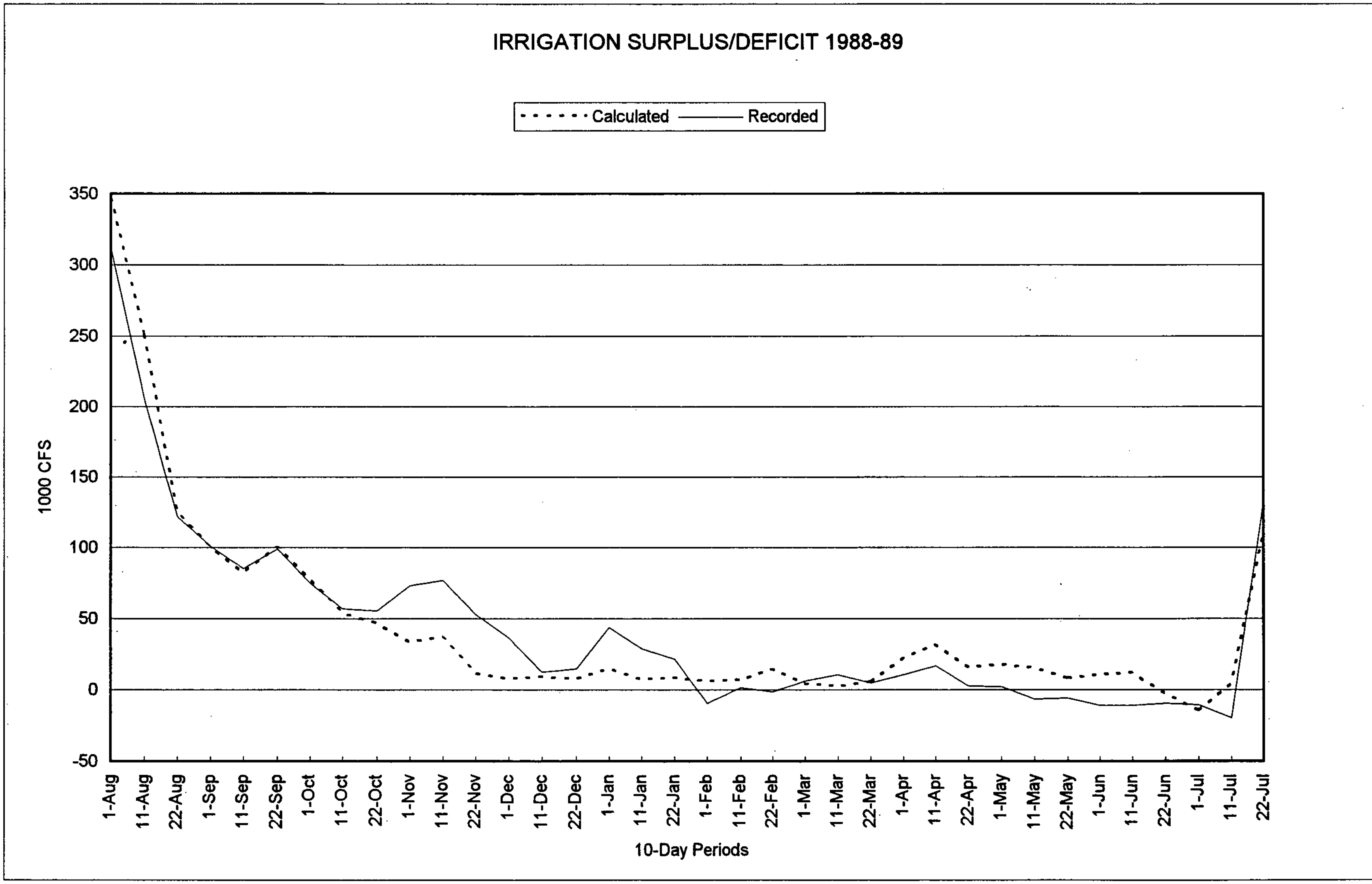

Figure 4.4. Irrigation Surplus/Deficit 1988-89

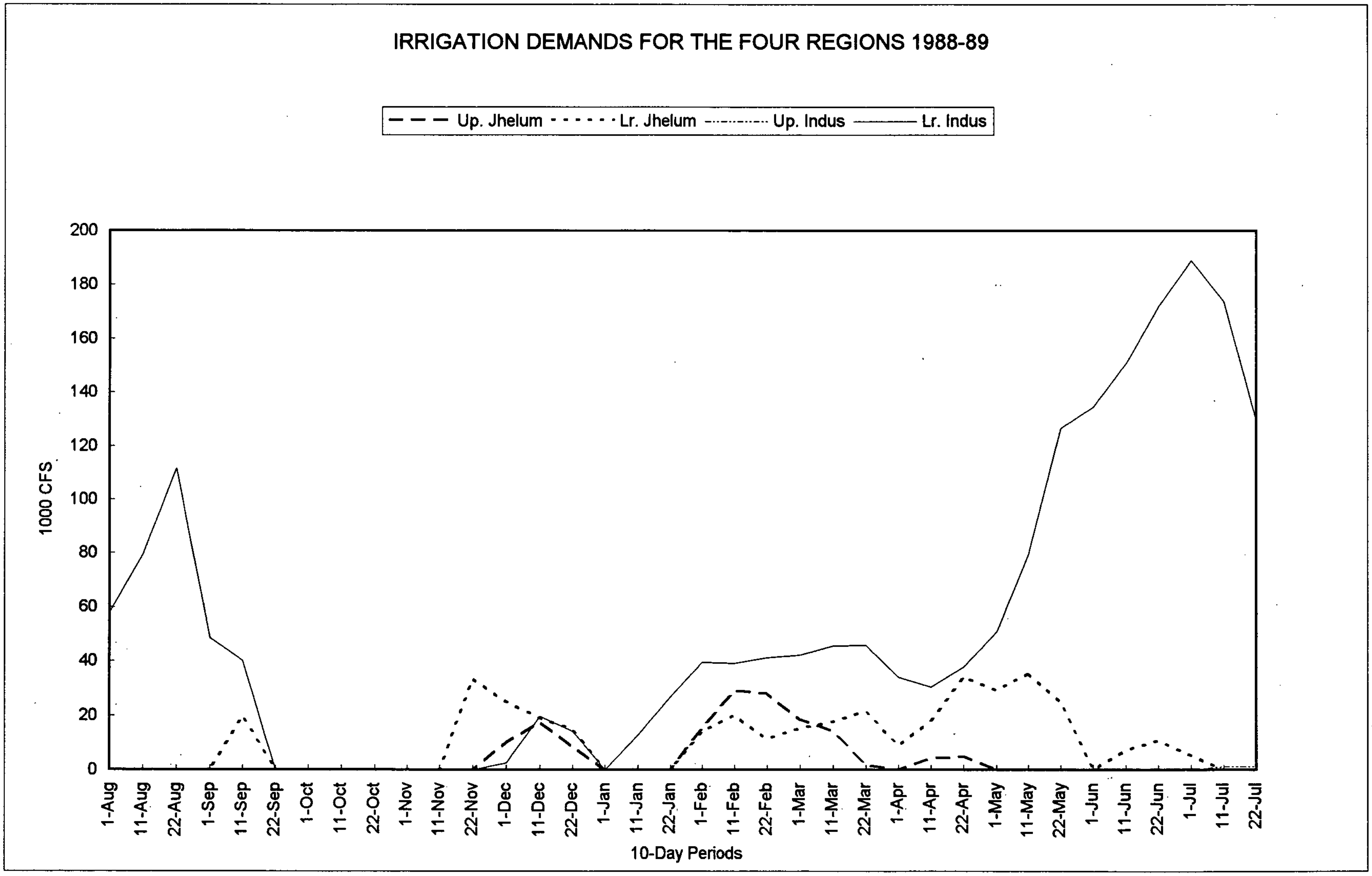

Figure 4.5. Net irrigation demands for the four regions 1988-89

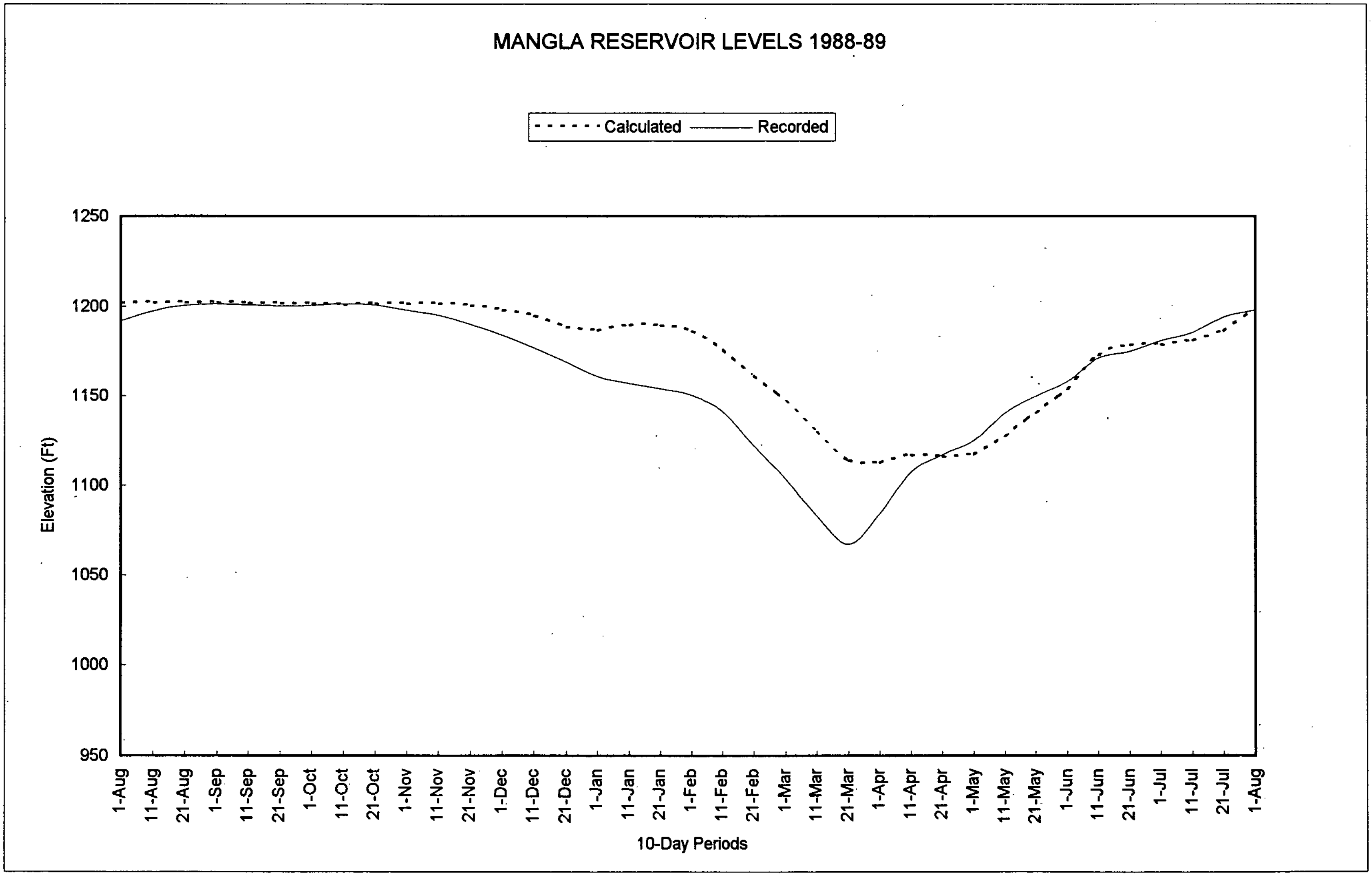

Figure 4.6. Reservoir levels (elevations) at Mangla 1988-89

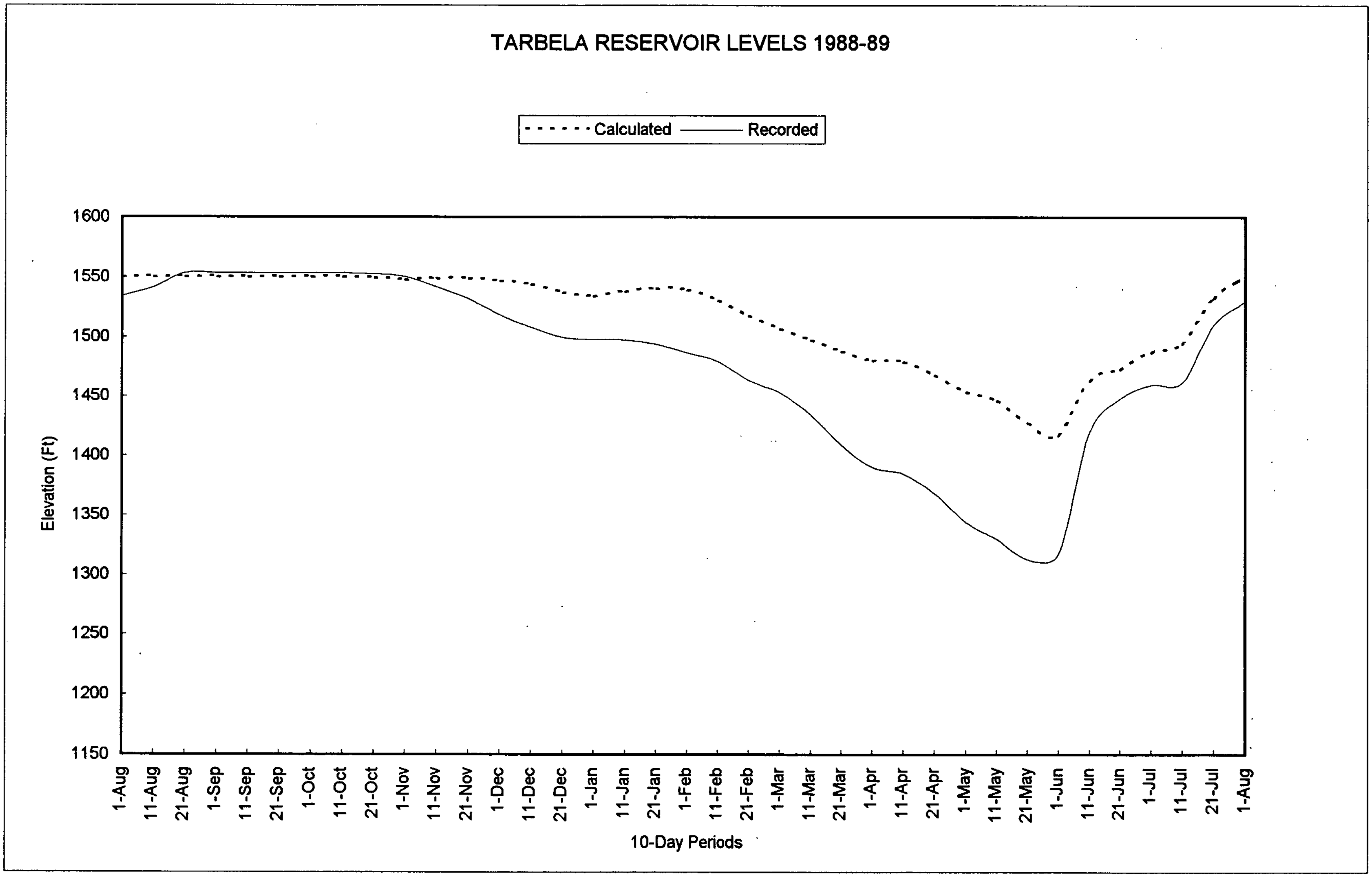

Figure 4.7. Reservoir levels (elevations) at Tarbela 1988-89

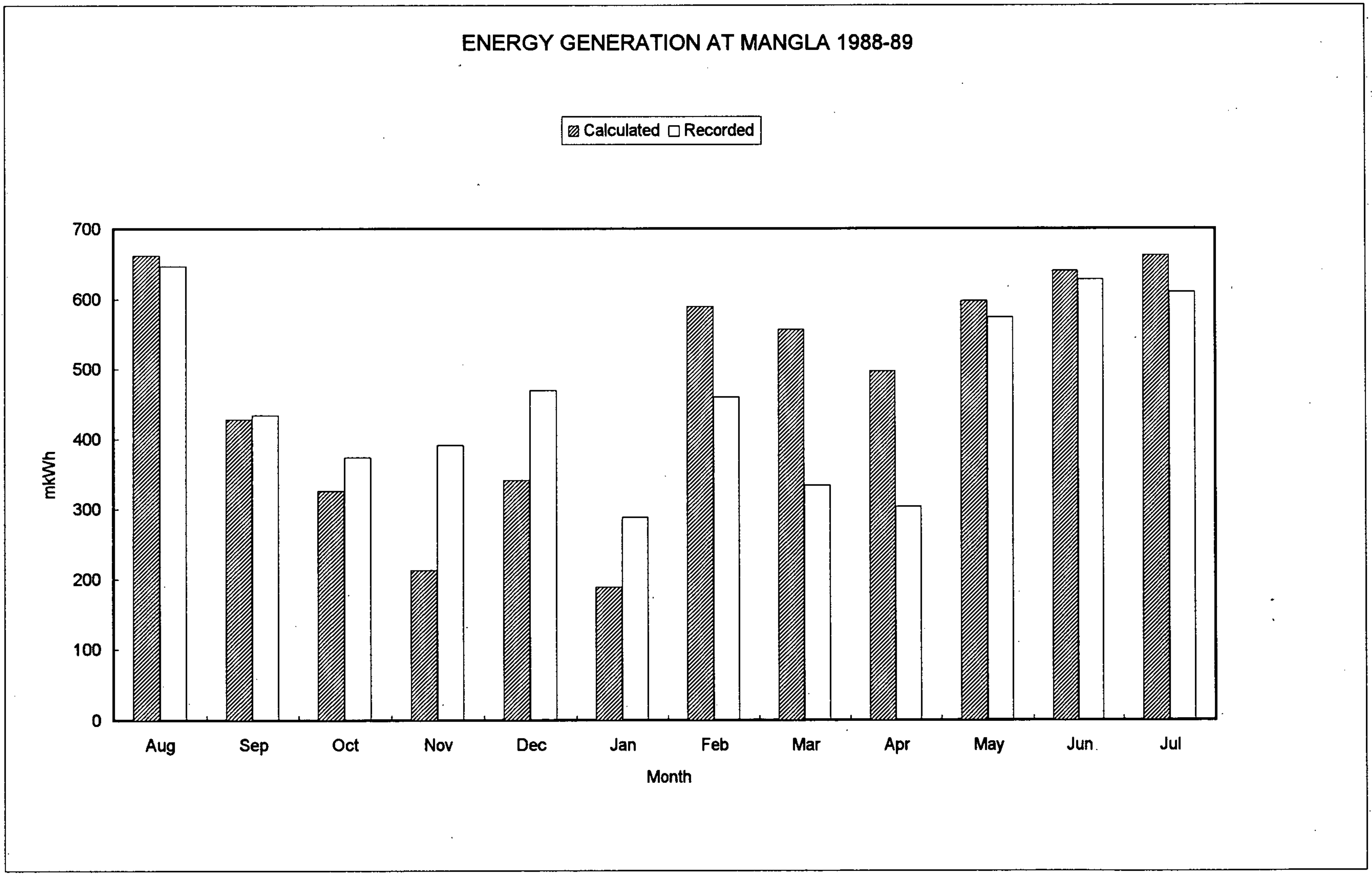

Figure 4.8. Monthly energy generation at Mangla reservoir 1988-89

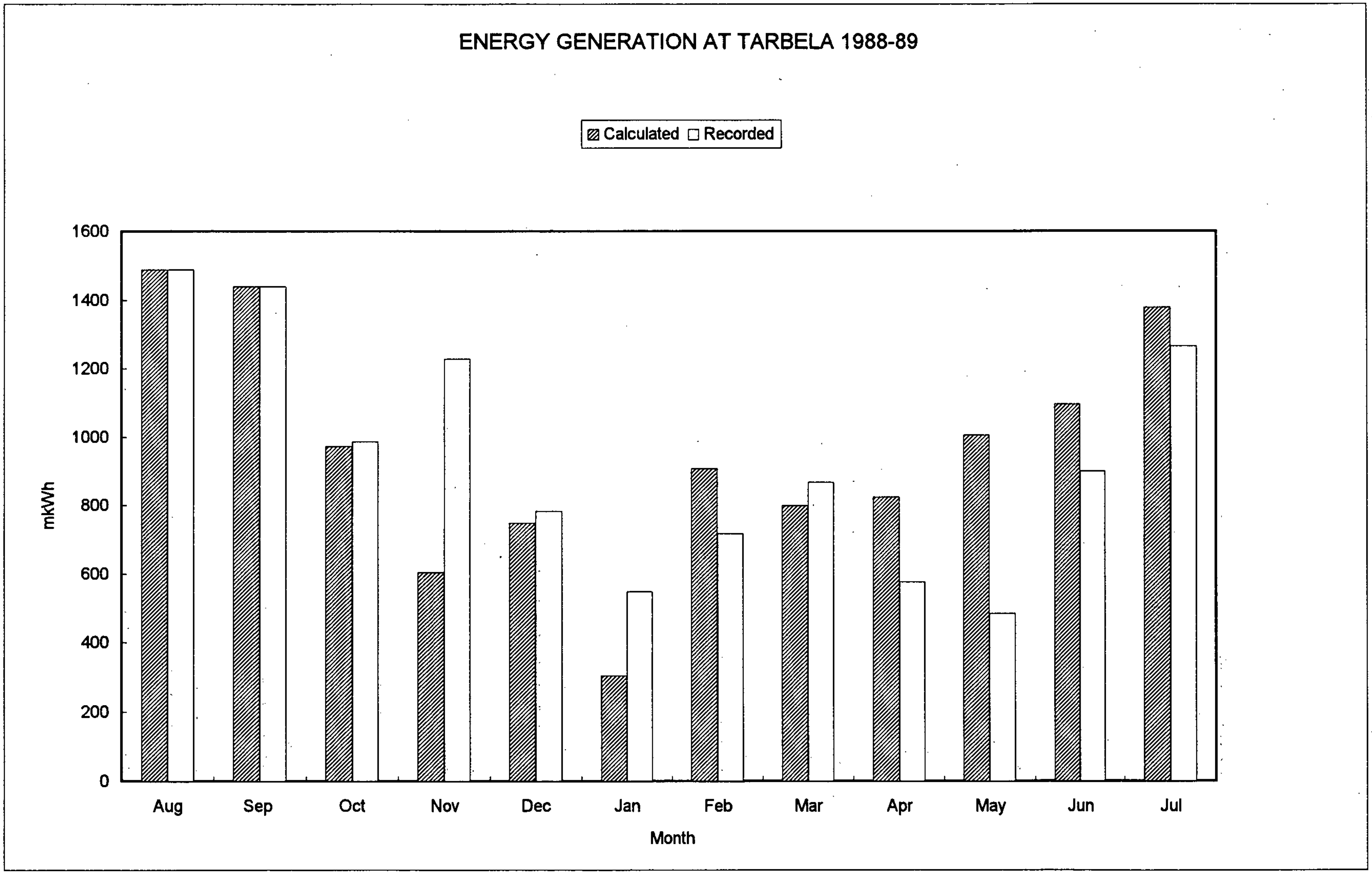

Figure 4.9. Monthly energy geneartion at Tarbela reservoir 1988-89

JOINT MANGLA-TARBELA OPERATION

5.1 THE TWO STATE DP PROBLEM

The Mangla and Tarbela multipurpose reservoir systems not only produce forty percent of the total electrical energy of Pakistan, they also share the irrigation demands of the various irrigation regions. Their joint operation, therefore, is essential in order to maximise benefits from both the agriculture and industry sectors. This stresses the need for the development of a two state DP optimisation routine for joint operation of the two reservoirs.

To achieve this purpose a two-state DP model PK-ROM (Pakistan Reservoir Operation Model) has been developed on the same lines as the single reservoir operation models PR1 and PR2. The two-state algorithm has the following dimensions:

1. Number of stages for the five-year period = 180 (on a 10-day basis)
2. Number of states for Mangla = 15, Number of states for Tarbela = 25
3. Decision variables for Mangla = 10, Decision variables for Tarbela = 10

The discretisation of the decision variables has been as follows.

For Mangla Reservoir: 5, 10, 15, ... , 50 (10^3 CFS); and

For Tarbela Reservoir: 10, 25, 40, ... , 145 (10^3 CFS).

Thus the number of computations involved in the DP optimisation process for a period of five years would be:

$$180 \times 15 \times 25 \times 100 = 4{,}050{,}000$$

This number is, respectively, 64 and 150 times greater than that for independent Mangla and Tarbela operation. Several three dimensional arrays of size (180, 15, 25) store all the data regarding $F_n(Sm, St)$, optimal discharge, etc. for every stage n, Mangla state Sm, and Tarbela state St. Appendix IV contains the main module of the Joint Mangla-Tarbela Operation Model, PK-ROM.

The analysis of joint Mangla-Tarbela operation was performed using two objective functions, separately.

I. Maximisation of energy production with constraints on reservoir releases to meet irrigation demands (Bijaya and Bogardi, 1990).

II. Maximisation of combined benefits from energy generation and irrigation water releases.

The main purpose, of first optimising the joint operation of the two reservoirs using objective function I and then repeating the same using objective function II, was to draw a comparison and hence examine the system performance indicated by the two approaches. In case of objective function II, the power and irrigation water supply benefits in Pakistani Ruppees (per WAPDA) were as follows:

Selling price of electricity, Rs. 1.00 per kWh (Cdn. $ 0.05)

Water supply benefits, Rs. 300 per Acre-foot (Cdn. $ 15.0)

The model which runs in Windows environment on a PC (486-33MHz) took 4.6 hrs. using Objective Function I and 5.9 hrs. using Objective Function II. The use of irrigation constraints has clearly reduced the time-of- run of the model by 1.6 hrs. in the case of the former approach by reducing the number of computations involved in the whole optimisation process.

In the foregoing discussion, the notations OF-I and OF-II, respectively, refer to results obtained from the computer run of PK-ROM using objective functions I and II.

5.2 IRRIGATION DEMANDS

As mentioned in chapter 2 (Figure 2.3), there are four irrigation regions namely Upper Jhelum, Lower Jhelum, Upper Indus, and Lower Indus. The irrigation demands (indents) for each region were input to the model for each 10-day period. The irrigation supply is provided by the available flow in the Sutlej, Ravi, Chenab, and Kabul rivers; plus the flow released from Mangla and Tarbela reservoirs. The 10-day flow values for Sutlej, Ravi, Chenab, and Kabul were, therefore, also considered to calculate the net irrigation demands (demands that can only be met by flow releases from Mangla and Tarbela reservoirs) for the four regions for each 10-day period (Project Direction and Review Report; WAPDA-BCHIL, 1991).

The net irrigation demand for the Upper Jhelum region represents the minimum release from Mangla reservoir during the corresponding 10-day period if the irrigation demand for this region is to be met. Similarly, because of the capacity limits on the link canals (set at 30,000 CFS) for diversion of Indus water to the Lower Jhelum region, Mangla releases cannot be less than the combined net irrigation demand for the Upper and Lower Jhelum regions less 30,000 CFS for each 10-day period.

Irrigation demand during each 10-day period for the Upper Indus region is met by the Kabul River flow plus Tarbela releases in excess of the flow diverted to the Lower Jhelum region. For the Lower Indus region, irrigation in each 10-day period is met by Tarbela and Mangla releases in excess of that used by the other regions plus any surplus flow from the Kabul, Chenab, Ravi, and Sutlej rivers.

The constraints on water supply for irrigation force the model to make releases from Mangla and Tarbela reservoirs to meet the irrigation demands for each 10-day period. If target outputs for irrigation supply are not met after releases from the reservoirs to the full extent allowed by constraints on storage levels, no further releases are made. The model also calculates the total system irrigation deficit. If there is no irrigation deficit the system surplus flow, representing that volume of water flowing directly to the Arabian Sea is calculated. The later value is important to limit salt water intrusion and preserve environmental and ecological conditions in the estuary. However, no information could be obtained from WAPDA in this regard. Appendix V contains the subroutine *IrriDems* which deals with irrigation constraints in the two-state DP model.

5.3 ENERGY GENERATION

As mentioned earlier in chapter 4, energy output was simulated on the basis that the total reservoir outflow up to the full discharge capacity of all turbine units at the available head was passed through the turbines. Head on the turbine is calculated by averaging the current and previous end-of-10-day reservoir level and subtracting a fixed tail water level.

Reservoir water level calculations are based on WAPDA Curve #2 (Stage-Volume Data) for Mangla and WAPDA Curve #8 for Tarbela (Appendix I). For simplicity, evaporation losses have been neglected and an overall constant turbine/generator efficiency of 85 % has been assumed. Pertinent data regarding power generation at Mangla and Tarbela reservoirs is given sections 4.3 and 4.4 of chapter 4. Appendix VI contains the subroutine *EnerCal* which calculates the energy generated at the two reservoirs for each 10-day period.

5.4 OPTIMISATION RESULTS FOR MANGLA & TARBELA

OUTFLOWS (OF-I): The model calculates discharge outflows lower than actual in the months of October and November and again at one stage in January for Mangla reservoir. Figure 5.1 shows the total outflows (through power tunnels and/or spillways) for the year 1988-89 for Mangla reservoir. The corresponding inflows to the reservoir are also shown. The slight dip in the curve in the month of January is due to the fact that irrigation demands for the regions Upper and Lower Jhelum fall to zero during two consecutive 10-day periods during that month. For Tarbela reservoir, discharge outflows lower than actual also occur in the months of October and November. Figure 5.2 shows the total outflows for the year 1988-89 for Tarbela reservoir.

The actual releases at both Mangla and Tarbela reservoirs are more than those calculated by the model during the period October-November. The reason for these high releases appears to be the irrigation demands of the early Rabi season. However, the DP model does not indicate that there was any total system deficit from the point of view of irrigation water supply. Figure 5.3 gives a plot of the total irrigation surplus/deficit for the year 1988-89.

OUTFLOWS (OF-II): For Mangla reservoir, the model calculates discharge outflows lower than actual during the months of September to November. Figure 5.4 shows the outflows from Mangla reservoir during 1988-89. For Tarbela reservoir, discharge outflows lower than actual occur from end of September to early December. Figure 5.5 shows the discharge outflows from Tarbela reservoir during 1988-89. For both Mangla and Tarbela reservoirs, the model calculates constant discharge for the rest of the months which is a significant from the point of energy generation.

The model, in the case of OF-II approach, shows large irrigation deficits in the months of May and June and also in November and December. The months of May and June are also critical from irrigation point of view since irrigation demands are high and the spring snowmelt has yet to commence. Figure 5.6 gives a plot of total irrigation surplus/deficit for the year 1988-89.

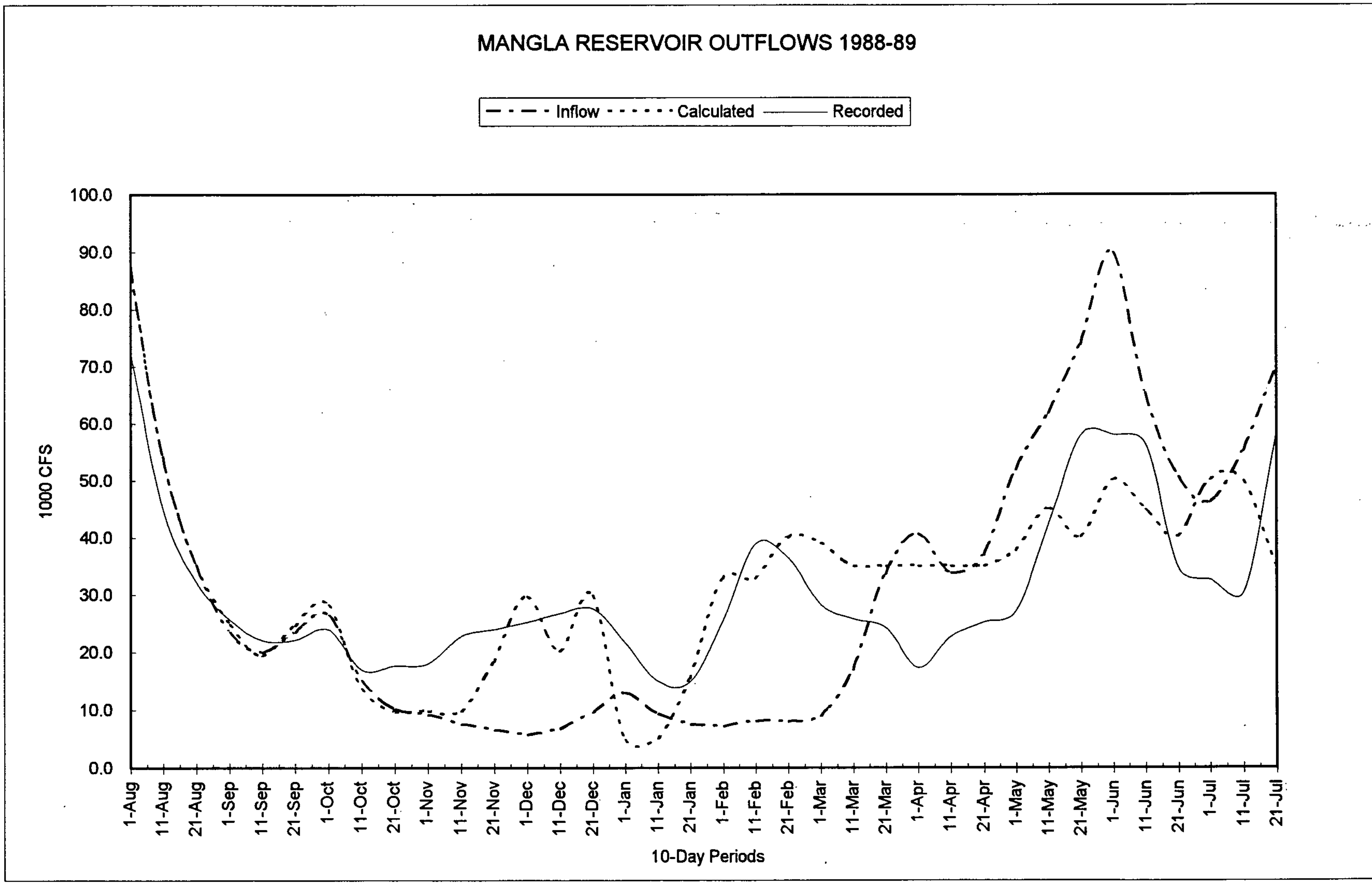

Figure 5.1. Outflows from Mangla reservoir 1988-89; Joint Operation (OF-I)

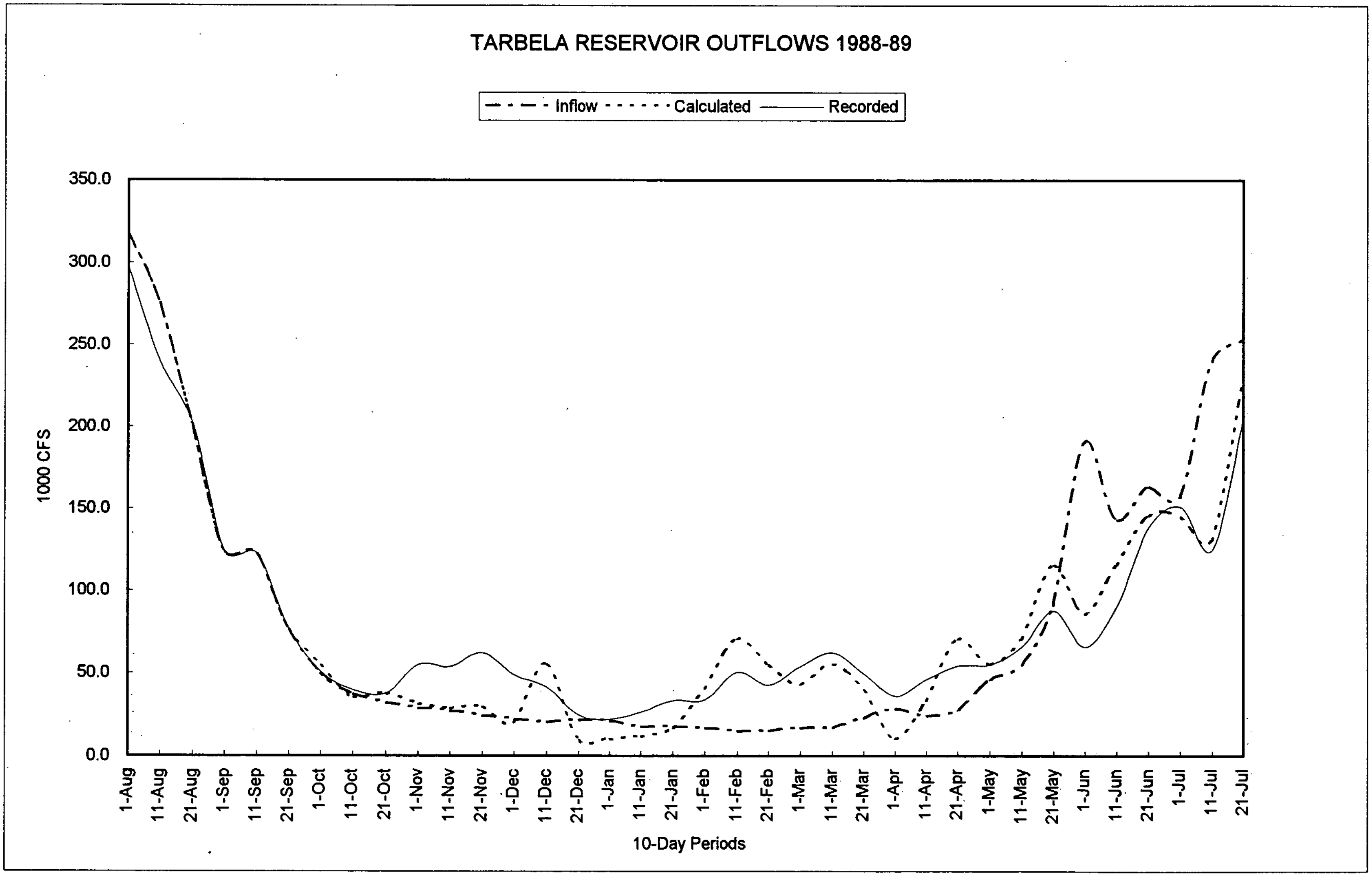

Figure 5.2. Outflows from Tarbela reservoir 1988-89; Joint Operation (OF-I)

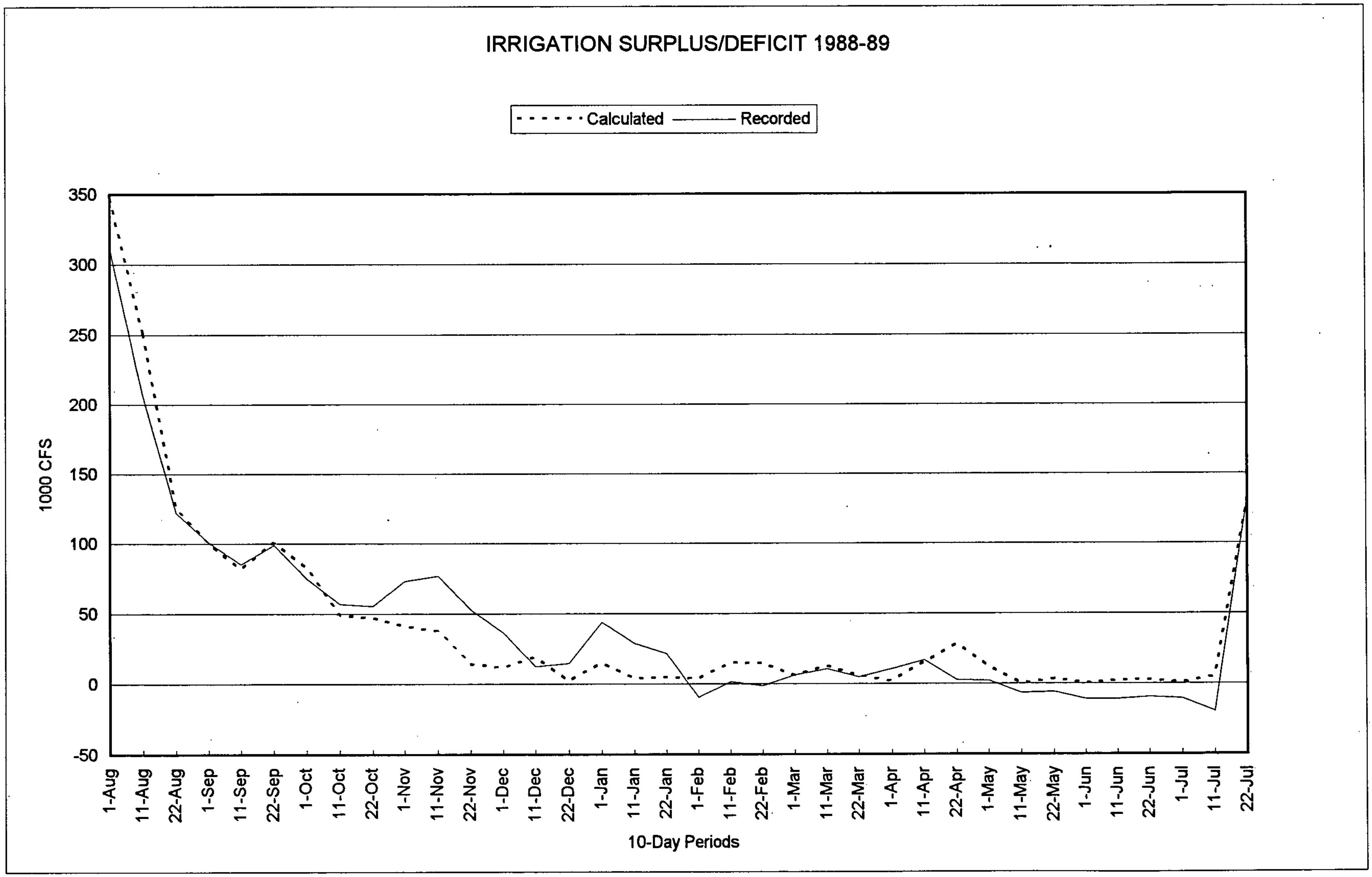

Figure 5.3. Irrigation Surplus/Deficit 1988-89; Joint Operation (OF-I)

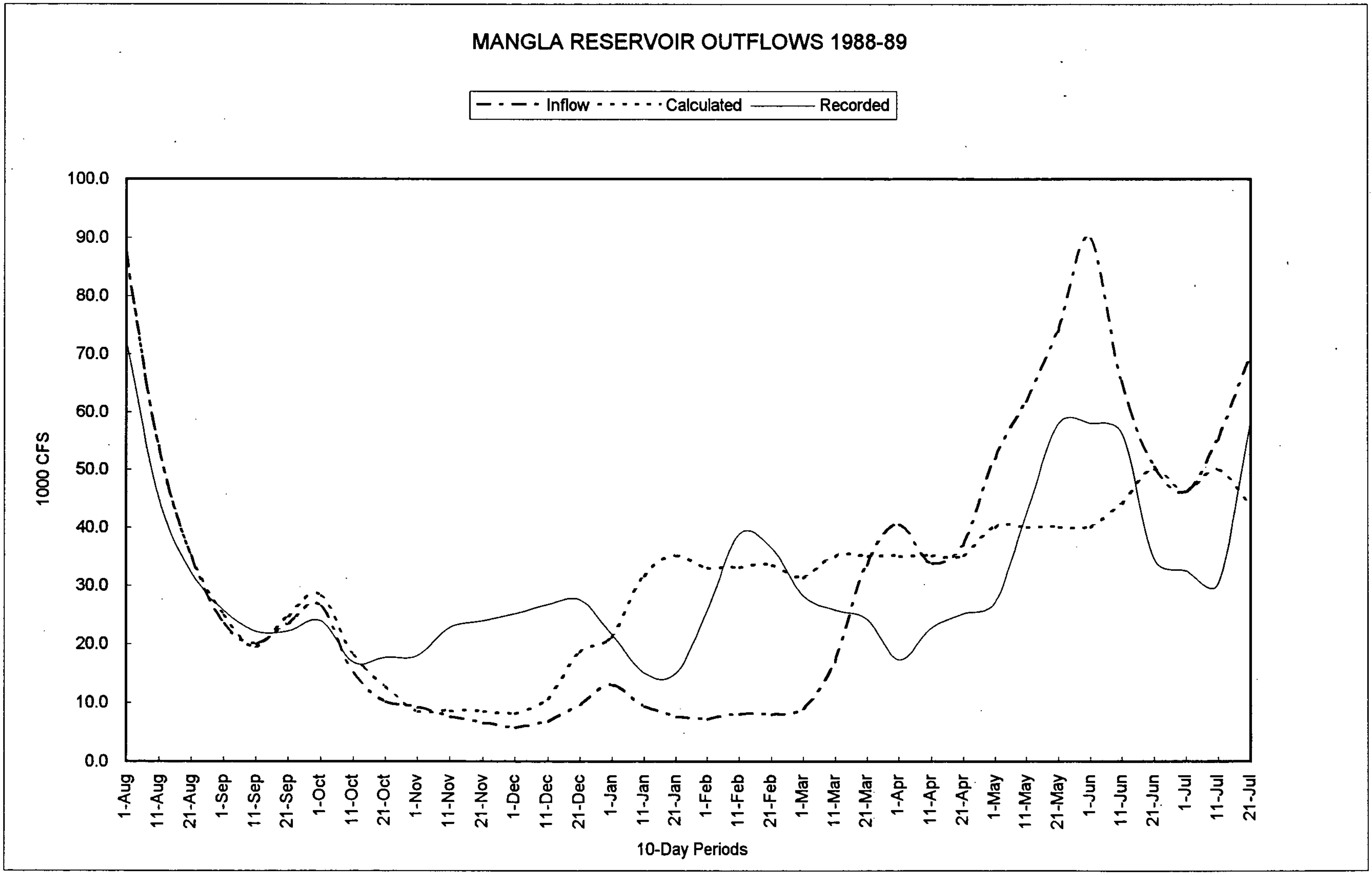

Figure 5.4. Outflows from Mangla reservoir 1988-89; Joint Operation (OF-II)

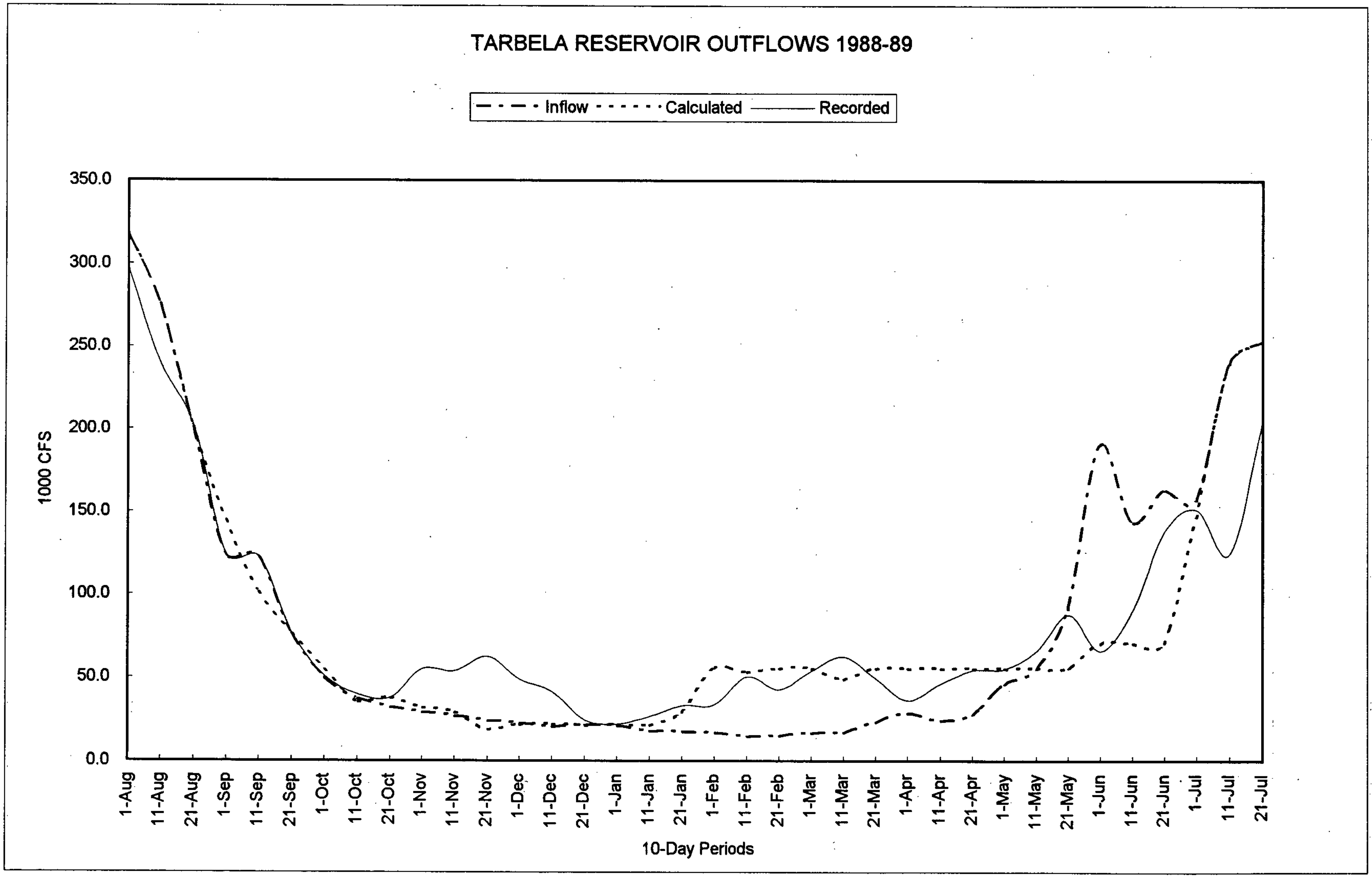

Figure 5.5. Outflows from Tarbela reservoir 1988-89; Joint Operation 1988-89 (OF-II)

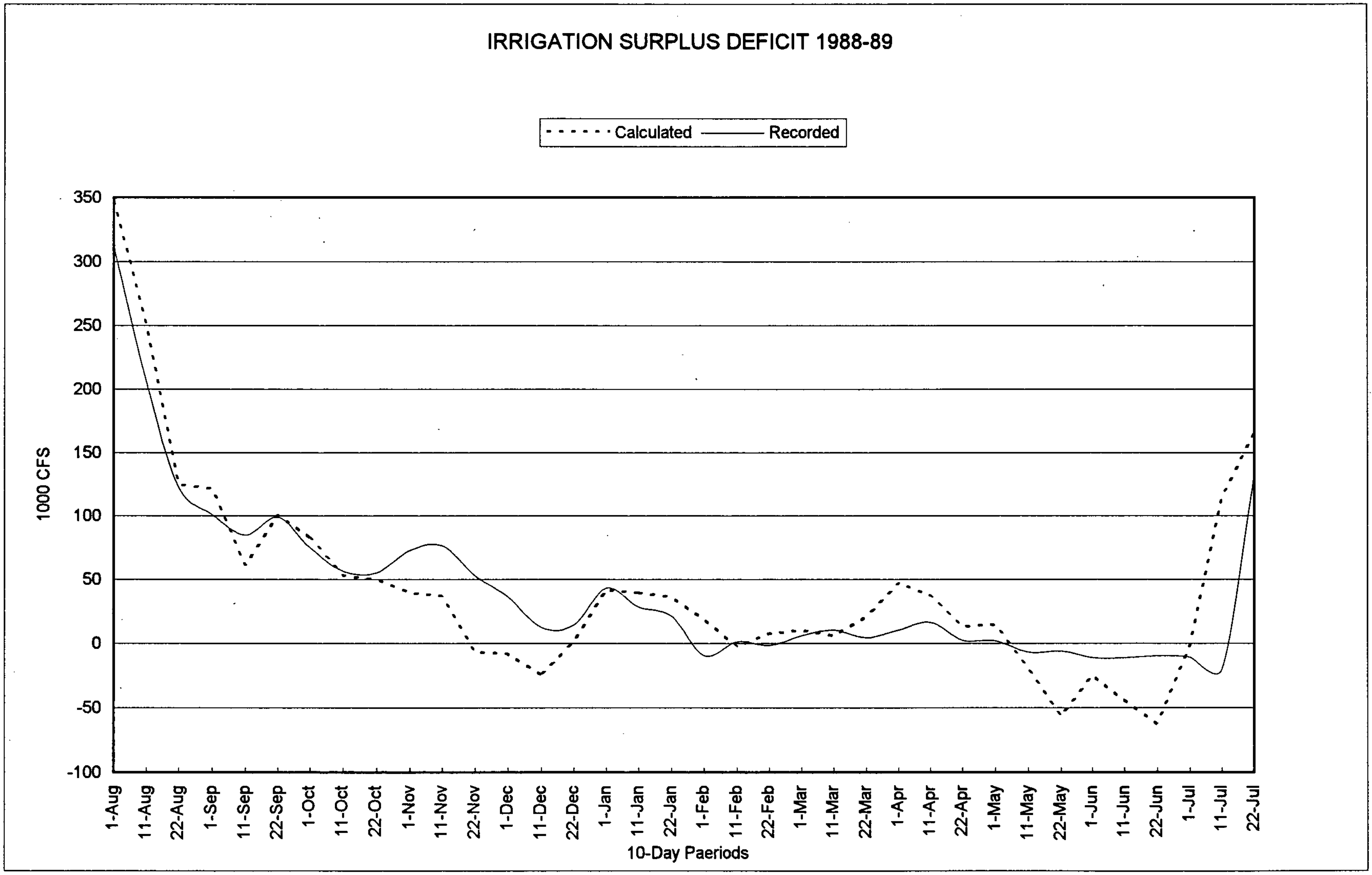

Figure 5.6. Irrigation Surplus/Deficit 1988-89; Joint Operation (OF-II)

RESERVOIR LEVELS (OF-I): The model begins to draw the reservoir levels, at Mangla, down by the start of January to a minimum by mid March before they start rising in early April. Thus the drawdown commences when inflows to river Jhelum begin to increase. Figure 5.7 shows the reservoir levels for Mangla during 1988-89. The minimum drawdown level occurs in the range of El. 1094 ft. to El. 1120 ft. In actual operation, this range is from El. 1060 ft. to El. 1098 ft. The actual operation provides approximately 0.80 MAF (15% of Live Storage Capacity at Mangla) extra storage to mitigate any possible flooding during the summer monsoon season.

At Tarbela, the reservoir levels are drawn down beginning the end of February to minimum by mid June before they start rising by the end of June. Figure 5.8 shows the reservoir levels at Tarbela during 1988-89. The average minimum drawdown level for Tarbela reservoir is El. 1430 ft. as calculated by the model while the actual average minimum for the same five-year period is El. 1330 ft. The difference of 100 ft. (or 2.65 MAF of extra storage) is quite substantial. This, given the sedimentation problem and the fact that the minimum conservation level has been raised (El. 1330 ft.), may be a significant benefit.

RESERVOIR LEVELS (OF-II): Figures 5.9 and 5.10 show the reservoir levels for Mangle and Tarbela, respectively, for the year 1988-89. The manner in which the draw down occurs at both Mangla and Tarbela is the same as in case of OF-I. The only difference is that, in case of Tarbela reservoir, the model begins to draw the levels down by the start of February instead of end of February.

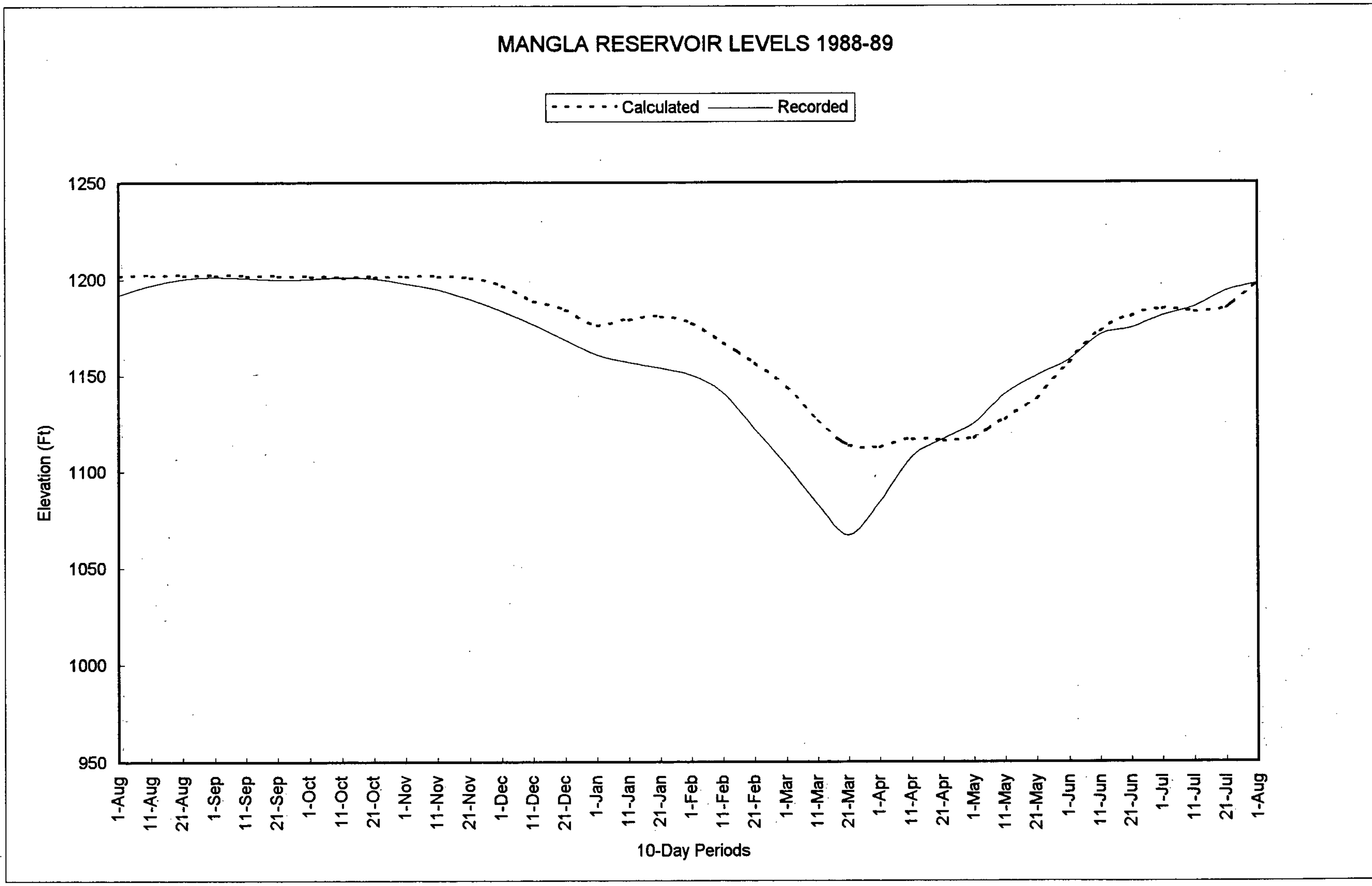

Figure 5.7. Reservoir levels at Mangla 1988-89; Joint Operation (OF-I)

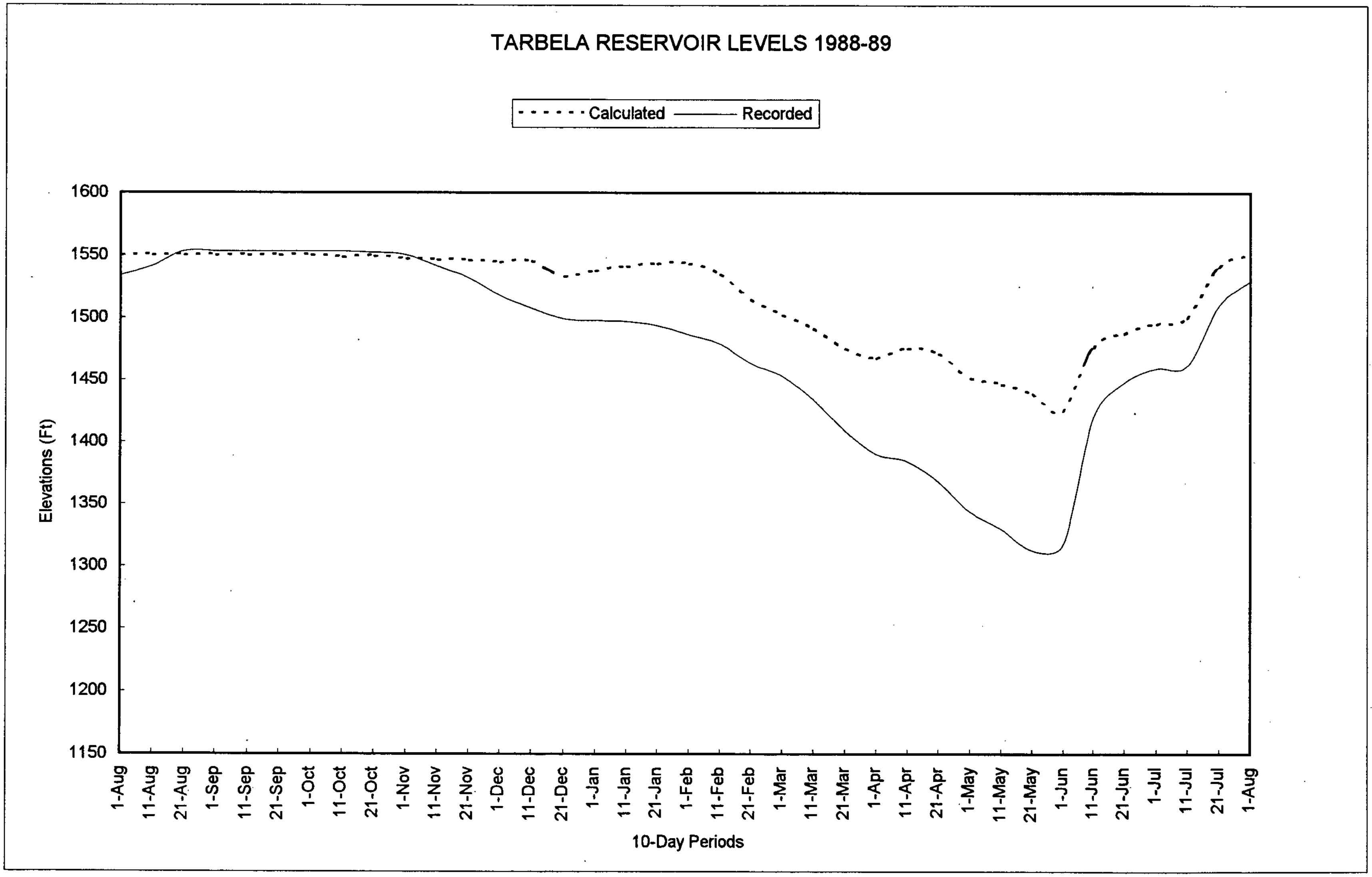

Figure 5.8. Reservoir levels at Tarbela 1988-89; Joint Operation (OF-I)

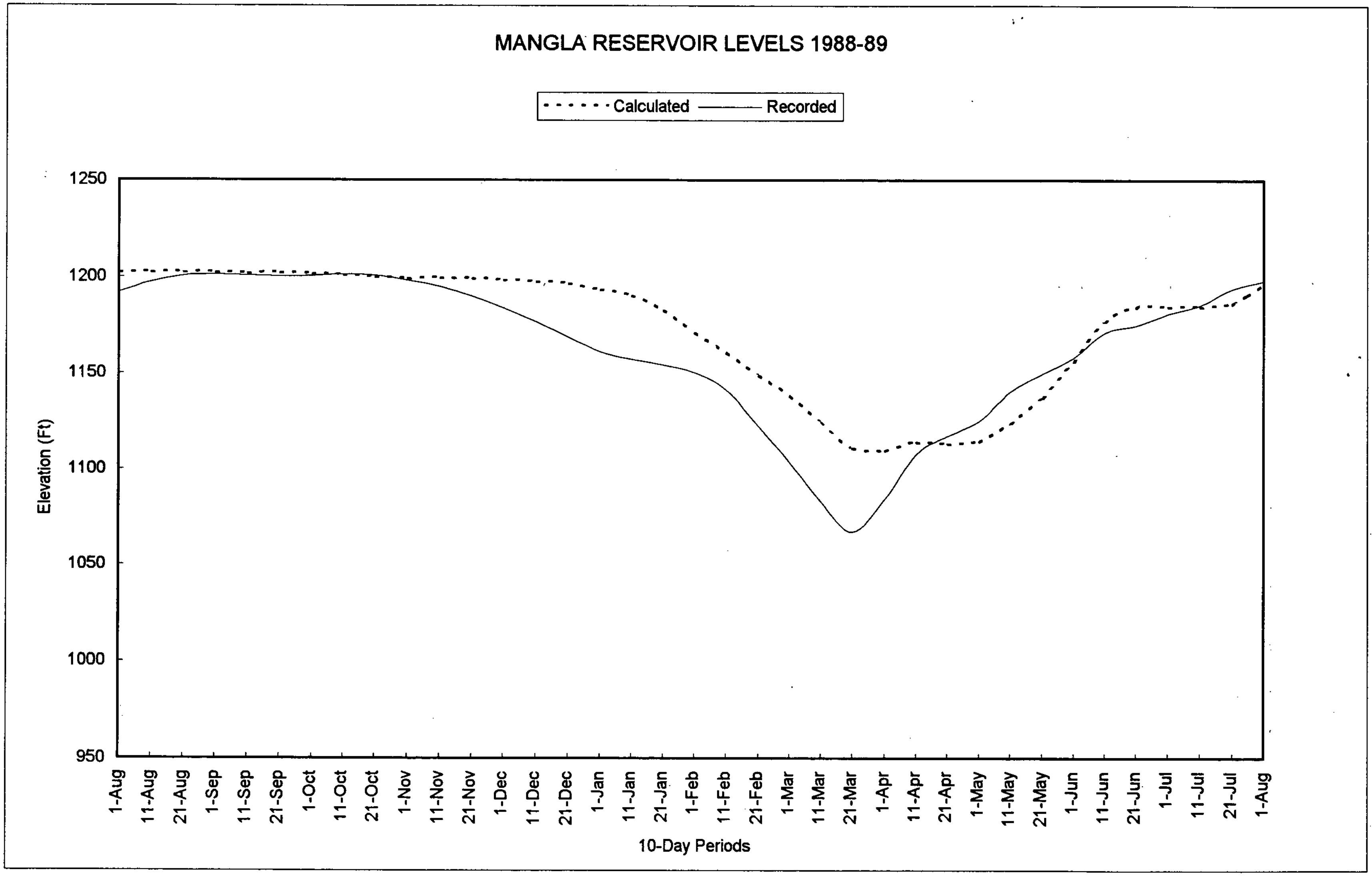

Figure 5.9. Reservoir levels at Mangla 1988-89; Joint Operation (OF-II)

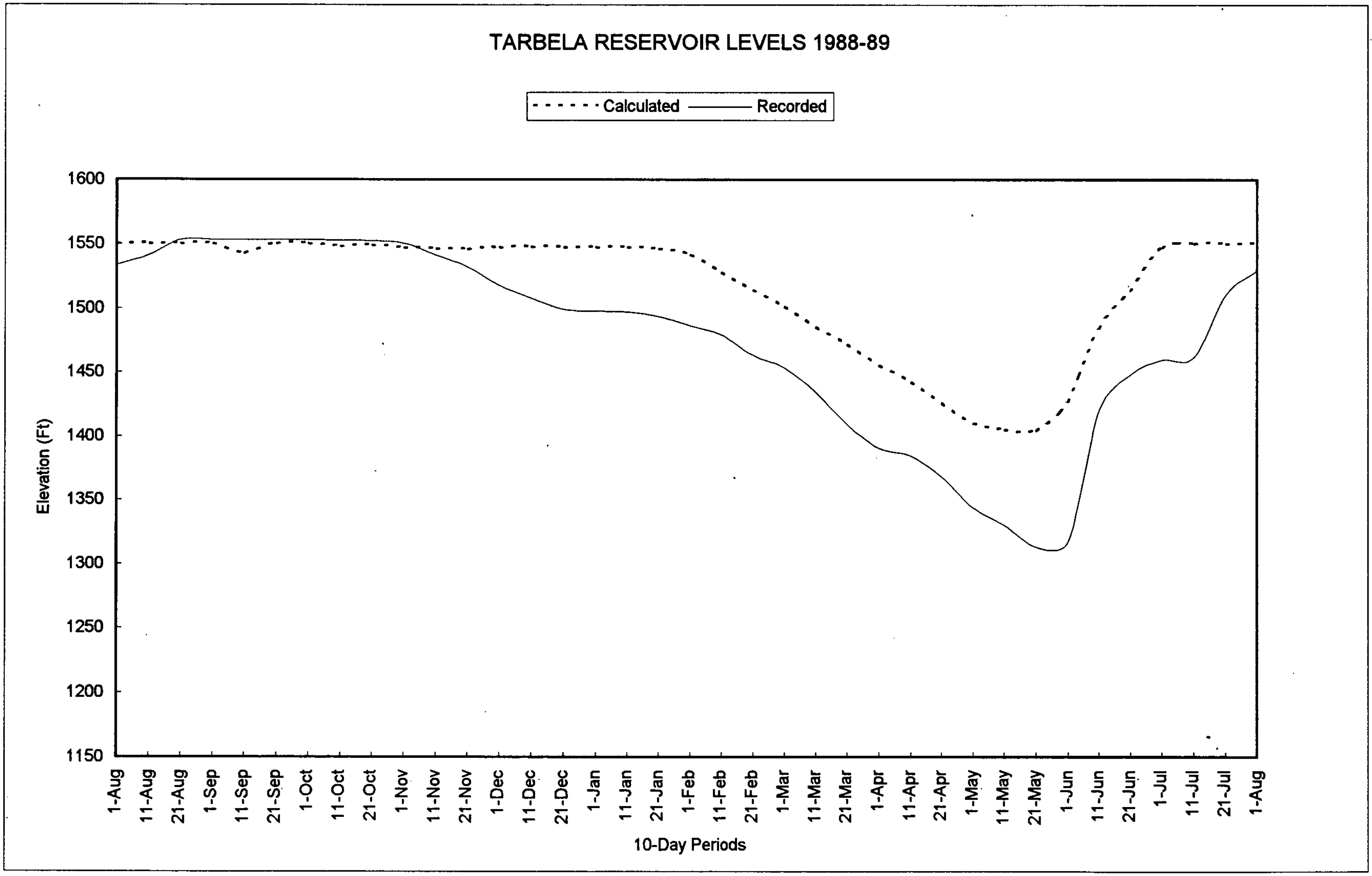

Figure 5.10. Reservoir levels at Tarbela 1988-89; Joint Operation (OF-II)

ENERGY GENERATION (OF-I): The total five-year energy generation at Tarbela reservoir, as calculated by the model, is 10.4% more than the actual energy generation at Tarbela for the same period (57589 Vs 52183 mkWh). On the other hand, the increase in energy production over the actual production is only about 1.6% in case of Mangla reservoir (29626 Vs 29170 mkWh). Figures 5.11 and 5.12 show the monthly energy generation at Mangla and Tarbela reservoirs, respectively, for the year 1988-89.

The minimum 10-Day energy generation recorded over the five year period of 1985-1990 at Mangla and Tarbela reservoirs is 60 and 80 mkWh respectively. The minimum 10-Day energy production calculated by the model was 30 mkWh in case of Mangla reservoir and occurred 13 times mostly in the month of January. For Tarbela reservoir the minimum 10-Day energy production over the five-year period was 34 mkWh and happened only once in March 1989-90.

ENERGY GENERATION (OF-II): OF-II results show an enormous increase in energy production at the two power plants. The increase over the actual energy production at Mangla and Tarbela reservoirs is 4.56% and 18.3% respectively. Figures 5.13 and 5.14 show the monthly energy production at Mangla and Tarbela reservoirs during the year 1988-89. The minimum 10-Day energy production at Mangla was 30 mkWh and occurred only once in August 1986-87, whereas, in case of Tarbela the minimum 10-Day energy production increased to 130 mkWh.

Table 5.1 shows the yearly energy production at Mangla and Tarbela and Table 5.2 shows the total five-year energy generation at the two reservoirs.

Table 5.1. Yearly energy generation at Mangla & Tarbela reservoirs in mkWh

YEAR	MANGLA			TARBELA		
	OF-I	OF-II	Recorded	OF-I	OF-II	Recorded
1985-86	5315	5448	5340	11009	11783	9515
1986-87	6486	6561	6153	11617	12102	9613
1987-88	6312	6412	6142	12268	12989	11001
1988-89	5768	5785	5516	11575	12059	11279
1989-90	5745	6265	6019	11120	12799	10775
Total	29626	30471	29170	57589	61732	52183

Table 5.2. Total energy generation (Mangla + Tarbela) in mkWh

YEAR	TOTAL ENERGY GENERATION		
	OF-I	OF-II	Recorded
1985-86	16324	17231	14855
1986-87	18103	18663	15766
1987-88	18580	19401	17143
1988-89	17343	17844	16795
1989-90	16865	19064	16794
Total	87215	92203	81353
% Increase	7.2	13.3	

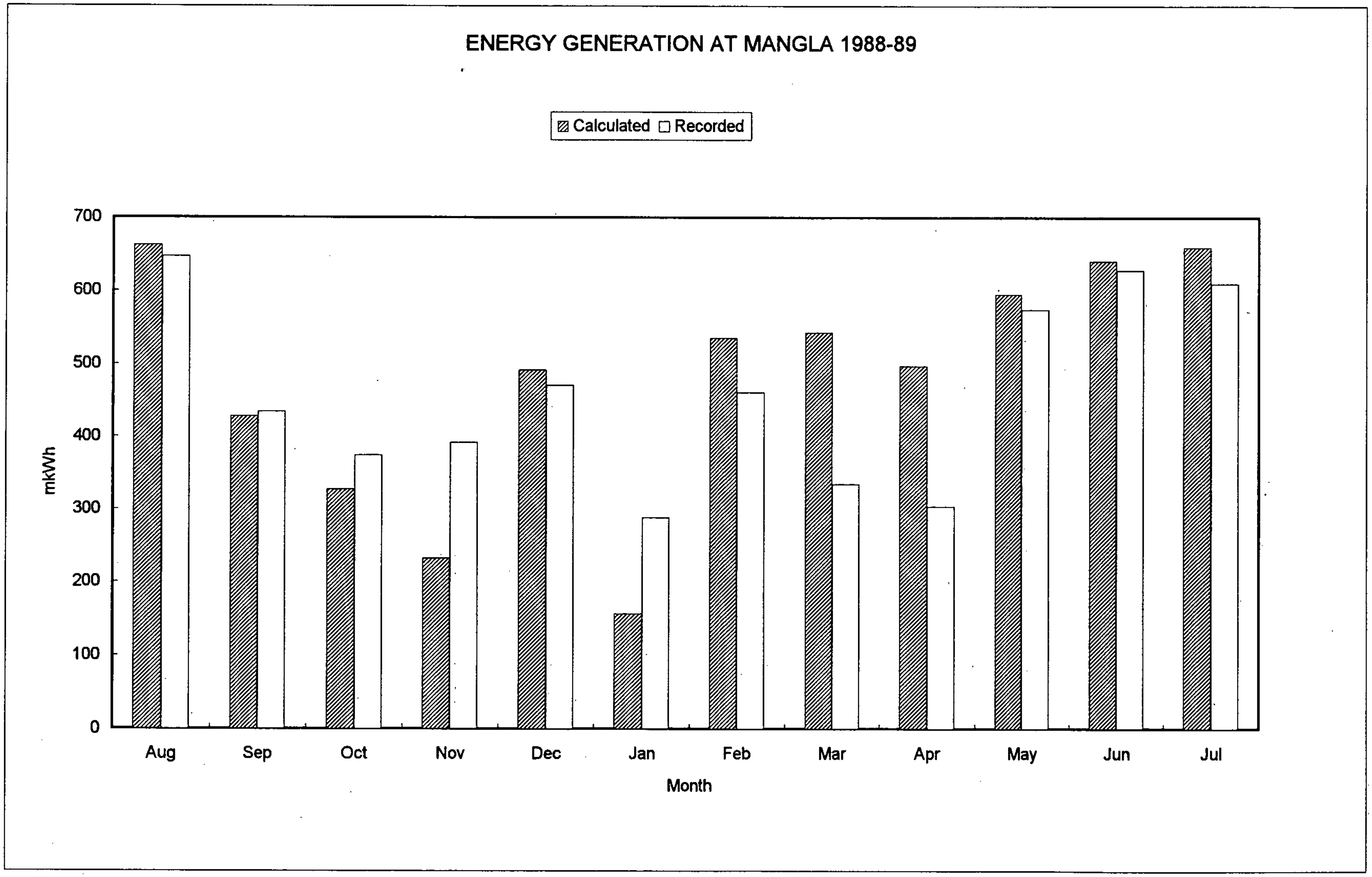

Figure 5.11. Energy generation at Mangla 1988-89; Joint Operation (OF-I)

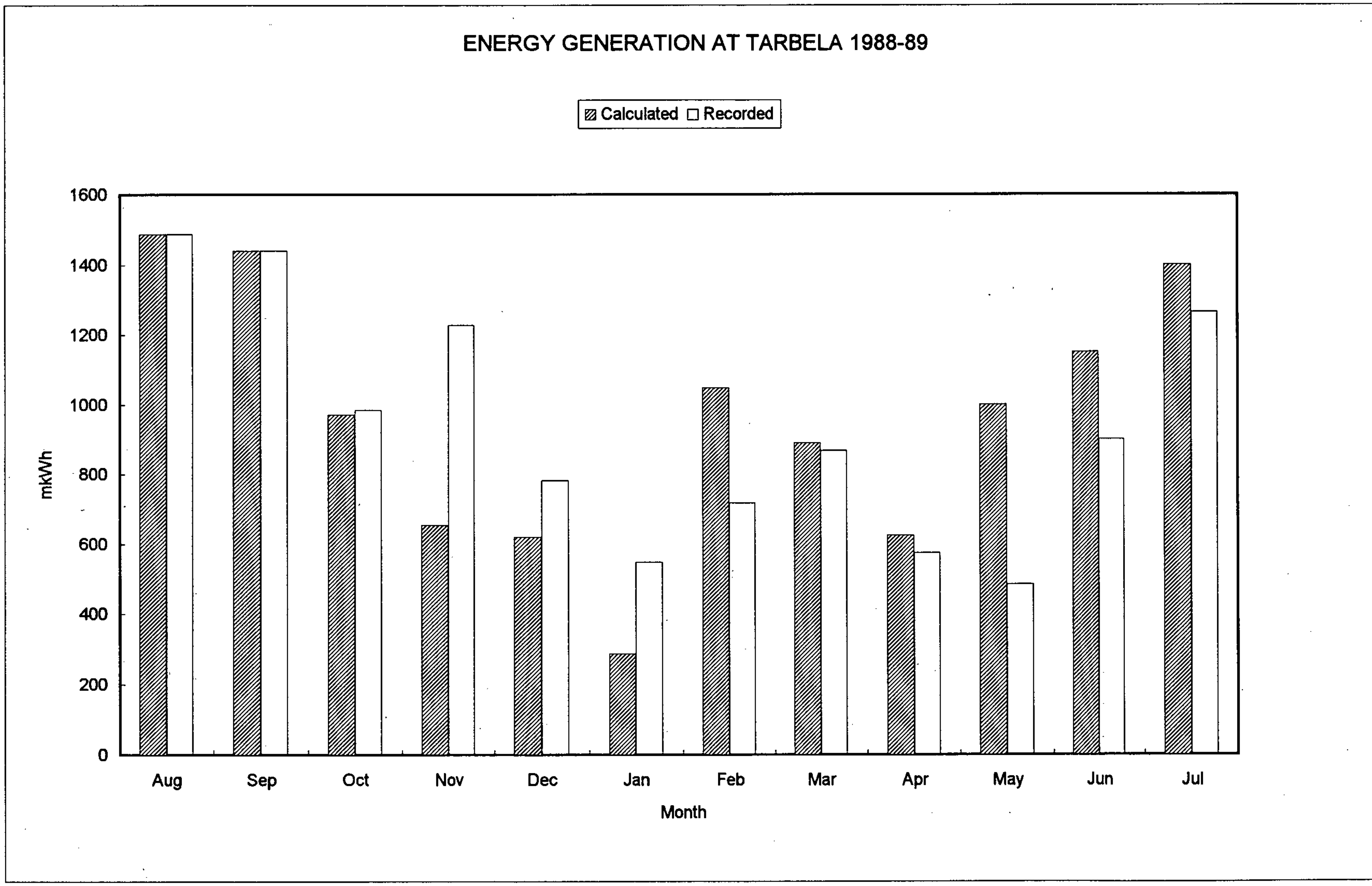

Figure 5.12. Energy generation at Tarbela 1988-89; Joint Operation (OF-I)

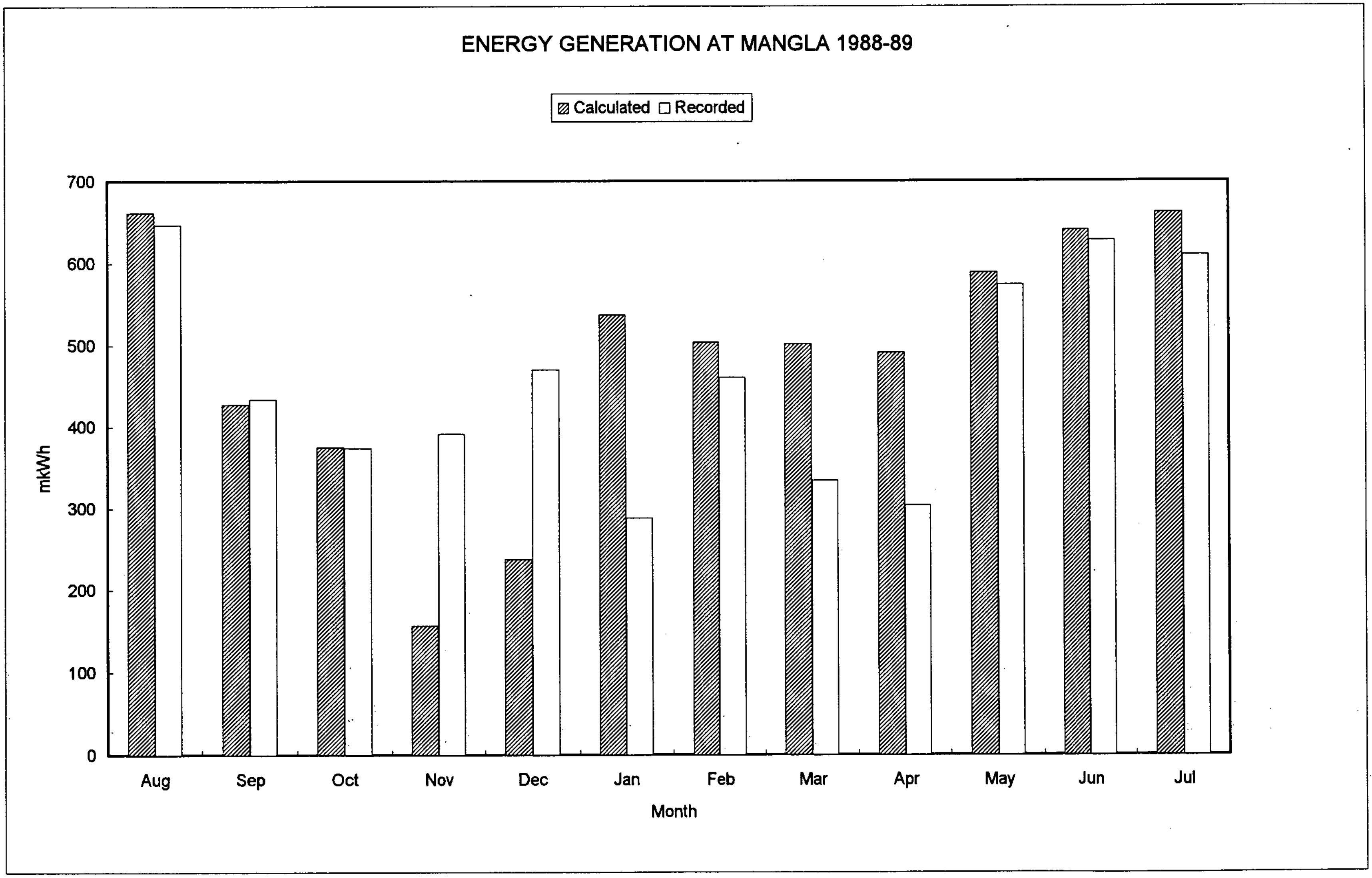

Figure 5.13. Energy generation at Mangla 1988-89; Joint Operation (OF-II)

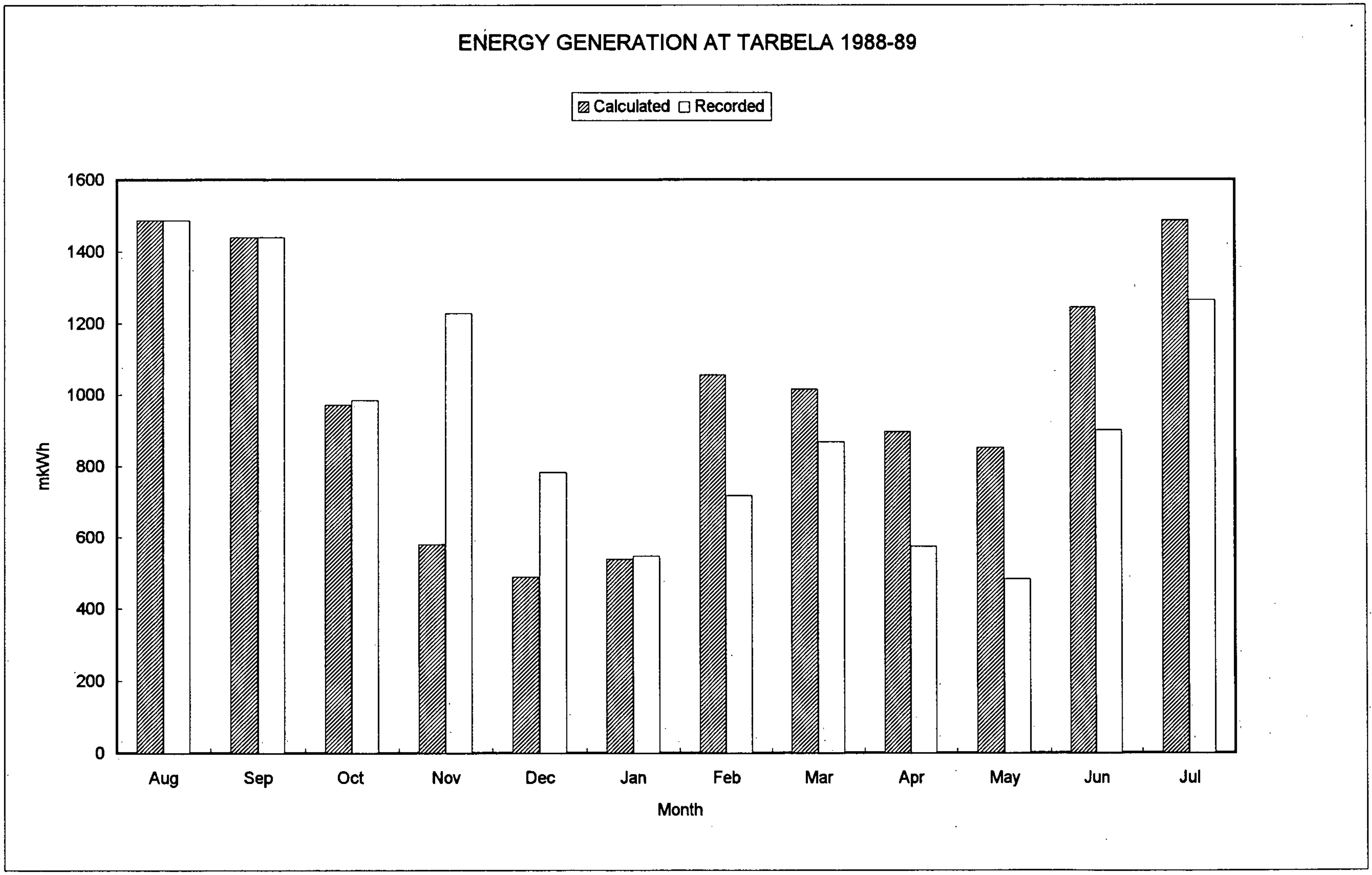

Figure 5.14. Energy generation at Tarbela 1988-89; Joint Operation (OF-II)

5.5 SOME TYPICAL OPTIMAL STATE TRAJECTORIES

Some typical optimal state trajectories for operation of Mangla and Tarbela reservoirs under three different initial conditions are provided for comparison of reservoir operation under three different initial conditions. The three different initial conditions are:

1. Reservoir level at Mangla on August 1, 1985 = 1202 ft.

   Reservoir level at Tarbela on August 1, 1985 = 1550 ft.

2. Reservoir level at Mangla on August 1, 1985 = 1182 ft.

   Reservoir level at Tarbela on August 1, 1985 = 1500 ft.

3. Reservoir level at Mangla on August 1, 1985 = 1152 ft.

   Reservoir level at Tarbela on August 1, 1985 = 1450 ft.

Figures 5.15 and 5.16 show the reservoir levels at Mangla and Tarbela, respectively, for the year 1985-86 for the three initial reservoir conditions (Reservoirs 100% full, 75% full, 50% full). The differences are minor since both the reservoirs reach their maximum conservation levels due to high inflows in August-September. The total irrigation surplus and/or deficit is represented by Figure 5.17. The comparison of energy generation for the three conditions is given by Table 5.3. The DP model PK-ROM was run using Objective Function I.

Table 5.3. Comparison of energy generated at Mangla and Tarbela corresponding to three different initial conditions (reservoir levels on August 1, 1985).

Initial Condition	ENERGY GENERATION	
	1986-86	Total 5-Year
	(mkWh)	(mkWh)
100% Full	16734.97	87625.56
75% Full	16490.29	87380.88
50% Full	15962.80	86853.38

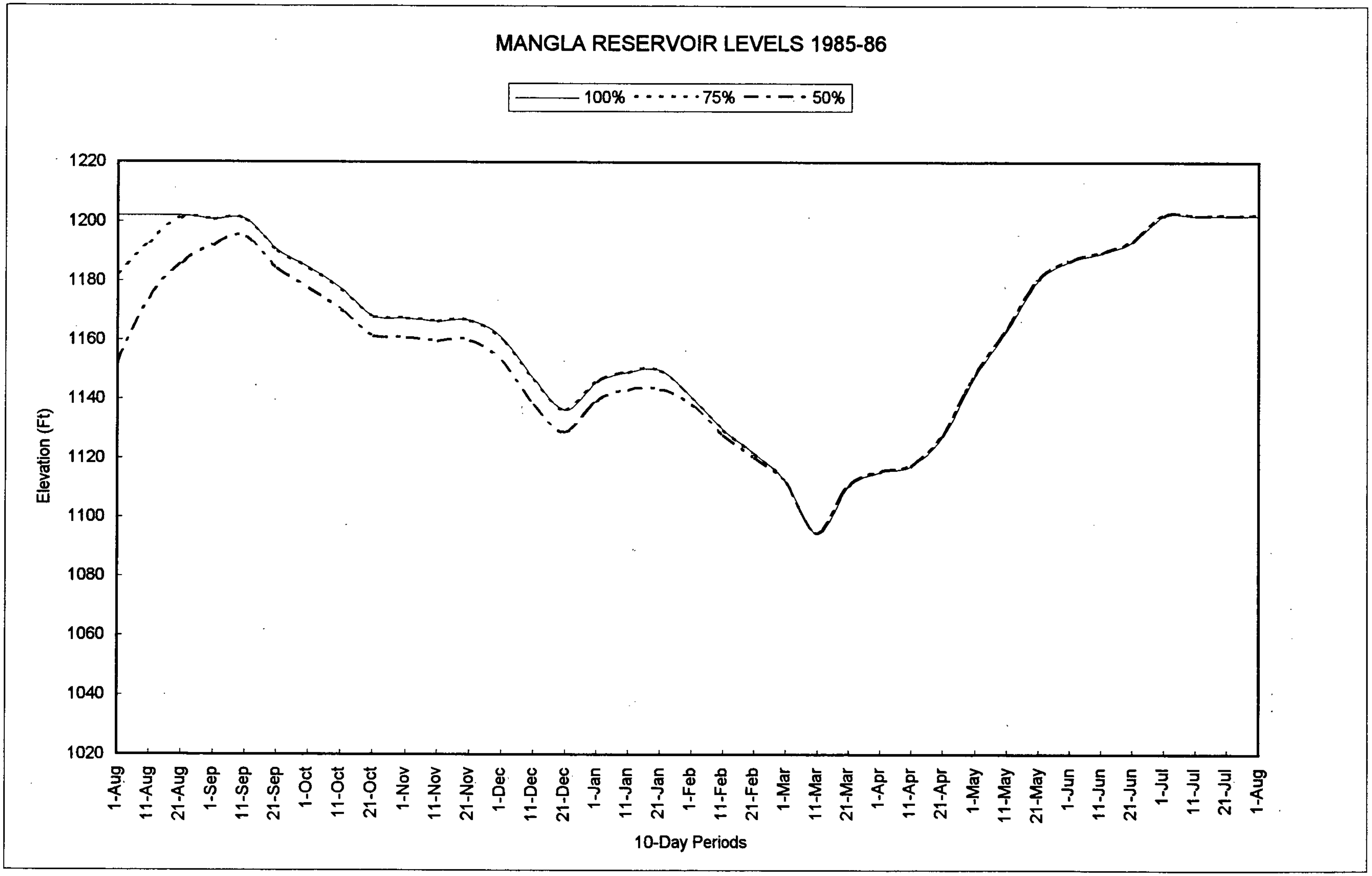

Figure 5.15. Reservoir levels at Mangla 1985-86; Joint Operation (OF-I)

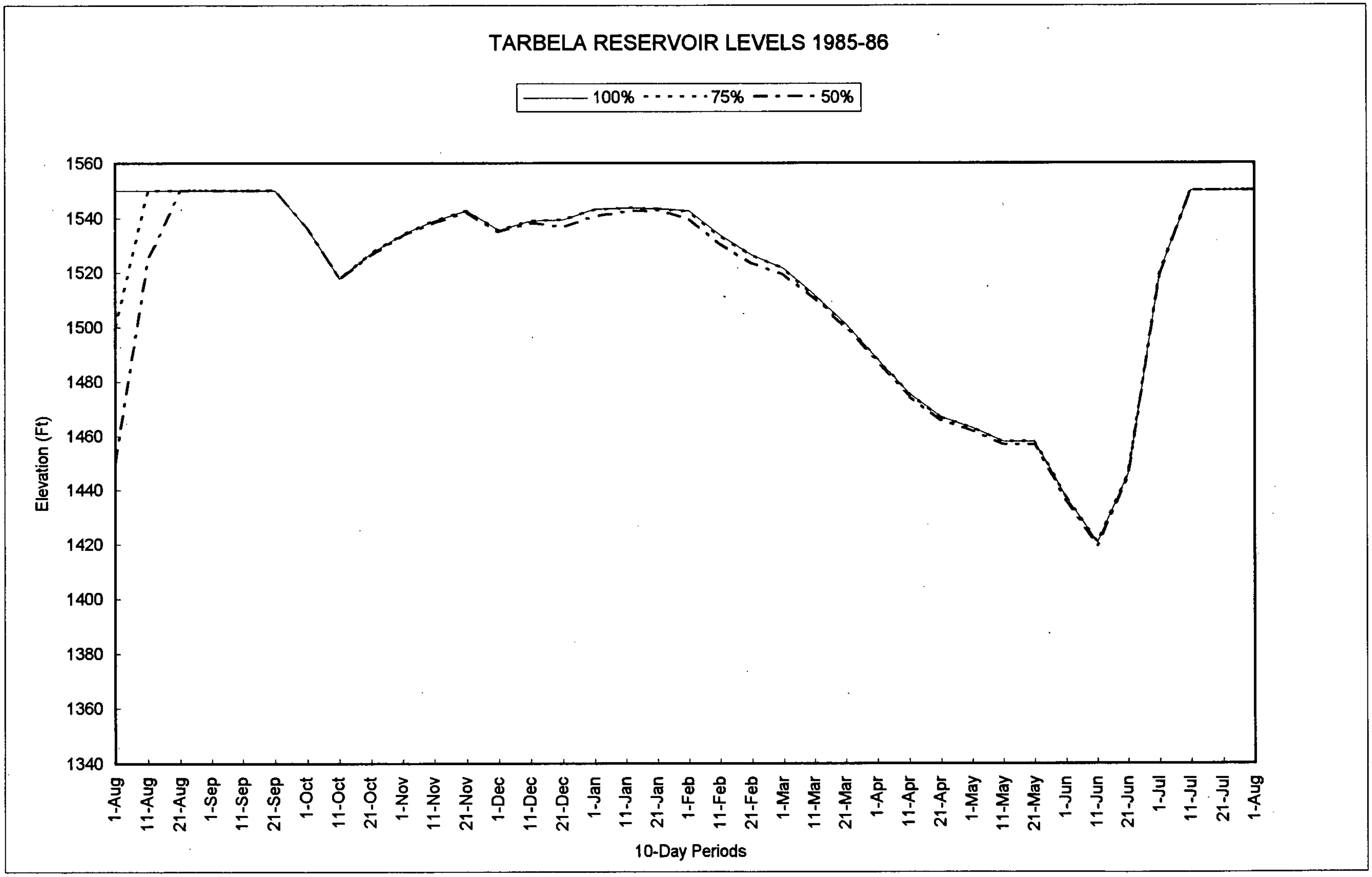

Figure 5.16. Reservoir levels at Tarbela 1985-86; Joint Operation (OF-I)

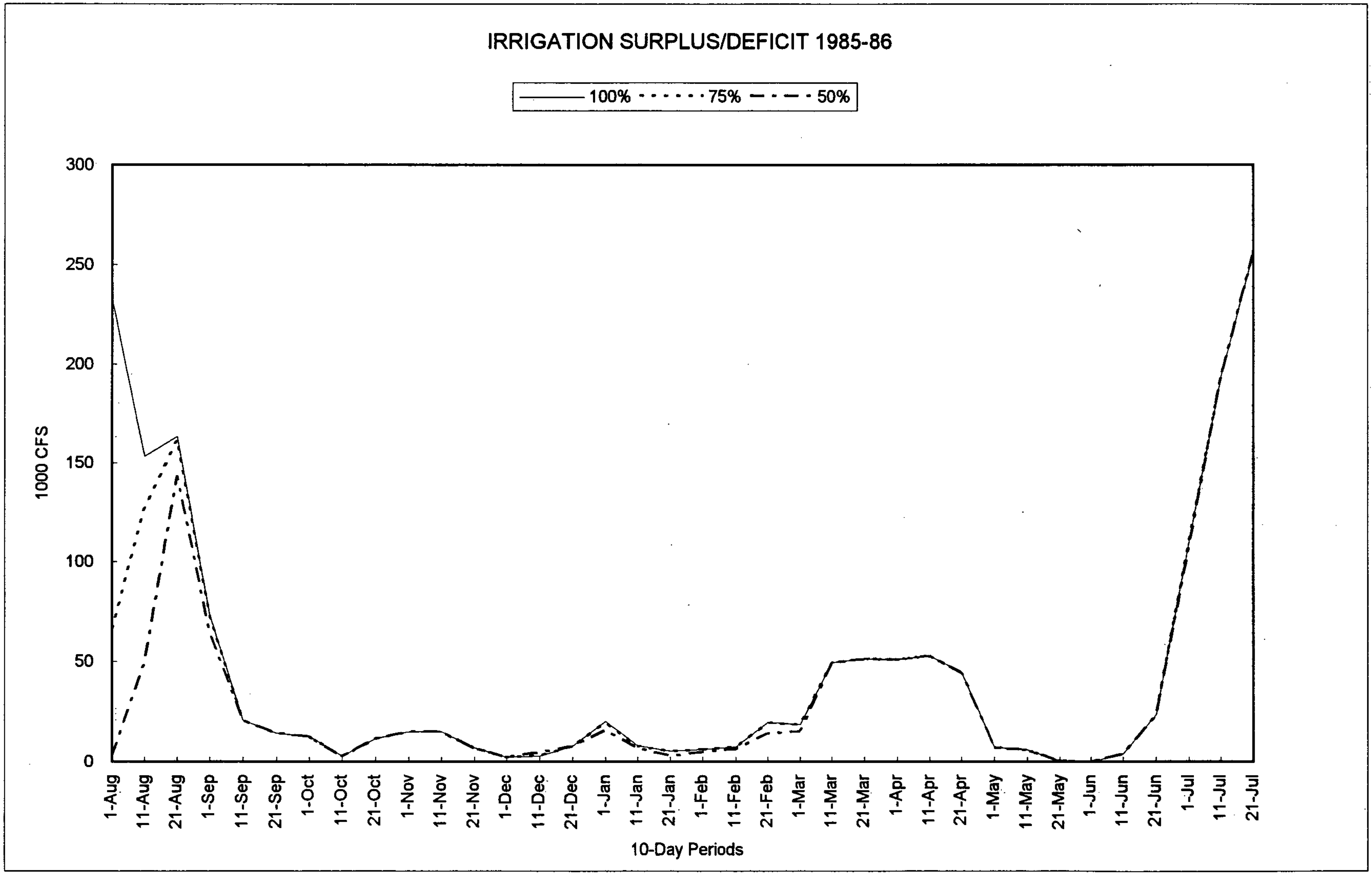

Figure 5.17. Irrigation Surplus/Deficit 1985-86; Joint Operation (OF-I)

5.6 ANALYSIS OF JOINT MANGLA-TARBELA OPERATION

Before continuing discussion on the results of Joint Mangla-Tarbela Operation it would be appropriate to examine the behaviour of the two reservoirs under the following situations; (1) Mangla and Tarbela operating independently, (2) Mangla and Tarbela joint operation under highly correlated hydrologic conditions.

In all subsequent figures the top right corner point (15, 25) refers to the condition when both the reservoirs are full (maximum conservation levels). Similarly, the bottom left corner point (1, 1) refers to the condition where both reservoirs are empty (minimum conservation levels). The states for Mangla and Tarbela represent the reservoir storage levels at the beginning of a particular 10-day period. The optimal releases are in the units 10^3 CFS. The F_n(Sm, St) contours represent cumulative energy production (mkWh) or combined benefits (Million \$) at a particular stage (working backwards from the end of the final stage or 10-day period).

1. INDEPENDENT OPERATION (ACTUAL HYDROLOGIC CONDITIONS): The two-state DP model PK-ROM was modified to make the two reservoirs operate independent of each other by deactivating the subroutine *IrriDems* which imposes constraints on releases from the reservoirs for irrigation purposes. Both reservoirs were thus operating to maximise energy production only.

A typical three dimensional plot of F_n(Sm, St) against state Mangla and state Tarbela is shown in Figure 5.18.

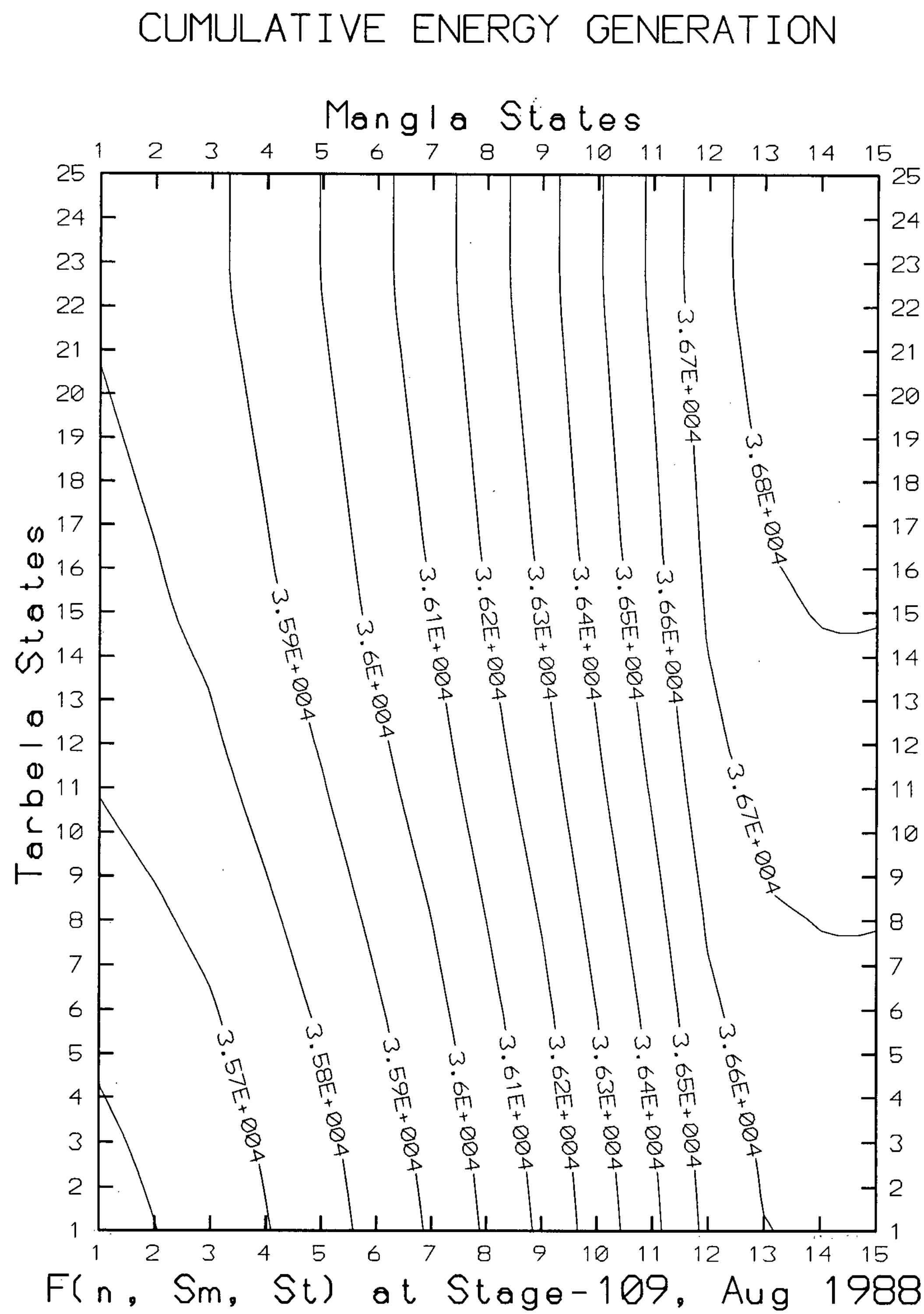

Figure 5.18. Independent operation under actual hydrologic conditions

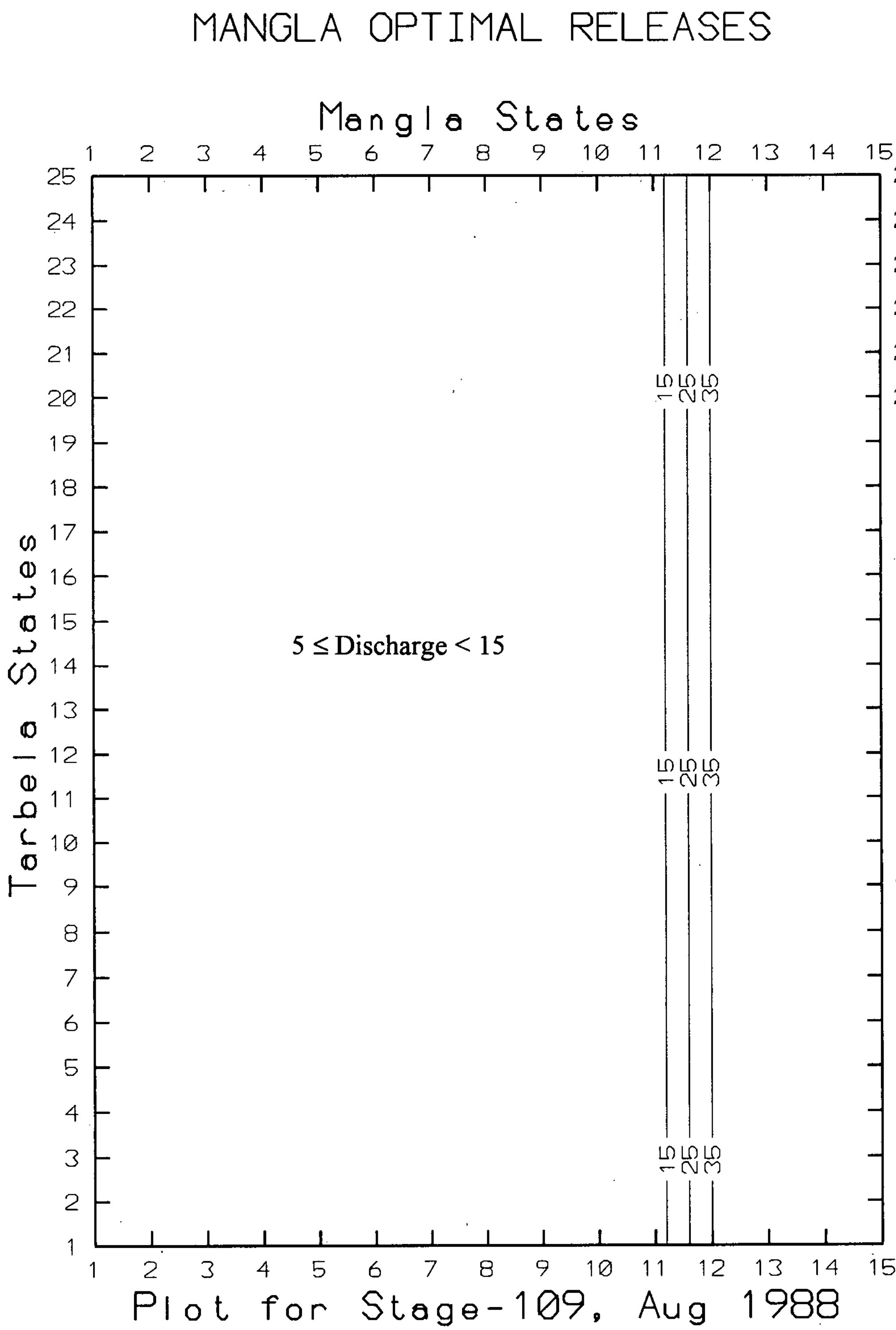

Figure 5.19. Independent operation under actual hydrologic conditions

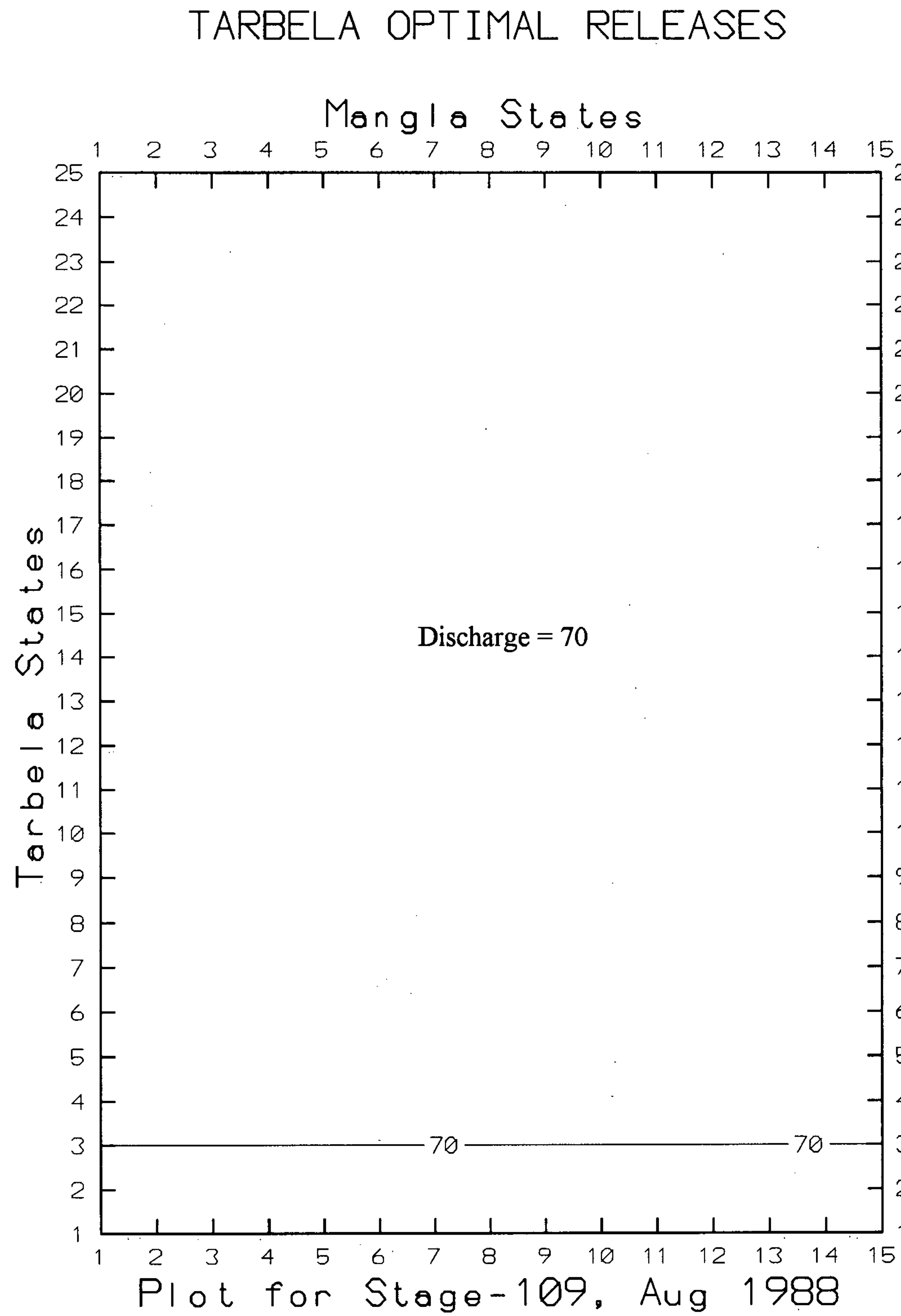

Figure 5.20. Independent operation under actual hydrologic conditions

As can be seen from Figure 5.18, the cumulative optimal energy production over the two year period 1988-1990 increases with increasing states for both projects. This is because the higher states provide higher heads and permit higher discharges for energy generation and there is an unlimited demand for energy. The vertical and horizontal contours in Figures 5.19 and 5.20 reflect that the optimal discharge for one project is insensitive to the other project's state. This reflects the essentially independent operation of the two projetcs under this object.

2. JOINT OPERATION UNDER HIGHLY CORRELATED HYDROLOGIC CONDITIONS: Synthetic inflow data was generated for the five year period 1985-90 for the two reservoirs. Inflows to Mangla reservoir were assumed to be 30% of the inflows to Tarbela reservoir. The model (PK-ROM) was run first using OF-I (maximising energy plus irrigation constraints) and then using OF-II (maximising combined benefits).

There is only about 3% variation in the 2 year cumulative energy production (Figure 5.21a) and about 5% variation in the 2 year cumulative combined benefits (Figure 5.21b) over the entire range of the Mangla and Tarbela states. This suggests that the operation is not very sensitive to the changes in Mangla and Tarbela states. The region of vertial contour lines, in case of OF-I (Figure 5.21a), suggests Mangla state dominates while the region of horizontal contour lines indicates Tarbela state dominates. In the case of OF-II (Figure 5.21b), however, the state "tradeoff" is evenly more balanced indicating an equal influence of marginal storage change at the two projects.

Both Mangla and Tarbela operate independently of each others states during the high inflow period since irrigation demands are being met without diverting any water from the Indus River. Figures 5.22a and 5.22b show the optimal releases (outflows) from Mangla corresponding to different states of Mangla and Tarbela reservoirs at a certain stage (10-day period) in August 1988 which is a high inflow period. Similarly, Figures 5.23a and 5.23b show the releases from Tarbela reservoir during the same stage. Although the contour plots of optimal releases for OF-I and OF-II results show the same pattern the optimal releases are higher at higher Mangla and Tarbela states in the case of OF-II. This is because in the case of OF-I, during high inflow periods, if the irrigation demands are being met by the power tunnels discharge plus the spillway discharge and/or irrigation tunnel discharge, and the palnt output is at its maximum limit then the model does not make any further releases. On the other hand, OF-II makes higher releases (through irrigation and power tunnels) in order to maximise benefits since a monetary value is associated with the amount of water released from the two reservoirs. This is the reason for discharges greater than 40 at Mangla and 70 at Tarbela in case of OF-II in Figures 5.22b and 5.23b respectively. The model, in this case, is releasing more water than is required for irrigation purposes. Setting some upper limits on the irrigation water releases, in the case of OF-Ii, will not only reduce the excess August-September releases but will also help in reducing the irrigation water deficit shown by this approach in the months of May and June.

The Mangla discharges during low inflow periods are in the range of 5 to 15 (1000 CFS) except only under conditions when the Mangla state is high and Tarbela is low. Tarbela's discharges are sensitive to both its own and Mangla's state over the full state ranges since it is the bigger of the two storage projects and, therefore, its states are more dominant in governing the system operation. Figure 5.24 shows the optimal releases (outflows) from Mangla reservoir corresponding to different states of the two reservoirs at a particular stage in

December 1988; a low inflow period. Likewise, Figure 5.25 shows the releases from Tarbela reservoir for the same stage.

There is a discontinuity in the progressive adjustment of Mangla discharges (Figure 5.24) to its own and Tarbela states. Low Mangla discharges (less than 15,000 CFS) are optimal in the low inflow stage (December) except under conditions when either its storage is very high and/or Tarbela is low. There were some irregularities in the contours at very low states for Mangla and Tarbela (not shown in Figures 5.24 & 5.25) which could be attributed to the discretisation of states and decisions inherent in a DP analysis but their cause was not fully investigated in this work.

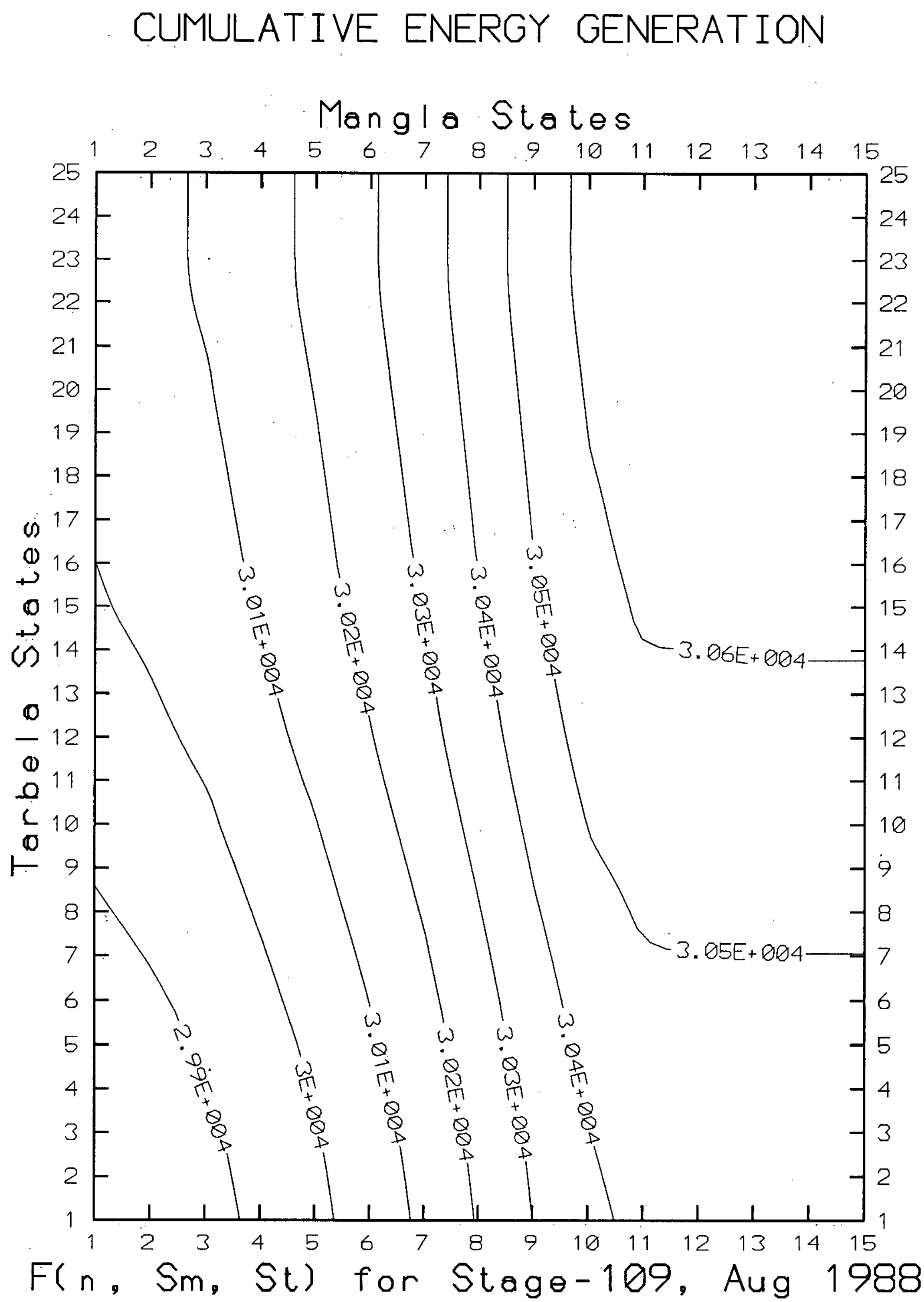

Figure 5.21a. Joint operation under highly correlated hydrologic conditions (OF-I)

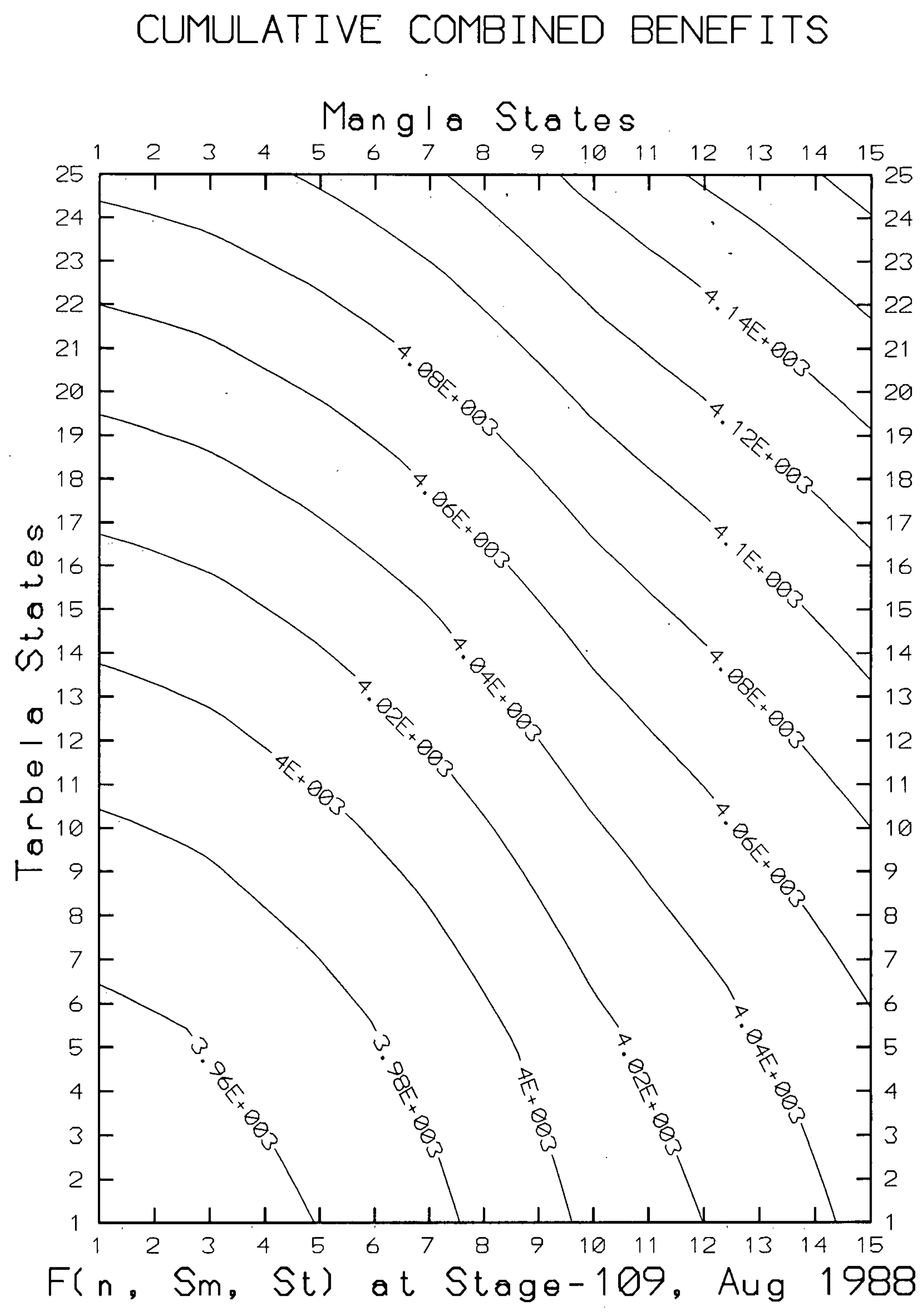

Figure 5.21b. Joint operation under highly correlated hydrologic conditions (OF-II)

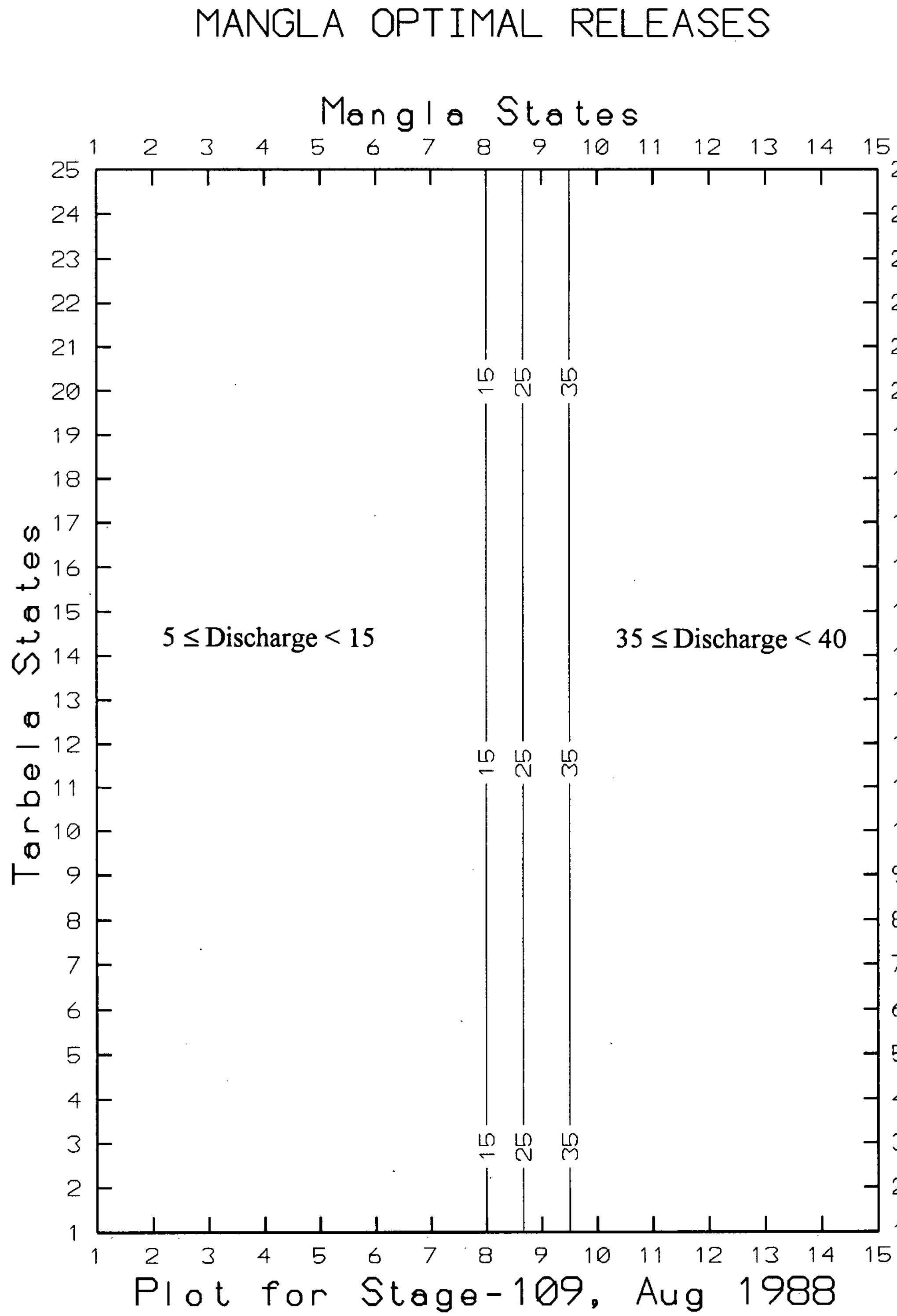

Figure 5.22a. Joint operation under highly correlated hydrologic conditions (OF-I)

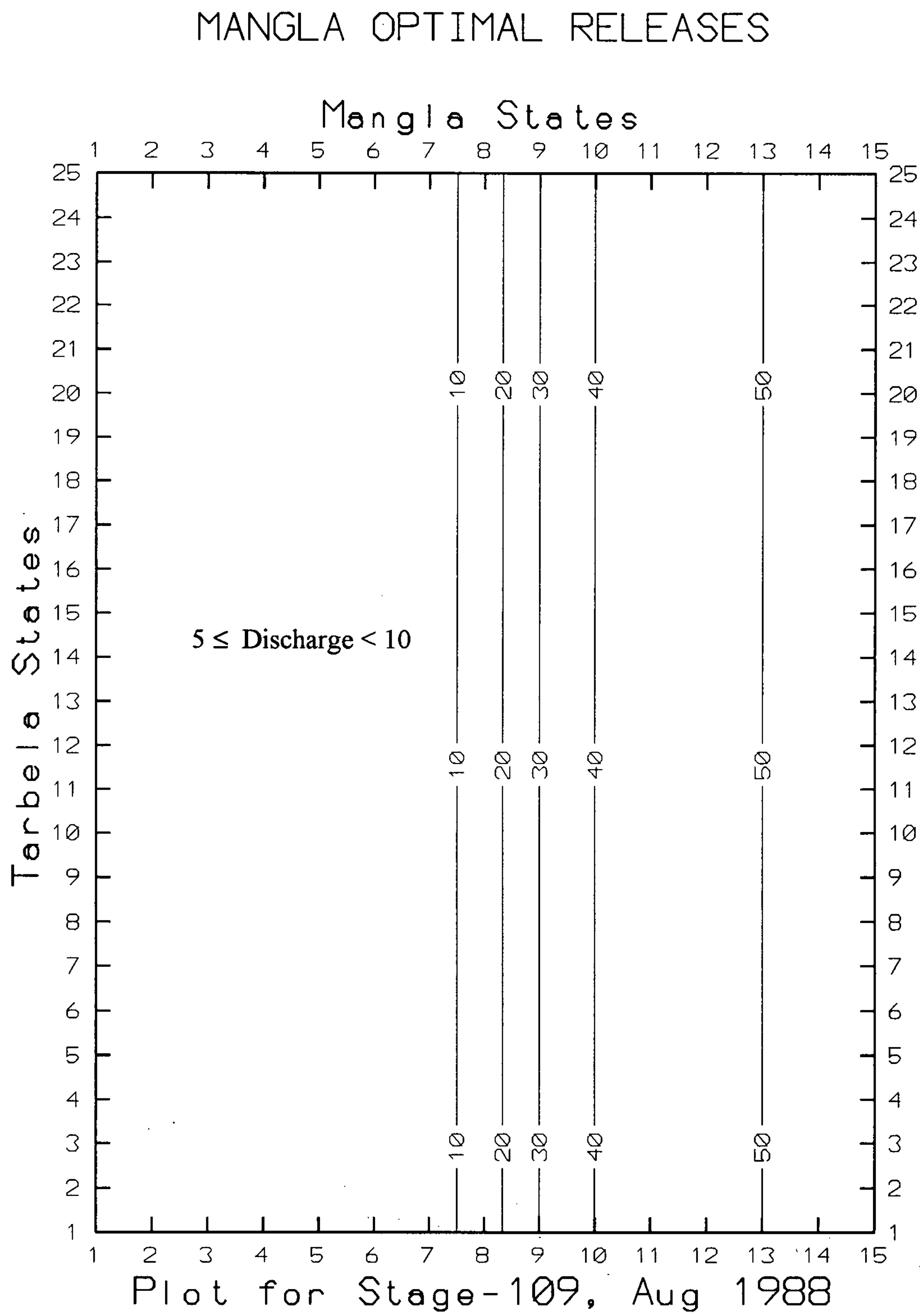

Figure 5.22b. Joint operation under highly correlated hydrologic conditions (OF-II)

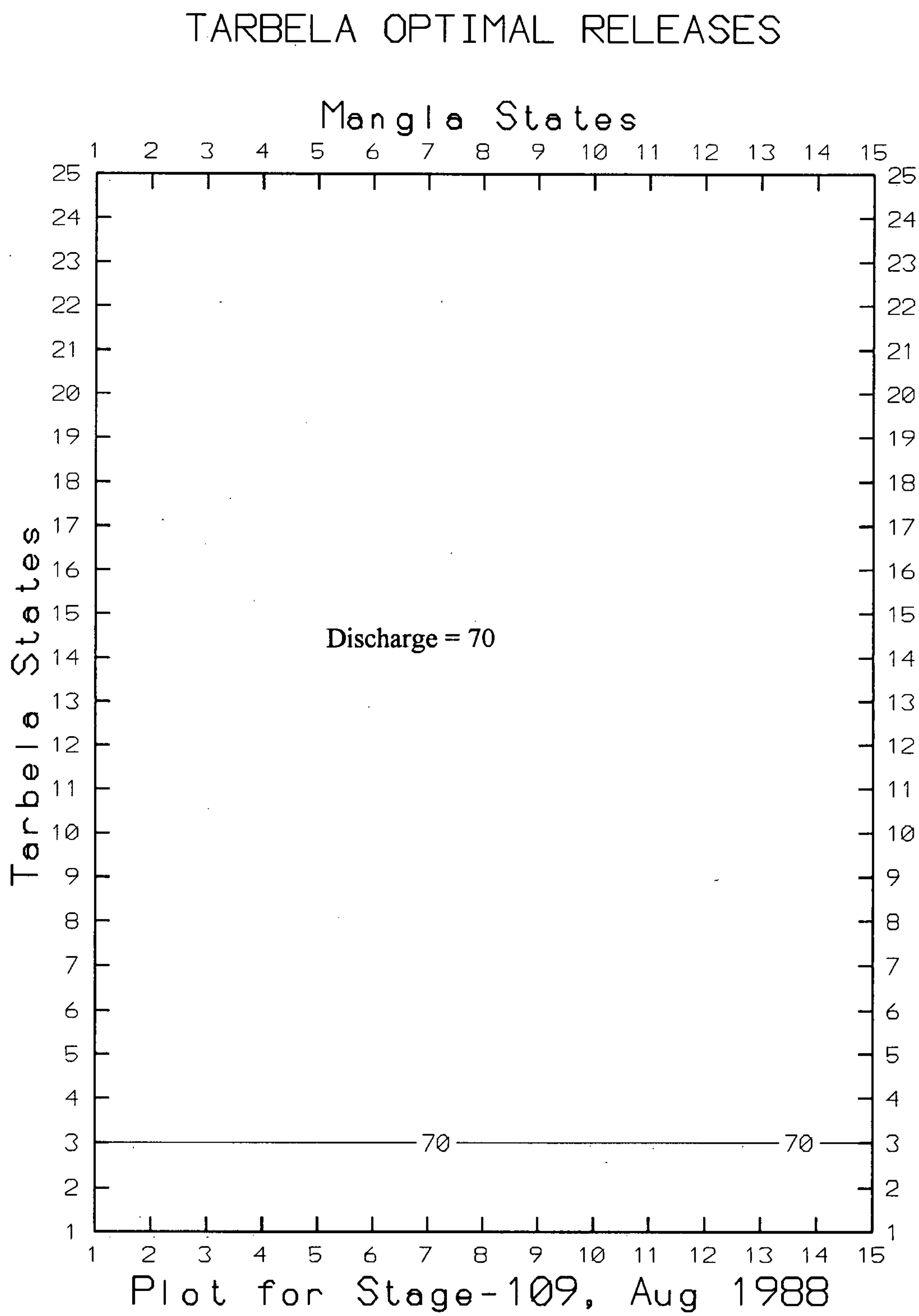

Figure 5.23a. Joint operation under highly correlated hydrologic conditions (OF-I)

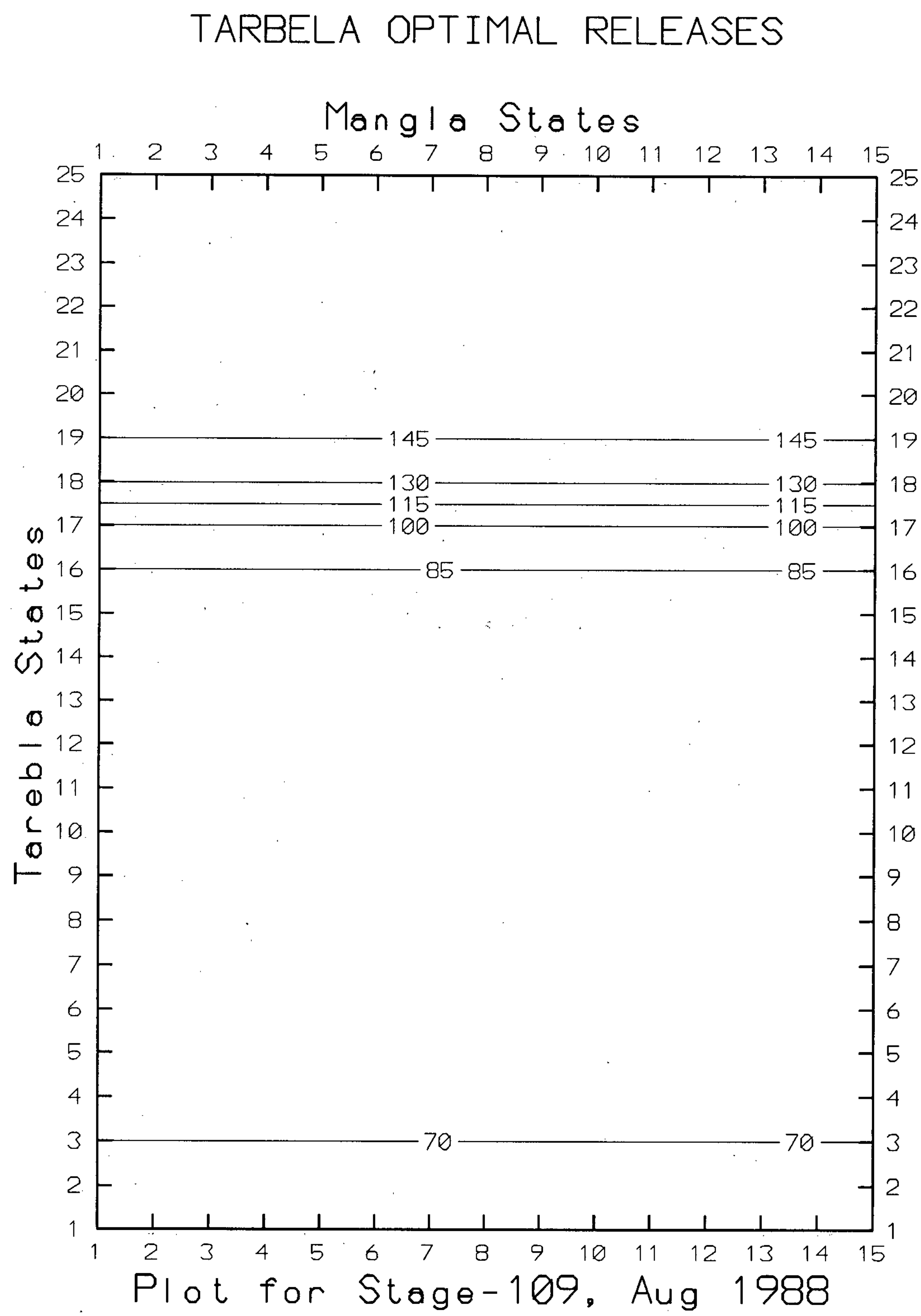

Figure 5.23b. Joint Operation under highly correlated hydrologic conditions (OF-II)

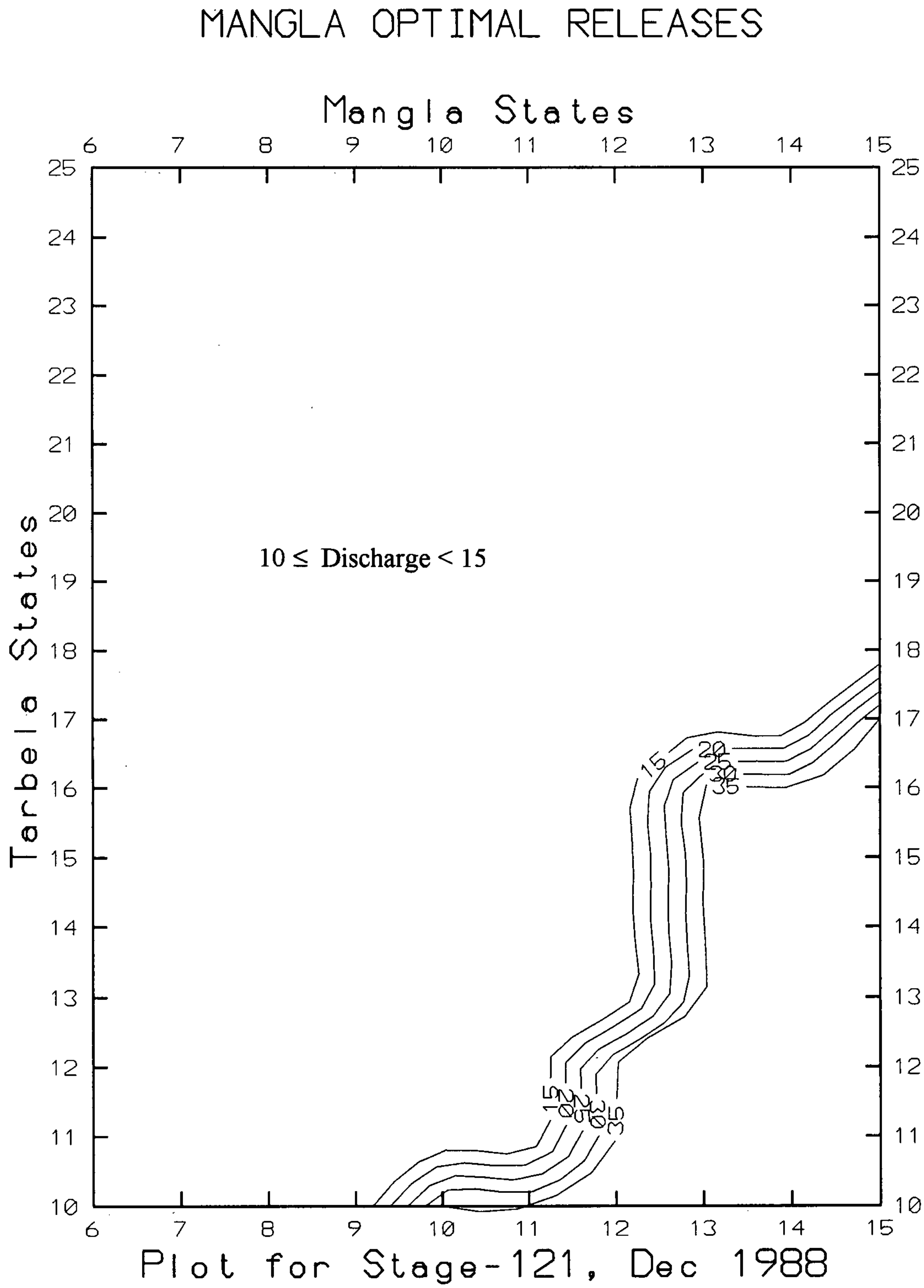

Figure 5.24. Joint operation under highly correlated hydrologic conditions (OF-I)

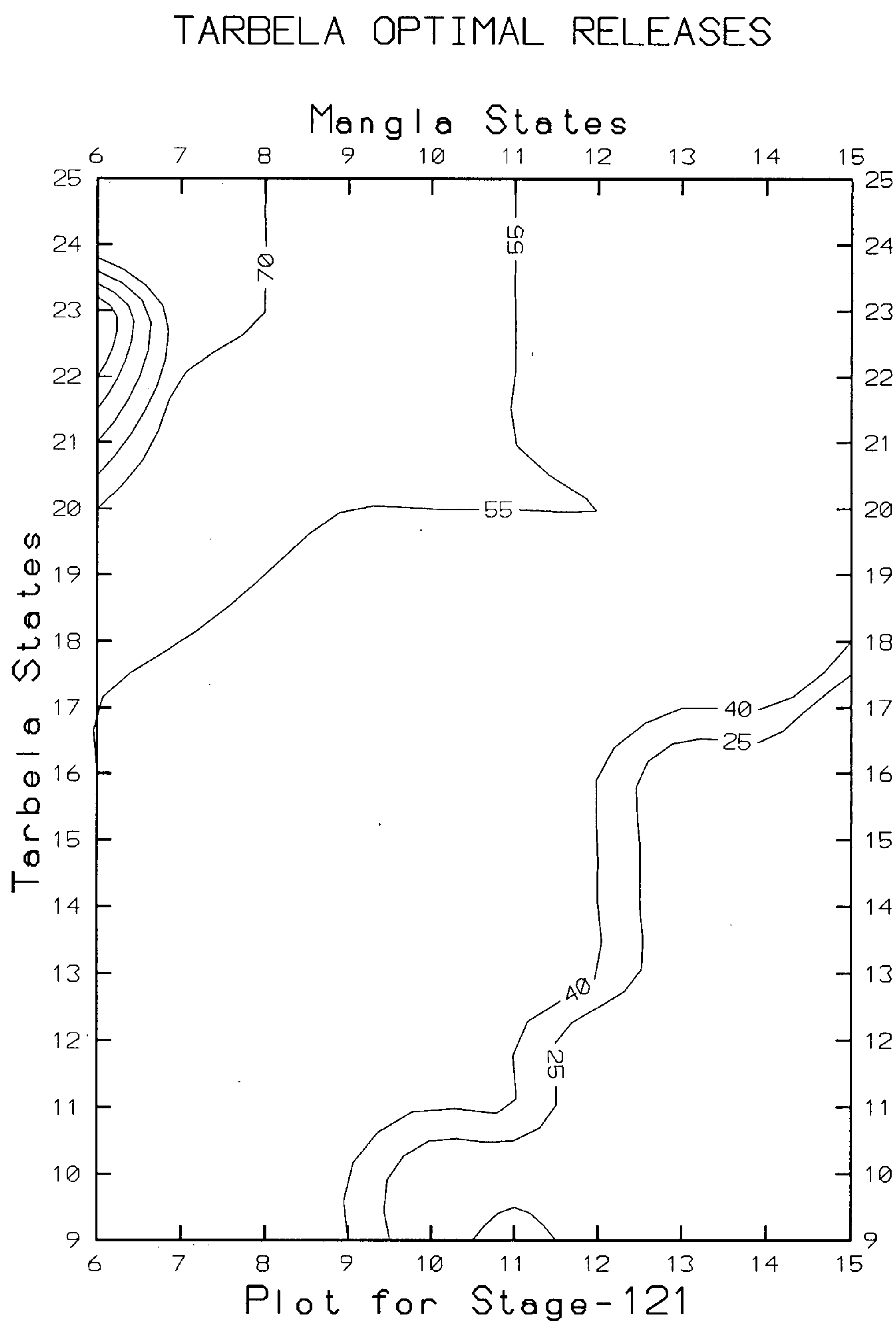

Figure 5.25. Joint operation under highly correlated hydrologic conditions (OF-I)

JOINT OPERATION (ACTUAL HYDROLOGIC CONDITIONS)

The F_n(Sm, St) contours in the case of OF-I (Figure 5.26a), plotted against the Mangla and Tarbela states Sm and St for a typical stage in August 1988, suggest that energy production is more sensitive to the Mangla state except when Mangla state is very high. This is because the stage-storage curve (Appendix I) for Mangla reservoir provides lesser storage between the states 1 to 10. Nearly half the storage volume of Mangla reservoir is contained between states 1-10 and the remaining half between states 11-15. On the other hand, OF-II indicates very similar influence of the two states (Figure 5.26b). The variation in the cumulative energy generation and the cumulative combined benefits, over the full range of the Mangla and Tarbela states, is small (3-5%).

To investigate the cause of the small amount of variation in the cumulative energy generation and the cumulative combined benefits over the entire range of the Mangla and Tarbela states, the inflows in two consecutive years 1986-87 and 1987-88 were reduced by 20% and 30%, respectively, and the model was run using OF-II. The variation in this case at a typical stage in August 1986 i.e., 4 year cumulative combined benefits for a period between 1986-87 to 1989-89 (Figure 5.26c), was approximately 16%. However, the variation in the cumulative combined benefits for the whole five year period (1985-86 to 1989-90) was about 5%. The limited five years of data which has been used in this research does not cover any "worst case scenario", for example, some dry years and/or extremely high irrigation demnads. Therefore, the cause of this small amount of variation in the F_n(Sm, St), over the full range of Sm and St, can not be explained in a greater detail.

Both the reservoirs operate independently during the high inflow periods. The contour plots of optimal releases (outflows), corresponding to different states of the two reservoirs, at the same stage in August 1988, are given by Figures 5.27a and 5.27b for Mangla, and by Figures 5.28a and 5.28b for Tarbela. The lower portions of Figures 5.29 and 5.30, which are, respectively, the contour plots of optimal releases (outflows) from Mangla and Tarbela reservoirs during a low inflow period in December 1988, suggest that the state of one project can influence the optimal discharge in the other. Whereas in the upper portions of these figures, except at the very top states (where reduction in spilling governs) the vertical contours indicate that the Mangla state dominates any adjustment in discharge at both project. The reason is that Mangla reservoir has to release more water to meet the irrigation demands of the Upper Jhelum region, which is served only by the Mangla reservoir, for the Rabi season.

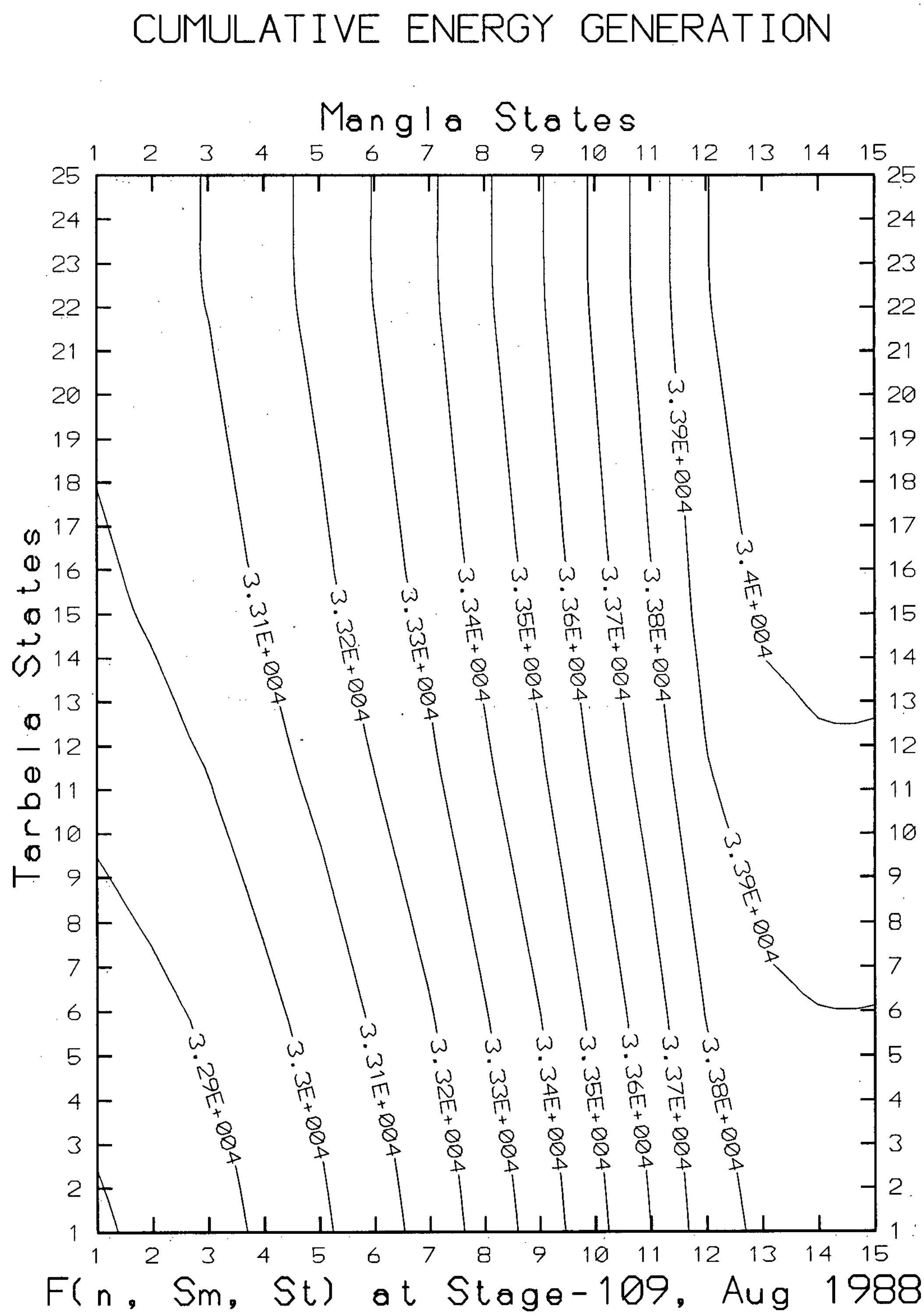

Figure 5.26a. Joint operation under actual hydrologic conditions (OF-I)

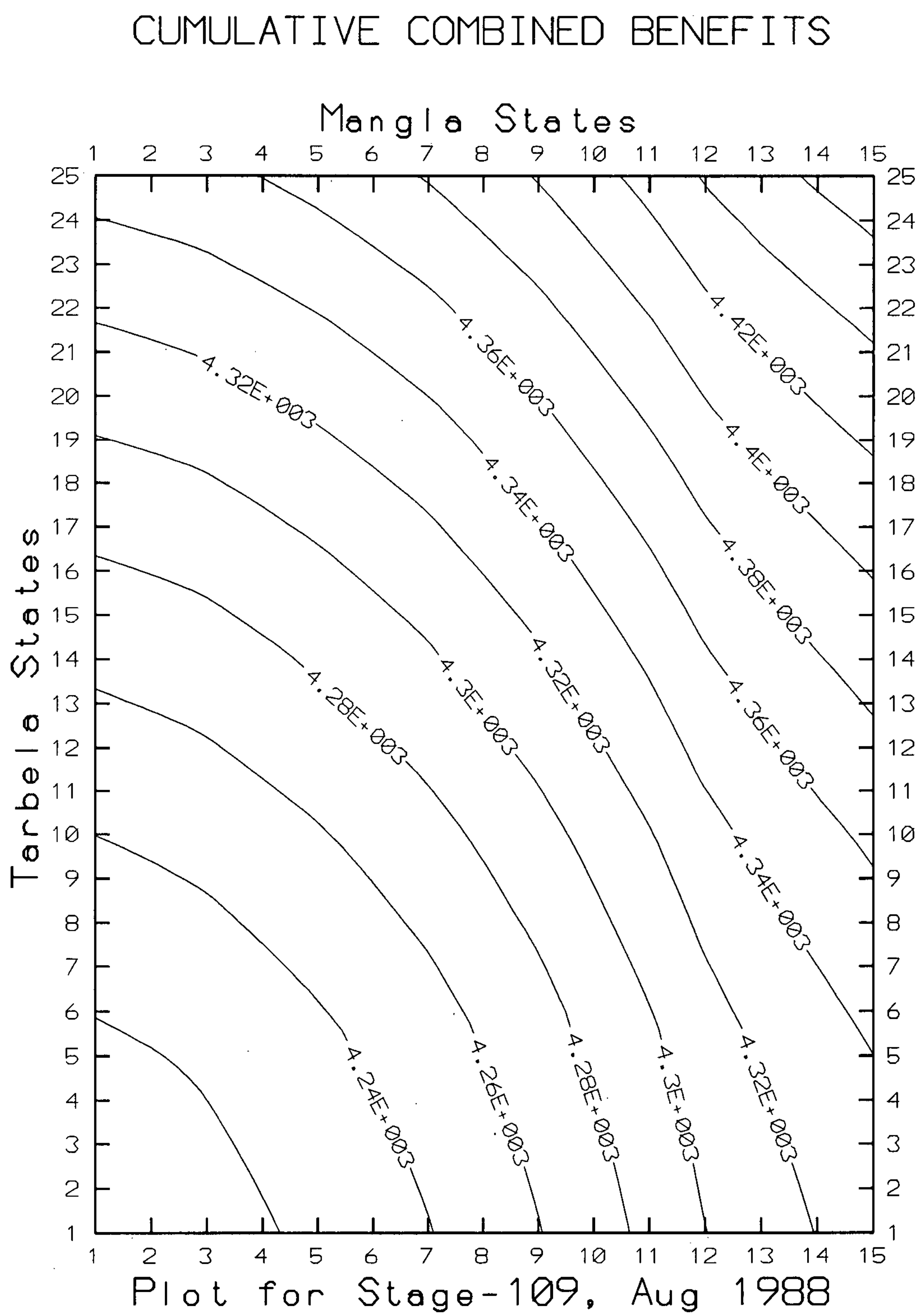

Figure 5.26b. Joint operation under actual hydrologic conditions (OF-II)

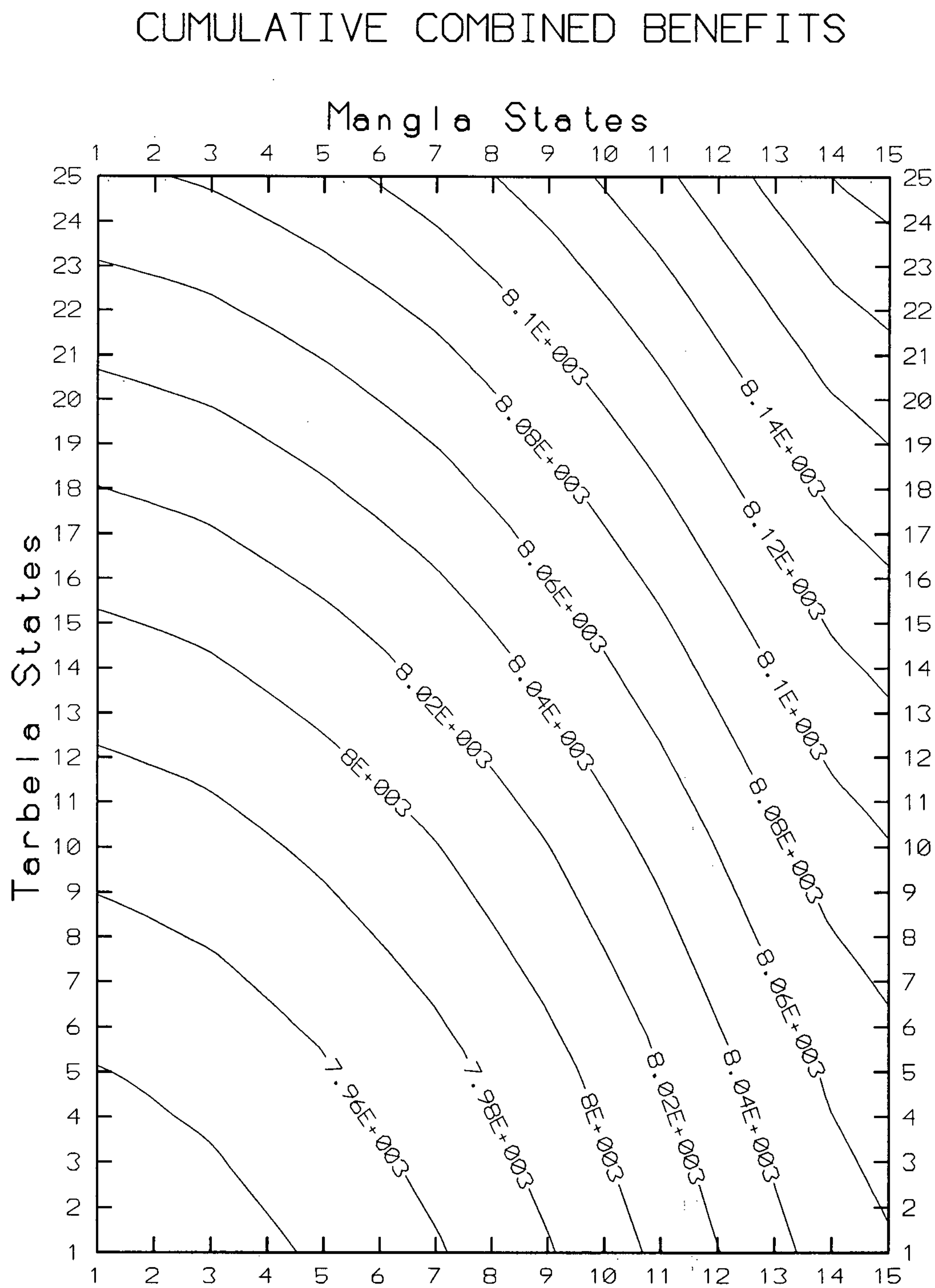

Figure 5.26c. $F_n(Sm, St)$ contours in case of Joint Operation under "dry" conditions (Synthetic inflow data for the years 1986-87 and 1987-88).

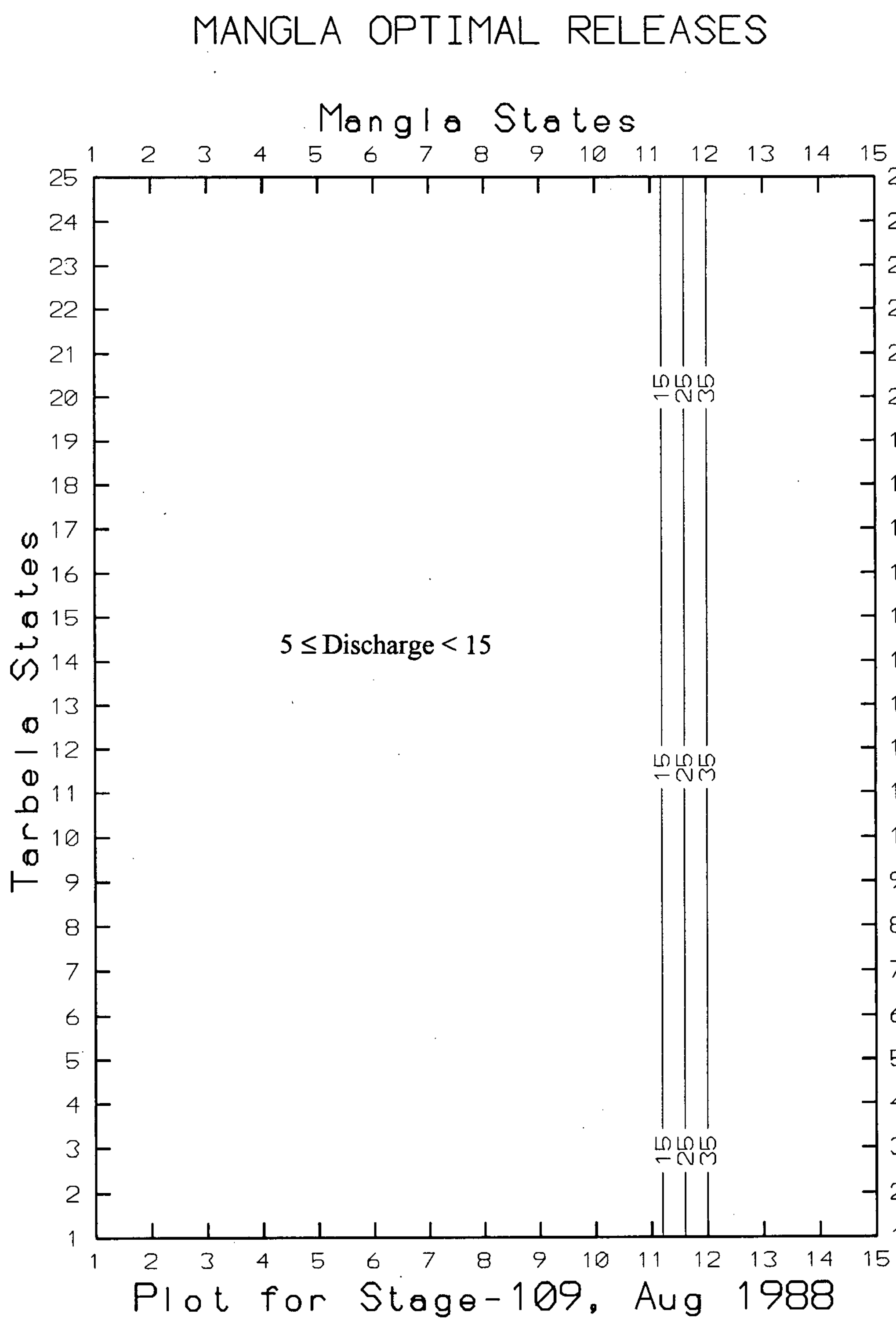

Figure 5.27a. Joint operation under actual hydrologic conditions (OF-I)

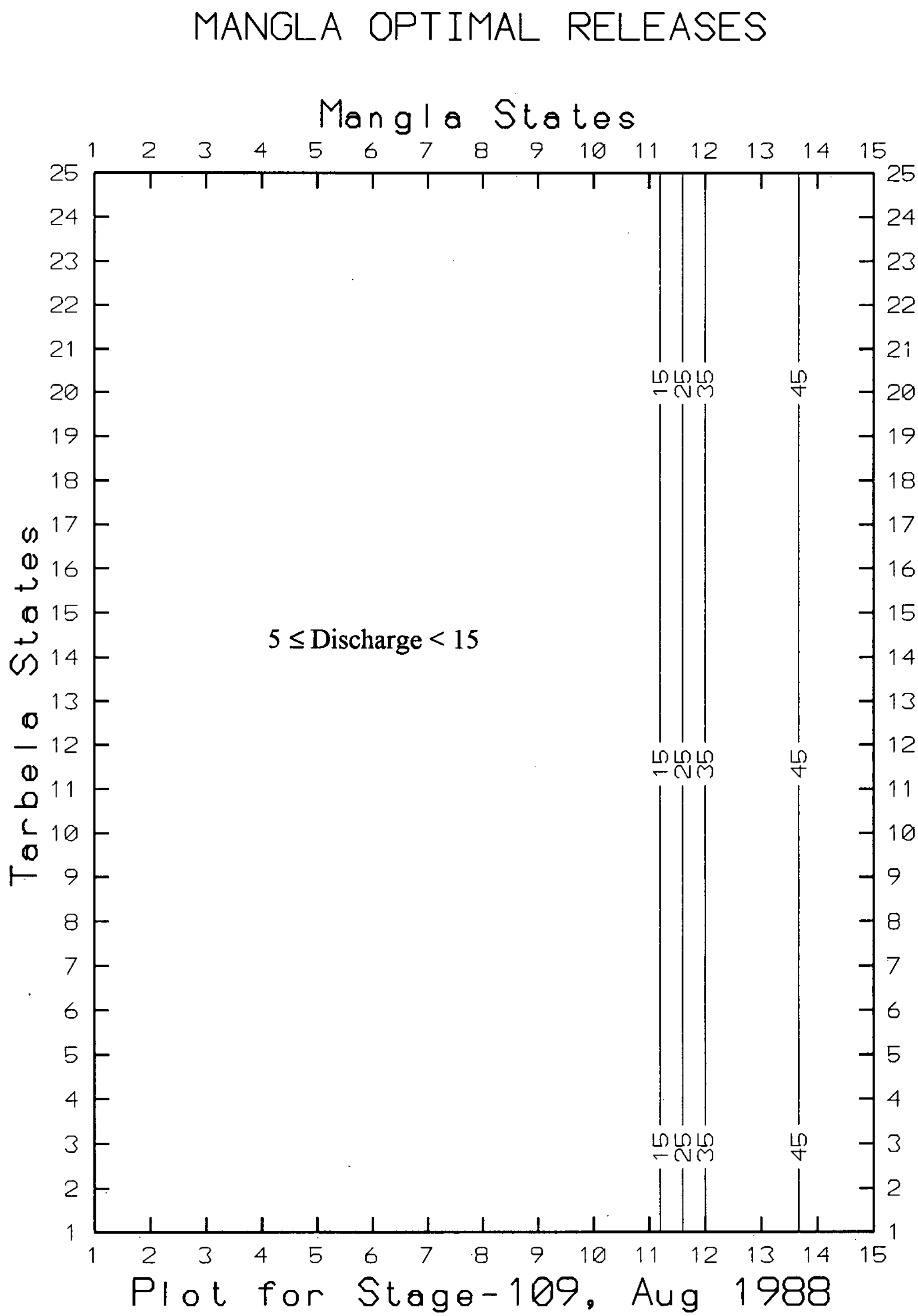

Figure 5.27b. Joint operation under actual hydrologic conditions (OF-II)

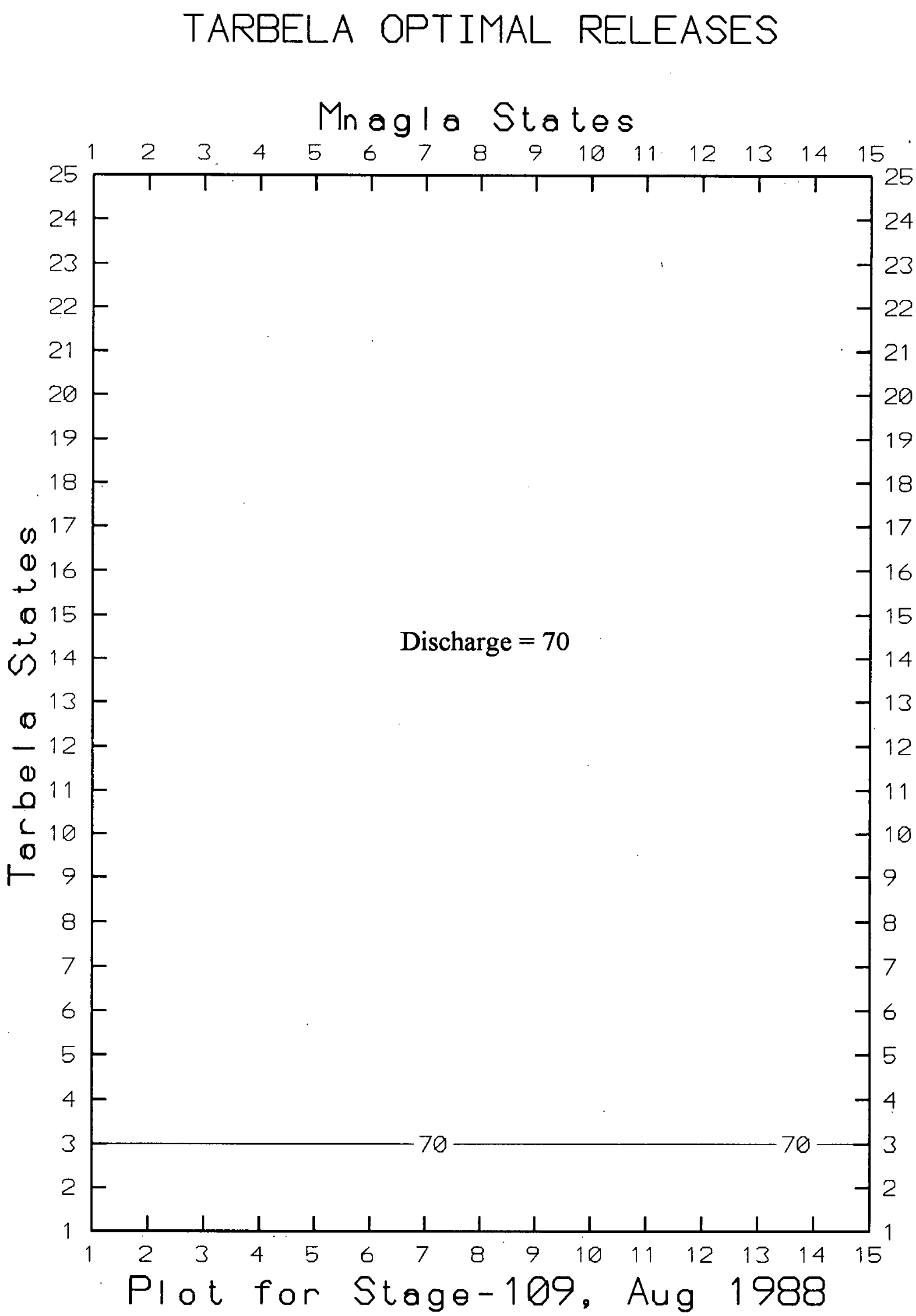

Figure 5.28a. Joint operation under actual hydrologic conditions (OF-I)

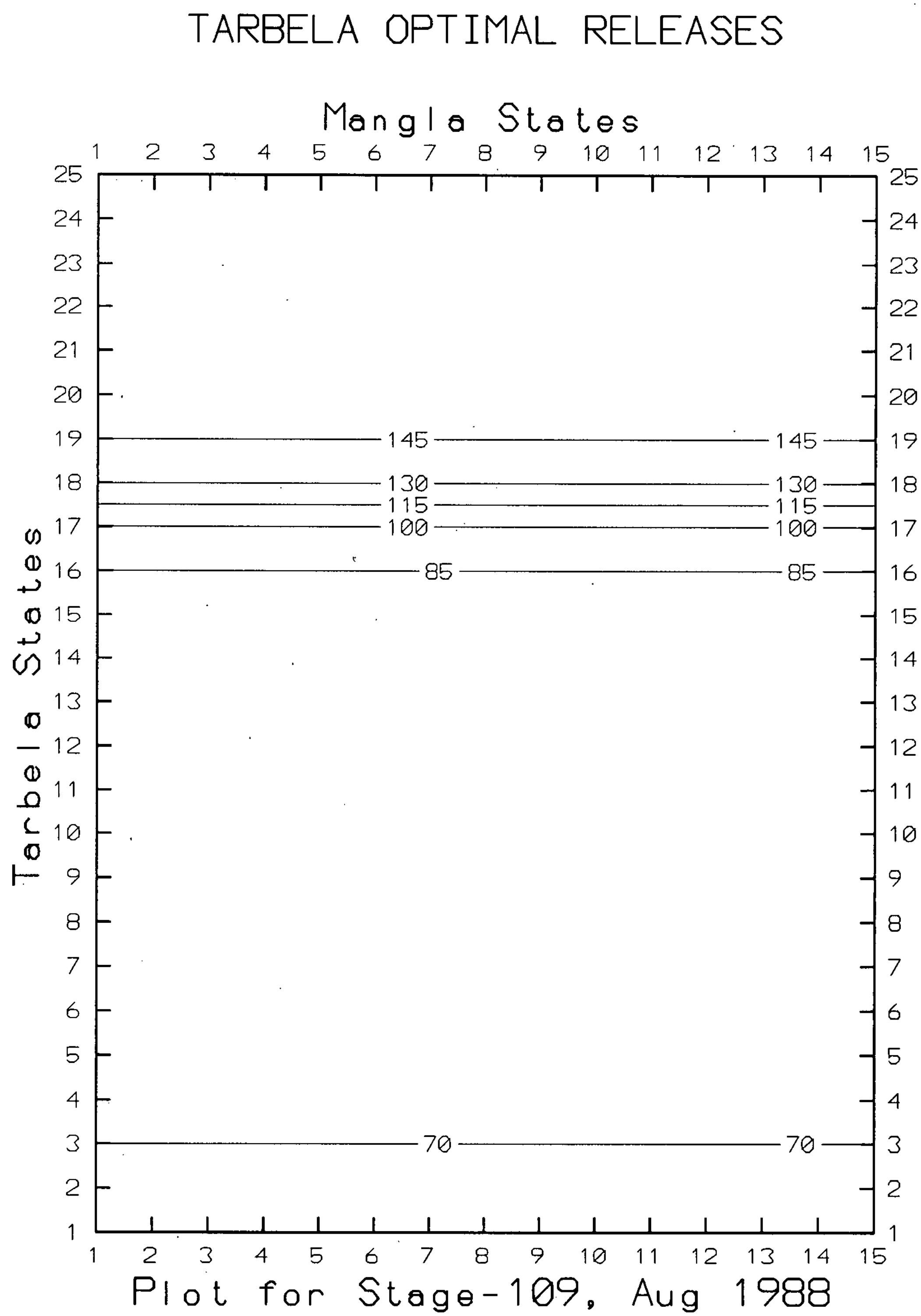

Figure 5.28b. Joint operation under actual hydrologic conditions (OF-II)

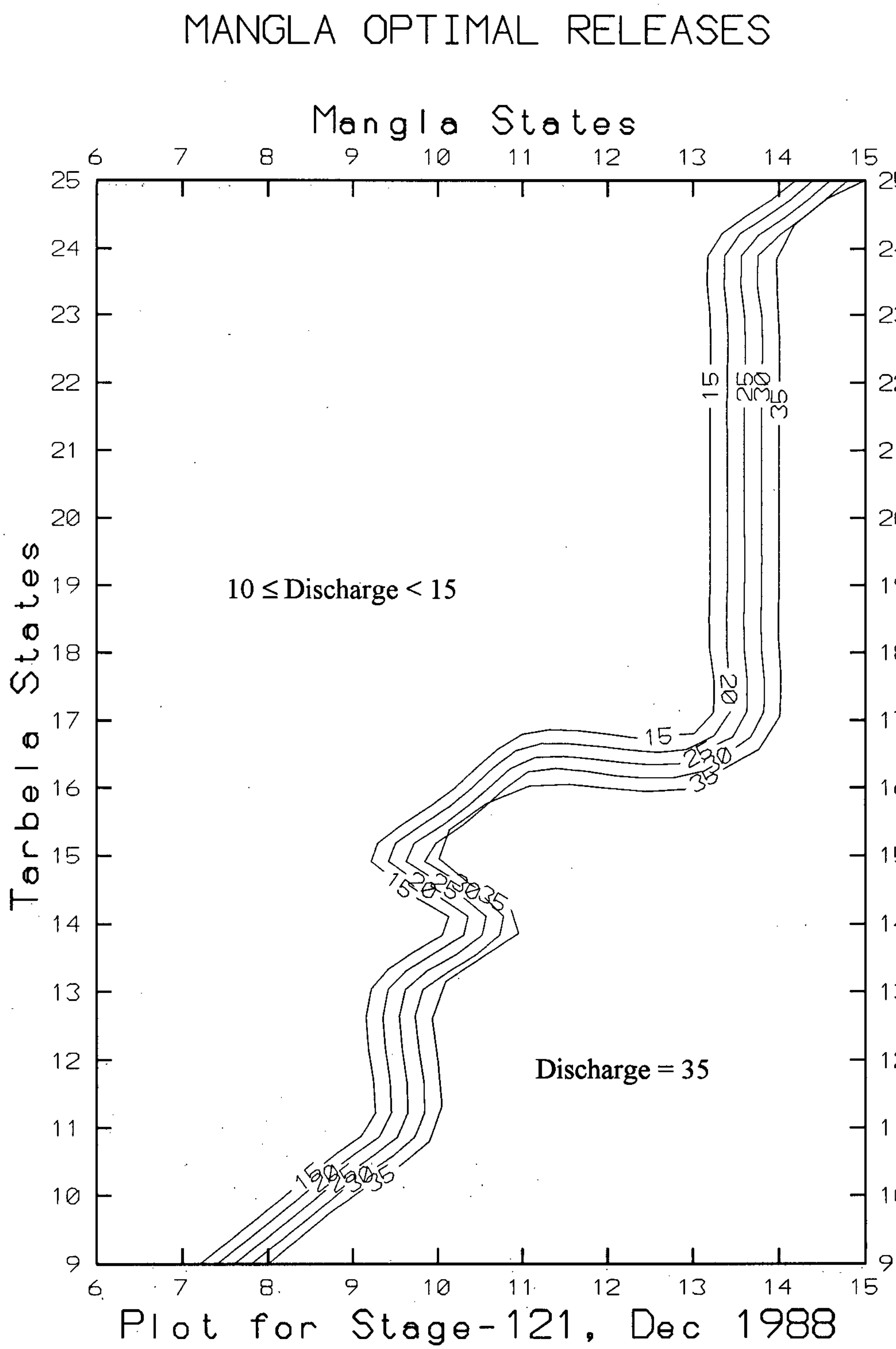

Figure 5.29. Joint operation under actual hydrologic conditions (OF-I)

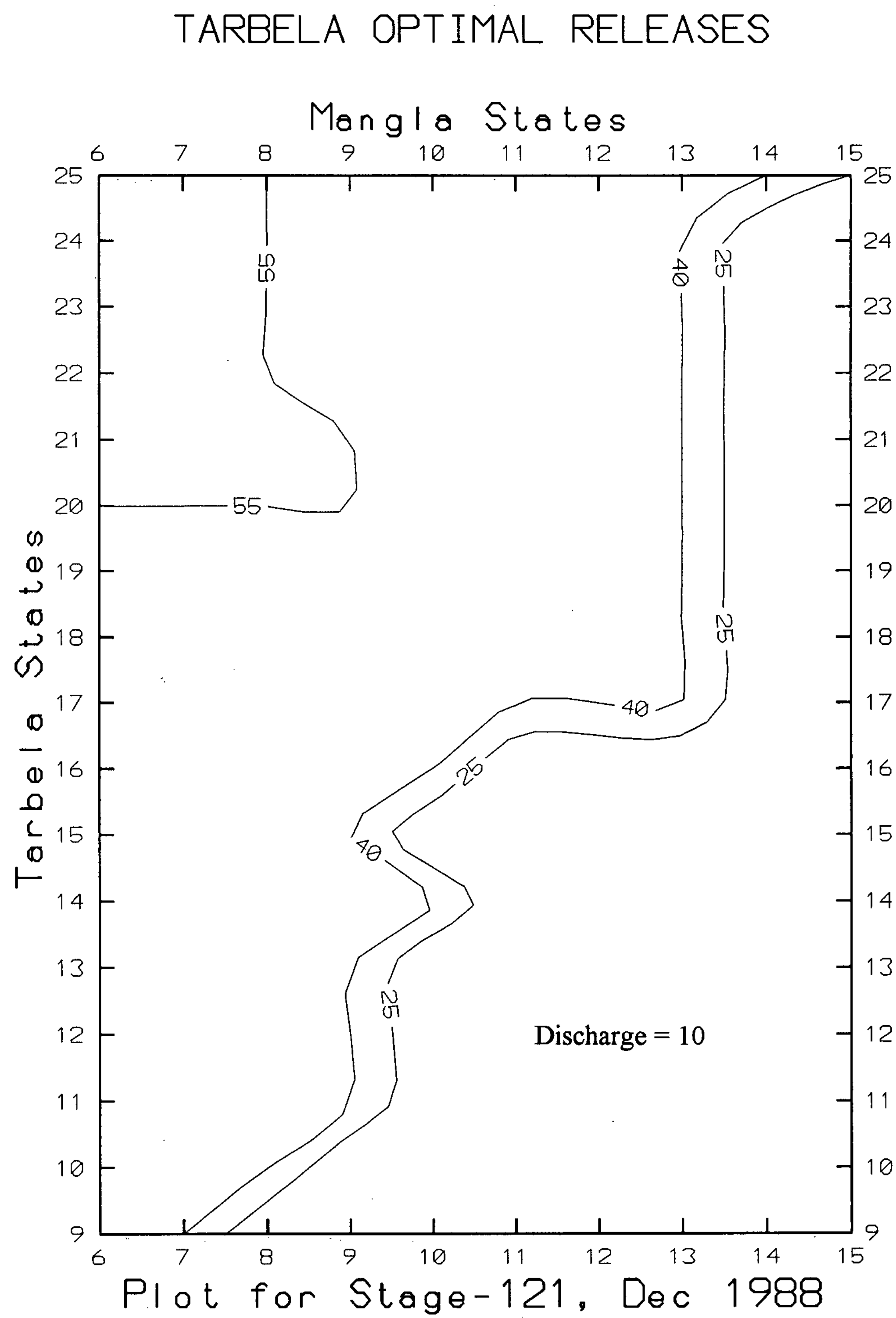

Figure 5.30. Joint operation under actual hydrolgic conditions (OF-I)

CONCLUSIONS AND RECOMMENDATIONS

6.1 GENERAL

In the course of this research three methods were developed, one using single-state DP and two using two-state DP, to maximise the benefits resulting from the operation of Mangla and Tarbela reservoirs. The operational conditions investigated in this optimisation process were:

I. Independent reservoir operation (single-state DP).

II. Joint Mangla-Tarbela operation (two-state DP);

  a) Maximising energy production with constraints on irrigation water supply (OF-I).

  b) Maximising combined benefits from energy production and irrigation water supply (OF-II).

Most of the information on the Indus River System and the Mangla and Tarbela Reservoir Systems was obtained from World Bank Reports (1969) and the Project Direction and Review Report (PSIHP, WAPDA-BCHIL 1991). The historic inflow and operational data for the two projects was provided by Les Parmley, Sr. Engineer, BC Hydro International Ltd. Although data for a limited period (5 years) was analysed in this research, the results do provide some insight into the joint operation of the Mangla and Tarbela reservoirs.

6.2 CONCLUSIONS

The optimisation results of the DP computer model have already been discussed in chapters 4 and 5. A comparison of these results with the actual operation of the two reservoirs during the period 1985 to 1990 reveals the following general information about the aforementioned approaches.

1. The Mangla operation, for all the three methods, matches closely with the actual operation of the reservoir especially in the years 1985-86 to 1987-88. But the difference between the calculated and recorded energy values for Mangla is 3.0% on the average. The same discrepancy was also observed by Les Parmley in his spreadsheet simulation program for the Mangla and Tarbela reservoirs using the same data as has been used in this research. The findings of this simulation program are mentioned in the Project Direction and Review Report (1991). According to this report, the difference between the calculated and recorded energy values is primarily the result of different operating procedures. In the DP model and the spreadsheet program as well, all reservoir outflows up to the full discharge capacity of the turbines are passed through the units. Until September 1991, however, Mangla and Tarbela hydroelectric plants were being operated as peaking plants with the thermal plants providing the base load. This resulted in a large portion of the reservoir outflow being released through irrigation outlets instead of through the turbine/generator units. For Tarbela reservoir, however, there is a considerable difference between the operational procedures suggested by the three DP models and the actual operational

drawdowns that occur at Tarbela reservoir. The difference between the calculated and the recorded energy values (over 9%) is also much greater for Tarbela reservoir.

2. Both reservoirs operate independently of each other, even with the two-state DP model for joint operation of the two projects, during the high inflow periods (later part of Kharif season). This indicates that the inflows to Mangla reservoir were sufficient to make releases for meeting the irrigation demands of the Upper and Lower Jhelum regions and no water was required to be diverted from the Indus river for this purpose.

3. During the low inflow periods (first half of Rabi season) except at very high storage states the Mangla state dominates any adjustments in the discharge at both projects. This is probably due to the irrigation demands of the Upper and Lower Jhelum regions which are at their peak during that time of the year.

4. The results also suggest that outflows from the two reservoirs can be increased during the early Kharif period (April-May) to increase energy production because the July-September inflows are sufficient to ensure refilling of the two reservoirs by the end of the Kharif season. This aspect of operation of the two projects, however, depends upon the reliability of forecast information of the future inflows.

5. Drawdowns for the two reservoirs are less than the actual values thereby increasing the flood risk especially at Tarbela. This, however, is consistent, to some extent, with the recommendations of the World Bank Report (1968) "Water and Power Resources of West Pakistan". The report suggests to keep the drawdown levels at Tarbela above El. 1332 ft. during the first 30 years after its construction and above El. 1400 ft. afterwards, in order to maximise energy production. Drawdown levels have a substantial effect on the

capability of power plants and consequently the amount of thermal energy required to meet the loads. An additional benefit of holding the reservoir levels up high would be to lessen the sedimentation effects by holding the advances of sediment, wedged down the reservoir, further upstream.

6. The minimum discharges from Mangla and Tarbela, as calculated by the model during the low inflow periods (Oct-Nov), are 5000 CFS for Mangla and 10,000 CFS for Tarbela. Under actual operation during 1985-90 the minimum discharges at Mangla and Tarbela (usually in January) were, on average, 10,000 CFS and 15,000 CFS, respectively, while the minimum outflows during October-November averaged 20,000 CFS at Mangla and 45,000 CFS at Tarbela under actual operation. This matter needs further investigation since it appears to be the only factor responsible for higher drawdown levels, as calculated by the DP model, especially in case of Tarbela reservoir. Unfortunately, no information regarding any restrictions on the minimum flows downstream of Mangla and Tarbela reservoirs, other than the demands for irrigation water supply, could be obtained from WAPDA.

7. The total five-year energy production at Mangla and Tarbela increased by 6.6% and 7.2% in the independent operation and the joint operation using OF-I, respectively, while the increase was 13.3% for joint operation using OF-II. The unit outages at Mangla and Tarbela power plants, either for scheduled maintenance or because of operating problems, were not taken into account in the DP models. These considerations, if taken into account, can bring down the above percent increases in energy production to some extent.

8. The optimisation results have shown little variation in the cumulative return $F_n(Sm, St)$ over the full range of the Mangla and Tarbela states (refer to section 5.6). The reason for this was that the data used in this research did not cover any severe conditions (e.g., dry years and/or high irrigation and power demands) and the years thus tested in the optimisation process were "water rich" which is evident from the large irrigation surpluses throughout the whole five-year period. The model was also run using synthetic inflow data for the years 1986-87 and 1987-88, the inflows being reduced by 20 and 30% respectively, for the two years. The variation in the $F_n(Sm, St)$ values at a typical stage in August 1986 was found to be approximately 16%.
9. Joint operation of Mangla and Tarbela reservoirs for maximising energy production with constraints on irrigation water supply, OF-I, not only increases energy production but also deals with irrigation requirements in an adequate manner. However, the discharges keep fluctuating during the Rabi season (Oct-Mar) in response to the variations in 10-day irrigation demands, thus, affecting the efficiency of the power turbines.
10. OF-II gives the maximum energy production (an increase of 13.3% over actual energy generated at Mangla and Tarbela during 1985-90). However, the results show deficits in irrigation water supply in the months of May and June. This suggests the need for revising the monetary values associated with energy and irrigation benefits. The minimum 10-day energy generation also increased to over 100 mkWh as compared to the actual (recorded) value of 80 mkWh. One important aspect of this approach is that it maintains a more constant discharge through the power tunnels throughout the year.

6.3 SUGGESTIONS

Based on this research, the following suggestions are made to modify the DP model in order to further improve its performance.

1. A finer increment of 2 ft., instead of 10 ft. as used in the model, for the state variables would greatly improve the accuracy of the method. This would, however, greatly increase the computational and memory requirements and the model, requiring a high speed machine.
2. In the DP model a constant turbine/generator efficiency of 85% was assumed for simplification. Since the performance of turbines is also affected by the head under which they operate thus affecting their efficiency, this factor has to be taken into consideration in the DP formulation of the optimisation model.
3. There is considerable loss to evaporation at both Mangla and Tarbela reservoirs. Therefore, evaporation losses must also be considered. This requires a little modification in the continuity equation which now becomes

$$s' = s + I_n - d_n^s - e_n$$

The inclusion of the evaporation term e_n poses no difficulty, since evaporation is a function of the average storage, which is equal to $1/2(s + s')$, and the time of the year.

4. More information regarding the limits on minimum releases from the two reservoirs must be obtained; the limits being imposed with regards to irrigation demands, minimum flow requirement to prevent salt water intrusion, turbine efficiency, and demands of other hydro-power projects downstream of Mangla and Tarbela reservoirs.

5. For flood mitigation some reserve in storage must be made at both the reservoirs. Any operation that reduces the amount of spill such as delaying filling of the reservoirs would result in potential flood reduction in years of high floods by indirectly providing flood storage. However, there is an associated risk of not filling the reservoirs with potentially severe social, economic, and more importantly, political consequences.
6. Impacts of hydro projects downstream of Tarbela reservoir, such as Ghazi-Barotha Hydel Power Project (presently under development) and the role of Chashma Barrage which provides regulation of Indus waters, also need to be taken into consideration.
7. The performance of the DP model using OF-II (maximising combined benefits from power and irrigation) can be greatly improved by reviewing the monetary values assigned to irrigation and power benefits and by introducing some constraints on the releases for irrigation water supply.

6.4 FUTURE RESEARCH

Based on the experience of this research, a real-time operational model can be developed for the multi-purpose multi-reservoir system in Pakistan. An optimal decision model for real-time operation can be considered as decomposable into long- and short-term models. These models require corresponding reservoir inflow forecasts. Commonly, the long-term model looks ahead over a time space of an year with seasonal, monthly, or weekly time increments. It should be updated each time increment. The short-term model looks ahead in accordance with the above time increments (over a time span of 7 to 30 days) with daily increments and should also be updated (Yeh, 1985; and Yazicigal, 1983). The daily model also needs to consider outages at power plants and canal closures for repairs and maintenance.

For the Indus River System, the long-term optimisation model can be operated on a ten day time increment for a period of one year (covering the Kharif and Rabi seasons) beginning the first of April, the start of the Kharif season. A set of year-end reservoir states for Mangla and Tarbela reservoirs can be determined from prior experience or from other overall considerations on a grosser scale.

One approach, as suggested by the *Project Direction and Review Report* (WAPDA-BCHIL, 1991), is to use each historical weather sequence used to produce an inflow forecast as the basis for forecasting irrigation and power demands. Thus, if ten sequences of historical weather data are available to produce ten inflow forecast hydrographs, then ten associated sets of irrigation and power demand forecasts could be produced. For each inflow forecast hydrograph and associated irrigation and power demand forecasts, an optimal sequence of releases could be determined by using the DP model. This would give ten operational strategies, each associated with benefits and risks (probabilities of occurrence). From these, an operational strategy could be selected that provides the desired combination of risk and economic return (maximum expected return). As the growing season progresses, this strategy would be updated with each updated seasonal inflow forecast.

Past studies (Pakistan Snow and Ice Hydrology Project, PD&R Report, 1991) show that the following requirements, regarding forecasting of inflows for Mangla and Tarbela reservoirs, must be met in order to increase benefits from the operation of the two reservoirs:

- Increase reservoir outflows during the Kharif (April to September) season immediately after the start of the freshet, thus allowing an increase in energy generation.
- Accurately forecast inflows during Rabi (October to March) and early Kharif (April-May) seasons.
- Forecast the date of the start of freshet during early Kharif.

The short-term model can be operated for various time spans and for use in Pakistan a ten day time span with daily increments may be used. In this case the number of stages (N) will be 10. The $F_n(s)$ values for stage-11 which represents the optimal cumulative expected return for operation beyond the 10-day period, will be obtained from the optimisation of long-term operation of the two reservoirs. The optimal releases selected for the 1-day ahead period would be implemented. The releases selected for 2 and more days ahead (i.e., n = 2, 3, ...10) will be revised during the next model run (at stage n+1) as updated forecast information is obtained. Thus, outputs from one model (10-day ending storage levels from the long-term model) shall be used as inputs into the next echelon model, and iterating and updating whenever new information on streamflow prediction becomes available. This hierarchical approach will not generally result in global optimum because of decompositions and uncertainties in flow predictions (Yeh and Becker, 1979). However, it does result in an optimal use of information at hand.

☆☆☆☆☆☆☆

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APPENDICES

APPENDIX-I

STAGE-STORAGE DATA

No.	Mangla	Curve#2	Tarbela	Curve# 8
	Stage (Ft)	Storage (MAF)	Stage (Ft)	Storage (MAF)
1	1062	0.620	1310	1.333
2	1072	0.715	1320	1.460
3	1082	0.828	1330	1.596
4	1092	1.009	1340	1.734
5	1102	1.201	1350	1.878
6	1112	1.432	1360	2.124
7	1122	1.680	1370	2.380
8	1132	1.996	1380	2.648
9	1142	2.331	1390	2.920
10	1152	2.739	1400	3.212
11	1162	3.166	1410	3.547
12	1172	3.666	1420	3.894
13	1182	4.183	1430	4.252
14	1192	4.764	1440	4.625
15	1202	5.365	1450	5.017
16			1460	5.442
17			1470	5.882
18			1480	6.334
19			1490	6.804
20			1500	7.292
21			1510	7.788
22			1520	8.304
23			1530	8.840
24			1540	9.401
25			1550	9.986

MODULE OPT (PR1) FOR MANGLA RESERVOIR

```
For N = 180 To 1 Step -1            'Stage loop begins

  For S = 15 To 1 Step -1           'State loop begins
    FMAX = -99999

    For R = 5 To 50 Step 5                         'Decision loop begins

      Call GetVol(N, S, SV)

       'Equation of continuity

      SVE = SV + ((InflwArray(N).Infs - R) * (1.983 * InflwArray(N).Days)) / 1000

      If SVE < .62 Then GoTo 100       'Min reservoir level 1062 El.

      SP = SVE - 5.365    'Spillway Discharge

      If SP < 0 Then SP = 0

      Vol2Q = 504.167 / InflwArray(N).Days

      TotQ = R + SP * Vol2Q

      Per = InflwArray(N).Mon

      'Irrigation Constraints

      Flag = 1
      If TotQ < NID(N) And R < 50 Then
        If Per = 1 Then
          Dem = .2 * NID(N)
          If TotQ < Dem Then
            Sm = SV + ((InflwArray(N).Infs - (R + 5)) * (1.983 *
                 InflwArray(N).Days)) / 1000
            If Sm > .62 Then
              Flag = 0
            Else
              Flag = 1
```

```
            End If
        End If
    ElseIf Per = 2 Then
        Dem = .3 * NID(N)
        If TotQ < Dem Then
            Sm = SV + ((InflwArray(N).Infs - (R + 5)) * (1.983 *
                    InflwArray(N).Days)) / 1000
            If Sm > .62 Then
                Flag = 0
            Else
                Flag = 1
            End If
        End If
    ElseIf Per = 3 Then
        Dem = .4 * NID(N)
        If TotQ < Dem Then
            Sm = SV + ((InflwArray(N).Infs - (R + 5)) * (1.983 *
                    InflwArray(N).Days)) / 1000
            If Sm > .62 Then
                Flag = 0
            Else
                Flag = 1
            End If
        End If
    ElseIf Per = 4 Then
        Dem = .5 * NID(N)
        If TotQ < Dem Then
            Sm = SV + ((InflwArray(N).Infs - (R + 5)) * (1.983 *
                    InflwArray(N).Days)) / 1000
            If Sm > .62 Then
                Flag = 0
            Else
                Flag = 1
            End If
        End If
    Else
        Msg3$ = "Value of (Per) does not lie between"
        Msg3$ = Msg3$ + "1 & 4 - Check inflow data file !"
        MsgBox Msg3$
    End If
End If

If Flag = 1 Then

    If SVE > 5.365 Then SVE = 5.365  'Max reservoir level 1202 El.
```

```
            Call GetElev(SVE, STE)

            'Energy Calculation

            PMAX = 4.32 * ((ST(N, S) + STE) / 2 - 842) - 461.2  'at full gate opening

            If PMAX > 890 Then PMAX = 890   ' Max plant output

            POWER = .85 * ((ST(N, S) + STE) / 2 - 842) * R / 11.8

            If POWER > PMAX Then POWER = PMAX

            Energy = (.024 * InflwArray(N).Days) * POWER

            If N + 1 = 181 Then
               FNS = 0
               TOTENGY = Energy
            Else
               Call GetFNS(N, STE, FNS)
               TOTENGY = Energy + FNS
            End If

            If TOTENGY > FMAX Then
               FMAX = TOTENGY
               RMAX = R
               SMAX = STE
               OMAX = SP
            End If

         End If

100 : Next R
              F(N, S) = FMAX
             ROPT(N, S) = RMAX
              SOPT(N, S) = SMAX
              SPLL(N, S) = OMAX

      Next S

Next N
```

MODULE OPT (PR2) FOR TARBELA RESERVOIR

```
For N = 180 To 1 Step -1           'Stage loop begins

   For S = 25 To 1 Step -1         'State loop begins
      FMAX = -99999

      For R = 10 To 140 Step 10           'Decision loop begins

         Call GetVol(N, S, SV)

          'Equation of continuity

         SVE = SV + ((InflwArray(N).Infs - R) * (1.983 * InflwArray(N).Days)) / 1000

         If SVE < 1.333 Then GoTo 100     'Min reservoir level 1310 El.

         SP = SVE - 9.986    'Spillway Discharge

         If SP < 0 Then SP = 0

         Vol2Q = 504.167 / InflwArray(N).Days

         TotQ = R + SP * Vol2Q

         Per = InflwArray(N).Mon

         'Irrigation Constraints

         Flag = 1
         If TotQ < NID(N) And R < 140 Then
            If Per = 1 Then
               Dem = .8 * NID(N)
               If TotQ < Dem Then
                  Sr = SV + ((InflwArray(N).Infs - (R + 10)) * (1.983 *
                           InflwArray(N).Days)) / 1000
                  If Sr > 1.333 Then
                     Flag = 0
                  Else
                     Flag = 1
```

```
            End If
        End If
    ElseIf Per = 2 Then
        Dem = .7 * NID(N)
        If TotQ < Dem Then
            Sr = SV + ((InflwArray(N).Infs - (R + 10)) * (1.983 *
                    InflwArray(N).Days)) / 1000
            If Sr > 1.333 Then
                Flag = 0
            Else
                Flag = 1
            End If
        End If
    ElseIf Per = 3 Then
        Dem = .6 * NID(N)
        If TotQ < Dem Then
            Sr = SV + ((InflwArray(N).Infs - (R + 10)) * (1.983 *
                    InflwArray(N).Days)) / 1000
            If Sr > 1.333 Then
                Flag = 0
            Else
                Flag = 1
            End If
        End If
    ElseIf Per = 4 Then
        Dem = .5 * NID(N)
        If TotQ < Dem Then
            Sr = SV + ((InflwArray(N).Infs - (R + 10)) * (1.983 *
                    InflwArray(N).Days)) / 1000
            If Sr > 1.333 Then
                Flag = 0
            Else
                Flag = 1
            End If
        End If
    Else
        Msg3$ = "Value of (Per) does not lie between"
        Msg3$ = Msg3$ + "1 & 4 - Check inflow data file !"
        MsgBox Msg3$
    End If
End If

If Flag = 1 Then

    If SVE > 9.986 Then SVE = 9.986  'Max reservoir level 1550 El.
```

```
        Call GetElev(SVE, STE)

        'Energy Calculation

        PMAX = 6.34 * ((ST(N, S) + STE) / 2 - 1120) - 644.5 'at full gate opening

        If PMAX > 2000 Then PMAX = 2000   'Max plant output

        POWER = .85 * ((ST(N, S) + STE) / 2 - 1120) * R / 11.8

        If POWER > PMAX Then POWER = PMAX

        Energy = (.024 * InflwArray(N).Days) * POWER

        If N + 1 = 181 Then
          FNS = 0
          TOTENGY = Energy
        Else
          Call GetFNS(N, STE, FNS)
          TOTENGY = Energy + FNS
        End If

             If TOTENGY > FMAX Then
                  FMAX = TOTENGY
                  RMAX = R
                  SMAX = STE
                  OMAX = SP
             End If

        End If

   100 : Next R

             F(N, S) = FMAX
             ROPT(N, S) = RMAX
             SOPT(N, S) = SMAX
             SPLL(N, S) = OMAX

        Next S

   Next N
```

MODULE OPT (PK-ROM)

```
'Optimisation Process

Start! = Timer    'Set start timer

For N = 180 To 1 Step -1   'Stage loop begins

   totstr$ = Space$(10)
   form1.Print totstr$
   form1.Print "                              Current Stage: "; N

   For Sm = 15 To 1 Step -1   'State loop for Mangla begins

      For St = 25 To 1 Step -1    'State loop for Tarbela begins

         FMAX = -99999

         For R = 1 To 100   'Decision loop begins

            Call GetVolMan(N, Sm, St, ElevMan(), Svm)    'Get Mangla storagevolume
                                                          from WAPDA Curve #2

           Im = InflwArray(N).MFlows: Dm = Rel(R, 1)

           'Equation of Continuity for Mangla

           SVEm = SVm + (Im - Dm) * (1.983 * (InflwArray(N).Days)) / 1000

          Call GetVolTar(N, Sm, St, ElevTar(), SVt)    'Get Tarbela storage volume
                                                        from WAPDA Curve #8

           It = InflwArray(N).TFlows: Dt = Rel(R, 2)

            'Equation of Continuity for Tarbela

           SVEt = SVt + (It - Dt) * (1.983 * (InflwArray(N).Days)) / 1000

           If SVEm < .62 Or SVEt < 1.333 Then GoTo 100    'Min permissible
                                                           reservoir level
```

```
'-----------------------
'Spillway Discharge
'-----------------------
SPm = SVEm - 5.365
If SPm < 0 Then SPm = 0

SPt = SVEt - 9.986
If SPt < 0 Then SPt = 0

Vol2Q = 504.167 / InflwArray(N).Days

TotQm = Dm + SPm * Vol2Q
TotQt = Dt + SPt * Vol2Q

Flag = 1    'Identifier

Call IrriDems (N,R,Im,It)

If Flag = 1 Then

  If SVEm > 5.365 Then SVEm = 5.365   'Max permissible reservoir level
                                       for Mangla

  If SVEt > 9.986 Then SVEt = 9.986   'Max permissible reservoir level for
                                       Tarbela

  Call GetElevMan(SVEm, ElevMan(), STEm)    'Get End-of-Stage
                                             Elevation for Mangla
                                             corresponding to SVEm

  Call GetElevTar(SVEt, ElevTar(), STEt)    'Get End-of-Stage Elevation
                                             for Tarbela corresponding to
                                             SVEt

   Call EnerCal(N, Sm, St, STEm, STEt, Dm, Dt, ENERGYm, ENERGYt)

  If N + 1 = 181 Then
    'TotBen = .05 * (ENERGYm + ENERGYt) + 15 * (TotQm + TotQt)
             * InflwArray(N).Days * .0019872
    TotEng = ENERGYm + ENERGYt
  Else
    Call GetFNS(N, STEm, STEt, ElevMan(), ElevTar(), FNS)       'GetFNS
                                                 calculates F(N+1, Sm', St')
```

```
        'TotBen = .05 * (ENERGYm + ENERGYt) + 15 * (TotQm + TotQt)
                * InflwArray(N).Days * .0019872 + FNS     'Total Benefits
                                                          in Million $Cdn. (OF-II)
        TotEng = ENERGYm + ENERGYt + FNS  'Cumulative energy production in
                                           mkWh (OF-I)
      End If

      'If TotBen > FMAX Then
      If TotEng > FMAX Then
        'FMAX = TotBen
        FMAX = TotEng
        EnM = ENERGYm
        EnT = ENERGYt
        RMAXm = Dm
        RMAXt = Dt
        SMAXm = STEm
        SMAXt = STEt
        OMAXm = SPm
        OMAXt = SPt
      End If

     End If

100 :   Next R

  F(N, Sm, St) = FMAX
  Em(N, Sm, St) = EnM
  Et(N, Sm, St) = EnT
  RelM(N, Sm, St) = RMAXm
  RelT(N, Sm, St) = RMAXt
  SopM(N, Sm, St) = SMAXm
  SopT(N, Sm, St) = SMAXt
  SplM(N, Sm, St) = OMAXm
  SplT(N, Sm, St) = OMAXt

  TIS(N, Sm, St) = RMAXm + RMAXt + (OMAXm + OMAXt) * Vol2Q
                                                   'Total Irrigation Supply
  TID(N) = IrriArray(N).UJ + IrriArray(N).LJ + IrriArray(N).UI +
          IrriArray(N).LI                     'Net Irrigation Demand for M & T

  DIFF(N, Sm, St) = TIS(N, Sm, St) - TID(N)      'Surplus or Deficit

  Next St

  form1.Cls
```

```
   Next Sm

   form1.Cls

Next N

form1.Cls

label1.Visible = 0  'Label1 made invisible

Finish! = Timer     'Set end timer
Msg$ = "The program took " + LTrim$(Str$(Finish! - Start!))
Msg$ = Msg$ + " seconds !"
MsgBox Msg$         'Display message

End Sub
```

APPENDIX-V

PROCEDURE IrriDems(PK-ROM)

```
'-----------------------------------------------------------------------------------------
'Compare Releases from the Mangla & Tarbela with Irrigation Demands of the
four Irrigation Regions
'-----------------------------------------------------------------------------------------
 Signal=1   'Identifier

        If TotQm < IrriArray(N).UJ Then
          D1 = Rel(R + 1, 1): D2 = Rel(R + 1, 2)
          If D1 = Dm And D2 > Dt Then
            SVEtar = SVt + (It - D2) * ((InflwArray(N).Days) * 1.983) / 1000
            If SVEtar > 1.333 Then
              Flag = 0
              Signal = 0
            End If
          ElseIf D1 > Dm And D2 < Dt Then
            SVEman = SVm + (Im - D1) * ((InflwArray(N).Days) * 1.983) / 1000
            If SVEman > .62 Then
              Flag = 0
              Signal = 0
            End If
          End If
        End If
      If Signal = 1 Then         '--------------------------------------------------------------A------
        If TotQm < IrriArray(N).UJ + IrriArray(N).LJ Or TotQ < IrriArray(N).UI
+ IrriArray(N).LI Then     '-------------------------------------------------------------------B------
          If TotQm < IrriArray(N).UJ + IrriArray(N).LJ And TotQt <
                          IrriArray(N).UI + IrriArray(N).LI Then '------------------C------
            D1 = Rel(R + 1, 1): D2 = Rel(R + 1, 2)
            If D1 = Dm And D2 > Dt Then
              SVEtar = SVt + (It - D2) * ((InflwArray(N).Days) * 1.983) / 1000
              If SVEtar > 1.333 Then
                Flag = 0
              End If
            ElseIf D1 > Dm And D2 < Dt Then
             SVEman = SVm + (Im - D1) * ((InflwArray(N).Days) * 1.983) / 1000
              If SVEman > .62 Then
                Flag = 0
              End If
```

```
    End If

  ElseIf TotQm >= IrriArray(N).UJ + IrriArray(N).LJ And TotQt <
              IrriArray(N).UI + IrriArray(N).LI Then
    DeT = IrriArray(N).UI + IrriArray(N).LI - (TotQm - (IrriArray(N).UJ)
      - (IrriArray(N).LJ))
    If TotQt < DeT Then
      D1 = Rel(R + 1, 1): D2 = Rel(R + 1, 2)
      If D1 = Dm And D2 > Dt Then
        SVEtar = SVt + (It - D2) * ((InflwArray(N).Days) * 1.983) / 1000
        If SVEtar > 1.333 Then
          Flag = 0
        End If
      ElseIf D1 > Dm And D2 < Dt Then
     SVEman = SVm + (Im - D1) * ((InflwArray(N).Days) * 1.983) / 1000
        If SVEman > .62 Then
          Flag = 0
        End If
      End If
    End If

  ElseIf TotQm < IrriArray(N).UJ + IrriArray(N).LJ And TotQt >=
                IrriArray(N).UI + IrriArray(N).LI Then
    DeM = IrriArray(N).UJ + IrriArray(N).LJ - 30: DeT =
      IrriArray(N).UI + IrriArray(N).LI + 30
    If TotQm >= DeM And TotQt < DeT Then
      D1 = Rel(R + 1, 1): D2 = Rel(R + 1, 2)
      If D1 = Dm And D2 > Dt Then
        SVEtar = SVt + (It - D2) * ((InflwArray(N).Days) * 1.983) / 1000
        If SVEtar > 1.333 Then
          Flag = 0
        End If
      ElseIf D1 > Dm And D2 < Dt Then
     SVEman = SVm + (Im - D1) * ((InflwArray(N).Days) * 1.983) / 1000
        If SVEman > .62 Then
          Flag = 0
        End If
      End If
    ElseIf TotQm < DeM And TotQt < DeT Then
      D1 = Rel(R + 1, 1): D2 = Rel(R + 1, 2)
      If D1 = Dm And D2 > Dt Then
        SVEtar = SVt + (It - D2) * ((InflwArray(N).Days) * 1.983) / 1000
        If SVEtar > 1.333 Then
          Flag = 0
        End If
```

```
            ElseIf D1 > Dm And D2 < Dt Then
           SVEman = SVm + (Im - D1) * ((InflwArray(N).Days) * 1.983) / 1000
              If SVEman > .62 Then
                 Flag = 0
              End If
            End If
          ElseIf TotQm < DeM And TotQt >= DeT Then
            D1 = Rel(R + 1, 1): D2 = Rel(R + 1, 2)
            If D1 = Dm And D2 > Dt Then
              SVEtar = SVt + (It - D2) * ((InflwArray(N).Days) * 1.983) / 1000
              If SVEtar > 1.333 Then
                 Flag = 0
              End If
            ElseIf D1 > Dm And D2 < Dt Then
           SVEman = SVm + (Im - D1) * ((InflwArray(N).Days) * 1.983) / 1000
              If SVEman > .62 Then
                 Flag = 0
              End If
            End If
          End If
        End If          '----------C-----------------------------------------------------------------
      End If            '----------B-----------------------------------------------------------------
    End If              '----------A-----------------------------------------------------------------
```

PROCEDURE EnerCal (PK-ROM)

```
'------------------------------------------------------------------------------------------
'Energy Calculation
'------------------------------------------------------------------------------------------

'Energy calculation for Mangla
'------------------------------------

PMAXm = 4.32 * ((STm(N, Sm, St) + STEm) / 2 - 842) - 461.2    'At full gate opening

If PMAXm > 890 Then PMAXm = 890     'Max plant output

POWERm = .85 * ((STm(N, Sm, St) + STEm) / 2 - 842) * Dm / 11.8

If POWERm > PMAXm Then POWERm = PMAXm

ENERGYm = .024 * (InflwArray(N).Days) * POWERm        'in mkWh

'Energy calculation for Tarbela
'------------------------------------

PMAXt = 6.34 * ((STt(N, Sm, St) + STEt) / 2 - 1120) - 644.5    'At full gate opening

If PMAXt > 2000 Then PMAXt = 2000     'Max plant output

POWERt = .85 * ((STt(N, Sm, St) + STEt) / 2 - 1120) * Dt / 11.8

If POWERt > PMAXt Then POWERt = PMAXt

ENERGYt = .024 * (InflwArray(N).Days) * POWERt        'in mkWh
```