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Optimized Operation of Kainji Reservoir

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Abstract

Niger River is the third largest river in Africa and it is impounded in Nigeria at Kainji and Jebba for the sole purpose of generating electricity. Kainji Reservoir has a capacity of generating 760 mW of electricity, while Jebba Reservoir which is 100 km downstream of Kainji Reservoir, has a capacity of generating 540 mW. Flooding of the plain downstream of the reservoirs is an annual phenomenon, especially in September. On the other hand, water level in the reservoirs is low between March and May resulting in low head for generating electricity. This study determines an operation policy for Kainji Reservoir using Stochastic Dynamic Programming. The policy was compared with the operation rules between 1996 and 1999. Inter-annual variation in inflow to Kainji Reservoir was attributed to flow in September when peak rainfall occurs in the catchment area that lies within Nigeria. The operation rules adopted by Managers between 1996 and 1999 could not handle instantaneous high inflow between August and September because the water level in the reservoir was high prior to the arrival of such flow. Thus, there was high spillage so as to avoid structural failure of the dam. It was also observed that volume of water released from the reservoir remained high after the cessation of high inflow. It is recommended that the managers should adopt an operation policy that could handle inter-annual variation in inflow to the reservoir so as to maximize the benefit of impounding the water of River Niger and also minimize the annual flooding of the river plain.

Keywords: *Operation policy, reservoir management, Kainji Reservoir, electricity generation, flooding, Stochastic Dynamic Programming.*

Introduction

River Niger runs over 4,000 km across West Africa, and is the third largest river in Africa. Its basin covers about a third of the land area of the sub-region, extending over nine countries, viz. Benin, Burkina Faso, Cameroun, Chad, Cote d' Ivoire, Guinea, Mali, Niger and Nigeria. The river takes its source less than 250 km from the coast of the highlands of the Guinea-Sierra Leone border, in the wet equatorial region (Fig. 1). River Niger, by its peculiar course, loses the water it gained from its source in the wet climatic region, before turning toward the sea. However, in its lower-middle and lower courses, the river receives many tributaries, which augment its volume. These tributaries mostly have their sources in the sub-humid Savannah region and their flows are very much subject to the highly variable and seasonal rainfall regime (Areola and Akintola 1995).

Rainfall is concentrated in the headwaters and near the outlet of the Niger system within Nigeria. The seasonal pattern is reasonably similar over most of the areas, with maximum rainfall in headwater occurring in August and the dry season centred on December to February period. However, in southern Nigeria as well as in northern Cameroun, the maximum rainfall is recorded in July or September. Seasonal variation in rainfall along the river system is due to seasonal migration of the Inter-Tropical Convergent Zone (ITCZ). The balance between rainfall and evaporation in the lower-middle and middle courses of the river system determines the flow regime of the river in the middle course. Consequently, the river exhibits, at certain sections, different regime types and anomalies, which reflect the climatic and physiographic characteristics of the component sub-basins. Two distinct (black and white) floods occur annually in Kainji.

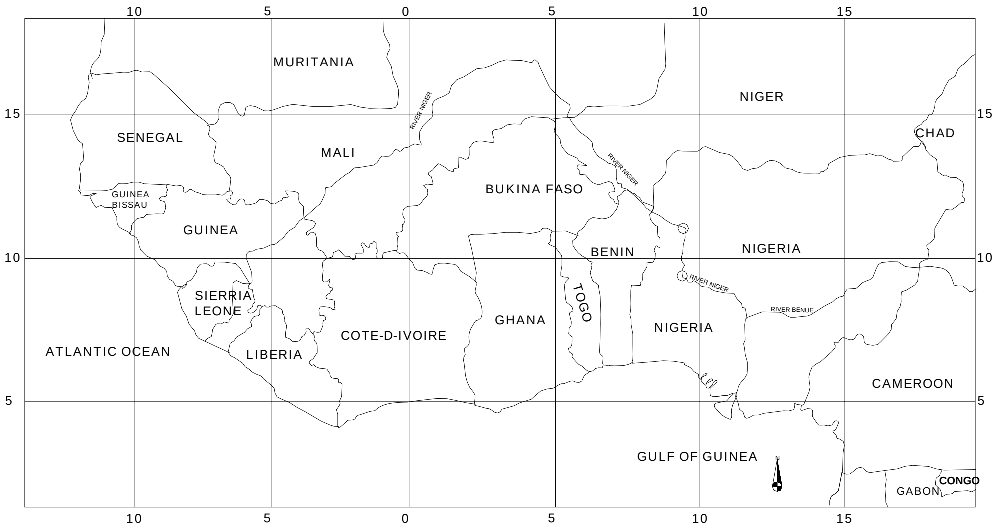


Fig. 1. The Niger River system.

The floods are separated by a period of 4 to 5 months. The black flood originates from high rainfall area in the headwaters. The flood arrives at Kainji in November and lasts until March at Jebba after attaining a peak in February (Oyebande 1995). The white flood becomes prominent only downstream of Sabon-gari (upstream of Kainji dam in Nigeria) soon after the river enters Nigeria, and carries a lot of heavy-laden with silt and other suspended particles. The flood derives its flow from the local tributaries and reaches Kainji in August in the pre-dam period, to attain peak between September and October in Jebba.

Kainji Dam was commissioned in December 1968 for the purpose of generating electricity. The reservoir has total storage volume of 15,000 MCM (Million Cubic Metres) with a total live storage of 11,500 MCM. The maximum water surface elevation is 141.9 masl. and the surface area at that elevation is 1,270 km^2. The dam has eight plants with total installed capacity of 760 mW (four-80 mW, two-100 mW and two-120 mW). Each plant is supplied with water from the reservoir through steel-lined penstocks about 8.5 m in diameter. The normal maximum tail water elevation is 106.8 masl. The hydraulic head of the unit is designed to be between 24.0 and 42.2 m. The spillway is equipped with 4 radial gates (15.3 m x 15.3 m) having a total spilling capacity of 7,900 m^3/s. Two ship locks with an intermediate pond secure the maintenance of navigation. Jebba Dam is located 100 km downstream of Kainji Dam and was commissioned in 1984 to utilize the run-off water from Kainji Reservoir for generating electricity. The dam has a storage capacity of 3,880 MCM. The maximum water surface elevation of Jebba Reservoir is 103 masl.

One of the problems associated with the operation of the reservoirs is the annual flooding of lower Niger plains when the spillways are opened in September during high inflows. While during the period of low inflows (March to May), head of water in the reservoir is often below the desired level. Operation of the two reservoirs is based on experience of the water managers. If a wet year is preceded by a dry year, the managers adopt the operation policy of the dry year for the wet year, which is inadequate and the effect is flooding of the river plain. Jimoh and Webster (1999), Adefolalu (1986) and Hulme (1992) among others discussed the intra-annual and inter-annual variation in rainfall in the sub-Sahara African countries. Thus, an optimized operation policy is essential for the management of impounded water on the river. The operation policies of Kainji Reservoir during a wet, near normal and wet years are discussed in this paper. The study was based on stochastic dynamic programming (SDP).

For hydropower generation (Harboe *et al.* 1970; and Guitron 1981), the objective function is:

$$f_t(s_t, r_t) = \\ = \sum_{i=1}^{n} k.\ e_i(s_{i,t}, s_{i,t+1}, r_{i,t}).\ \bar{h}_{i,t}(s_{i,t}, s_{i,t+1}).\ r_{i,t}\ .\ \Delta._{i,t} \qquad (1)$$

where e_i = overall power plant efficiency of reservoir *i* as a function of average head and discharge during period *t*, $\bar{h}_{i,t}$ = average head as a function of beginning and ending period storage levels (calculated from the reservoir mass balance or system dynamics equation), as well as possibly the discharge if tailwater effects are included; *k* = unit conversion factor; and $\Delta t_{i,t}$ = number of on-peak hours related to the load factor for power plant *i*. This is a highly non-convex function characterized by many local maxima (Tauxe *et al.* 1980), and may be discontinuous and non-differentiable if loading of individual turbines in the power plant is considered.

The constraints of the system are summarised in Eqs. (2), (3) and (4).

$$\mathbf{s}_{t+1} = \mathbf{s}_t + \mathbf{C}\mathbf{r}_t + \mathbf{q}_t - \mathbf{l}_t(\mathbf{s}_t, \mathbf{s}_{t+1}) - \mathbf{d}_t, \text{ for } t = 1,\ldots,T, \qquad (2)$$

where $\mathbf{s}_t$ = storage vector at the beginning of time *t*; $\boldsymbol{q}_t$ = inflow vector during time *t*; $\mathbf{C}$ = system connectivity matrix mapping flow routing within the system; $\mathbf{l}_t$ = vector combining spills, evaporation, and other losses during time *t*; and $\mathbf{d}_t$ is required demands, diversions, or depletions from the system. Accurate calculation of evaporation and other water losses in the term $\mathbf{l}_t(\mathbf{s}_t, \mathbf{s}_{t+1})$ creates a set of nonlinear implicit equations in $\mathbf{s}_{t+1}$ which can be difficult to evaluate and constitute a non-convex feasible set. Initial storage levels $\mathbf{s}_t$ are assumed known and all flow units in Eq. (2) are expressed in storage units per unit time. Spatial connectivity of the reservoir network is fully described by the routing or connectivity matrix **C**. The connectivity matrix takes into consideration the attenuation of downstream releases.

For lower and upper bounds for dead storage, power plant operation and flood control,

$$s_{t+1,\min} \le s_{t+1} \le s_{t+1,\max}\ . \qquad (3)$$

For downstream flow the release (r) at any time must satisfy Eq. (4),

$$r_{t,\min} \le r_1 \le r_{t,\max}\ . \qquad (4)$$

Equations (3) and (4) could be expressed as a function of head, but difficulties may arise in finding feasible solution that satisfies the constraints (Labaide 2004). One way out of the difficulty is to relax these as explicit constraints, and indirectly consider them through use of weighted penalty terms on violation of these constraints in the objective function. The features of the equations which possess difficulty in solving the equations are:

- The system is dynamic;
- The equations are potentially nonlinear, non-convex and large scale; and
- The unregulated inflows, net evaporation rates, hydrologic parameters, system dynamics, economic parameters are often treated as random variables.

Thus, we have large scale, nonlinear stochastic optimisation problem. Labaide (2004) presented a review of optimisation techniques in reservoir operation and management. We would summarise the potential and limitation of the techniques, with special reference to those techniques that address nonlinearity as it applies to hydropower generation.

Stochastic optimisation problems could be addressed as implicit stochastic optimisation (ISO) or explicit stochastic optimisation (ESO). ISO optimizes over a long continuous of historical or synthetically generated unregulated inflow time series, or many shorter equally likely sequences. It is also referred to as Monte Carlo optimisation. ESO is designed to operate directly on probabilistic description of random stream flow process (as well as other random variables) rather than deterministic hydrologic sequences. In ESO, optimisation is performed without presumption of perfect foreknowledge of future events. In addition, optimal policies are determined without the need for inferring operating rules from results of optimisation (Yeh 1985).

Several researchers (Stedinger *et al.* 1984; Huang *et al.*, 1991; Labaide 1993; Vasiliadis and Karamouz 1994) have successfully applied SDP to single reservoir problems. Unfortunately, extensions of SDP to multireservoir systems are more aggravated by state dimensionality than in the deterministic case, particularly when spatial correlation of unregulated inflows must be maintained (Tjeda-Gubert *et al.* 1995). The present study is considering two reservoirs in series and the main purpose of both reservoirs is electricity generation. The secondary function of the reservoirs is flood control. The reservoirs are close to each other so that the release from the upper reservoir (Kainji reservoir) is the main inflow to the lower reservoir (Jebba Reservoir). The contribution from catchment between the reservoirs is less than 10% of the release from the upper reservoir. Thus, the system could be considered as a single reservoir with the demand for power generation of the lower reservoir satisfied as downstream requirement.

The Optimization Model for Kainji Reservoir

The schematic diagram of the reservoir system is presented in Fig. 2.

For the optimisation of Kainji Reservoir, the objective function is:

$$f_t = B_t + B_{t-1} + \ldots\ldots B_T + f_{T+1}, \qquad (5)$$

where B_t is the return at stage t due to the release R given the initial and final storages, f_{T+1} describes the value of water at the end of stage T, the last stage in the planning period (planning period is 12 months in this study). The benefit is to maximize power generated at Kainji and release sufficient water for Jebba reservoir. The analysis starts at time T and moves backward using the Bellman's principle which states that: an optimal policy has the property that whatever the initial state and initial decisions are, the remaining decisions must constitute an optimal policy with regard to the state resulting from the first decision.

The constraints on the reservoir system operation at Kainji Dam are:

(i) continuity equation:

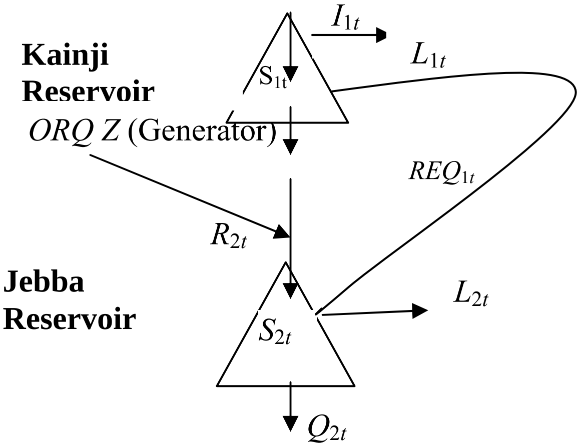
$$S_{t-1} + I_t - L_t - Q_t = S_t, \qquad (6)$$

where $Q_t = REQ_t + ORG_t$.

The loss function is a function of storage level and outflow Q.

(ii) storage constraints:

$$S_{\min} < S_t < S_{\max,t}, \qquad (7)$$
$$S_{t+1} \le S_{\max,t}, \qquad (8)$$
$$S_{\max,t} = RCAP - SFLD_t. \qquad (9)$$



Notation: I is inflow, Q is outflow, R is runoff into river between Kainji and Jebba, S is storage, L denotes evaporation and seepage losses, REQ is the discharge through the turbine and ORQ represents other releases.

Fig. 2. Schematic diagram of Kainji and Jebba reservoir systems.

where $S_{\min}$ is the reservoir dead capacity and $S_{\max,t}$ is the maximum storage at time t and $SFLD_t$ is the volume reserved for flood control in time t. Equation (9) is meant to ensure flood control policy of the system is maintained. Based on historical record (inflow series to Kainji Reservoir), the reserved volume at monthly time step is presented in Fig. 3.

(iii)Release constraint

$$Q_t \ge \text{maximum}(MQ_t, FQ_t), \qquad (10)$$

where MQ_t is the obligatory water requirement at time t which is the release from Kainji Reservoir to meet the minimum demand at Jebba Reservoir. The term FQ_t denotes the

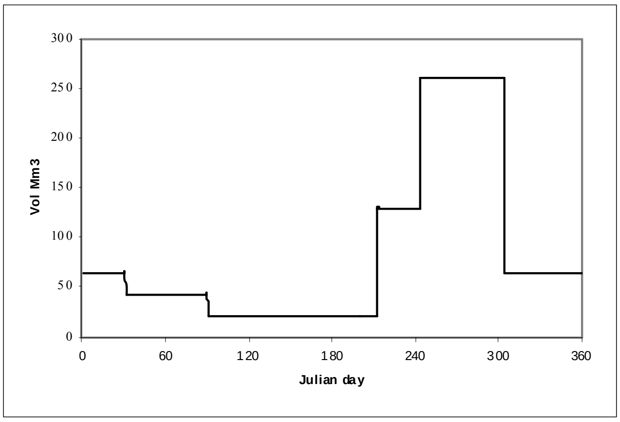


Fig. 3. Reservoir volume for flood control.

firm water delivery at time *t* which is the release from Kainji Reservoir to meet the minimum energy demand at Kainji during period of drought.

(iv) energy production.

This is a function of the turbine release. The energy production capacity (*EPC*) is represented as:

$$EPC_t = C * REQ_t * H_t * \eta, \tag{11}$$

where *C* is the conversion factor for potential to electrical energy, *H* is the average head over turbine and η is the energy plant efficiency.

The energy that can be produced is restricted by the plant capacity (*PCAP*) and number of hours available for energy production (*NHP*). Thus, the maximum peak energy produced (*MPEP*) is:

$$MPEP_t = PCAP_t * \eta * NHP_t. \tag{12}$$

The energy produced at any time t is:

$$PKE_t = \text{minimum}(TEP_t, MPEP_t), \tag{13}$$

where *PKE* is the peak energy produced and *TEP* is the total energy that can be produced at a particular time.

The objective function becomes maximising the energy produced at Kainji and to solve the Eqs. (5) to (13), the characteristics and parameters of Kainji Reservoir, summarised in Table 1, are needed. A monthly reservoir release patterns for the Kainji Reservoir are obtained where the state variable is the reservoir storage S_t at the beginning of a stage, while the decision variable is the reservoir release R_t. The solution to the recursive Eq. (5) is obtained by working backwards in time from the end of the decision horizon.

The Optimized Policy

Figure 4(a-b) shows optimized policy at monthly time step for Kainji Reservoir. The figure shows the region when the release from Kainji Reservoir is less than 1,500 m^3/s (lower left hand portion of each chart). During this period, the head at the reservoir is optimised but the water released to Jebba Reservoir is inadequate. The upper right hand portion of each chart indicates when release to Jebba Reservoir exceeds 1,500 m^3/s. The figure shows that there are hydrologic conditions (inflow to reservoir and storage at reservoir) when spillage (release exceeds 2,000 m^3/s) occurs in January, February, August, September and October.

Table 1. Characteristics of Kainji Reservoir.

Parameter	Value
Maximum capacity	15,000 Mm^3
Minimum capacity	3,500 Mm^3
Minimum downstream requirement	1,500 m^3/s
Minimum head on turbine	24 m
Maximum water surface elevation	141.9 m.a.s.l.
Annual energy target	3,000 GWh
Plant capacity	760 MW

The 1996-1999 Operation Policy

Flooding of Niger River plain in September and October is an annual phenomenon. The 1999 event was severe, and according to the managers, the situation was attributed to the opening of the spillways at the dam during high inflow to the reservoir so as to avoid failure of the dam. Figure 5(a-c) shows the inflow to the reservoir, the outflow and the optimized release policy under the hydrologic condition. The inflow to Kainji Reservoir during the 1999 black flood season did not differ significantly from the previous year record as shown in Fig. 5(a). However, the inflow during the 1999 white flood season differed significantly from the previous year record. The managers adopted the operation policy of the previous year for the 1999 season and the reservoir was not emptied in anticipation of the incoming high inflow, thus, the flooding of river plain was experienced. The result underscores the importance of operation policy and forecasting inflow series.

There is no significant variation between the monthly inflows in November to July during the period 1996 to 1999. The monthly inflow in August, September or October varies with year. Significant difference is observed in September when peak rainfall occurs in the area within Nigeria that contributes to flow in Niger River. The highest monthly inflow occurred in 1999, followed by 1998 and the least value occurred in 1997.

Figure 5(b) shows the outflow from Kainji Reservoir, that is water released, which includes turbine and other discharges. There is one-month lag between the outflow and inflow series. The outflow series has peak value in October, while inflow series has peak in September. An assessment of the storage level in Kainji Reservoir shows that the reservoir is within the full zone when high inflow in September arrives resulting in high spillage in September and October, especially in 1998 and 1999. In addition the outflow between December and February brings the reservoir to a low level in subsequent month without commensurate inflow to augment the reservoir water. The outflow was higher than 2,000 m^3/s in September and October during the period. The optimized release from the reservoir is presented in Fig. 5(c). The figure shows that the release could be maintained below 2,000 m^3/s throughout the year and thereby maximize the impounded water.

Conclusion

The operation policy of Kainji Reservoir has been developed using a stochastic dynamic technique. Inter-annual variation in inflow to Kainji Reservoir was attributed to flow in September when peak rainfall occurs in the catchment area that lies within Nigeria. The operation rules adopted by managers between 1996 and 1999 could not handle instantaneous high inflow to the reservoir because the water level in the reservoir was high prior to the arrival of such flow. It was also observed that volume of water released from the reservoir remained high after the cessation of high inflow, resulting in low reservoir level between March and May. It is recommended that the managers should adopt an operation policy that could handle inter-annual variation in inflow to the reservoir so as to maximize the benefit of impounding the water of River Niger and also minimize the annual flooding of the river plain. The study showed that the operation of the Kainji Reservoir contributes to the annual flooding of the lower Niger plain in Nigeria and available water resources can be optimised for both Kainji and Jebba Reservoirs.

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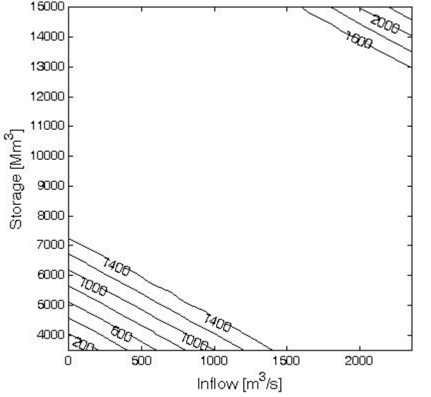
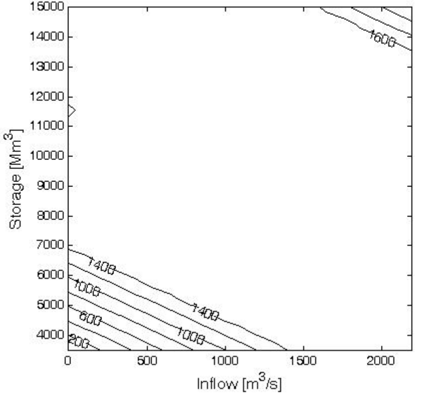
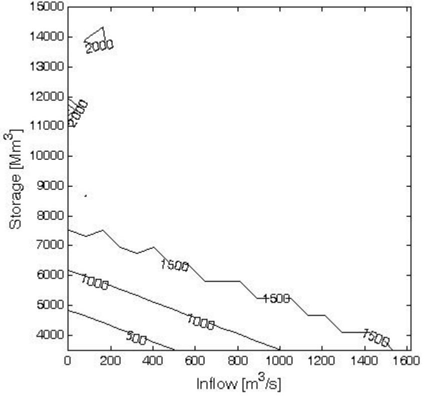
Optimized Release Policy (Kainji Reservoir) for month :



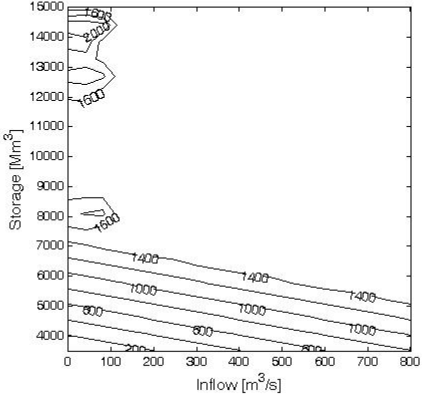
Optimized Release Policy (Kainji Reservoir) for month :2



Optimized Release Policy (Kainji Reservoir) for month :



Optimized Release Policy (Kainji Reservoir) for month :4



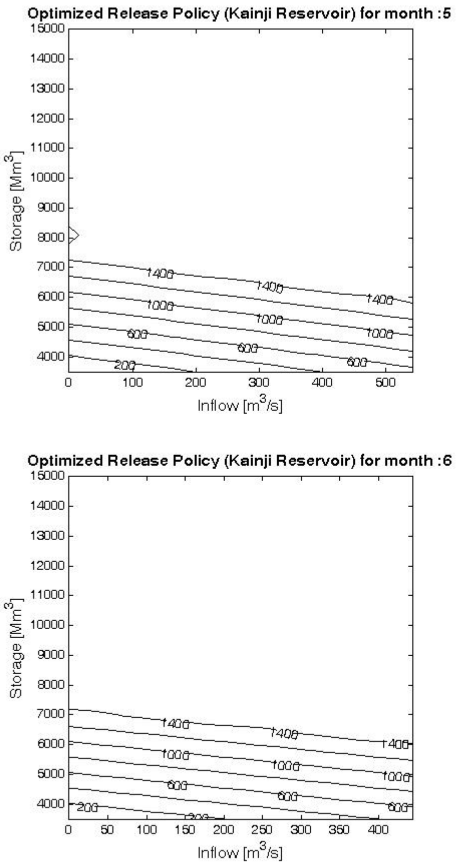
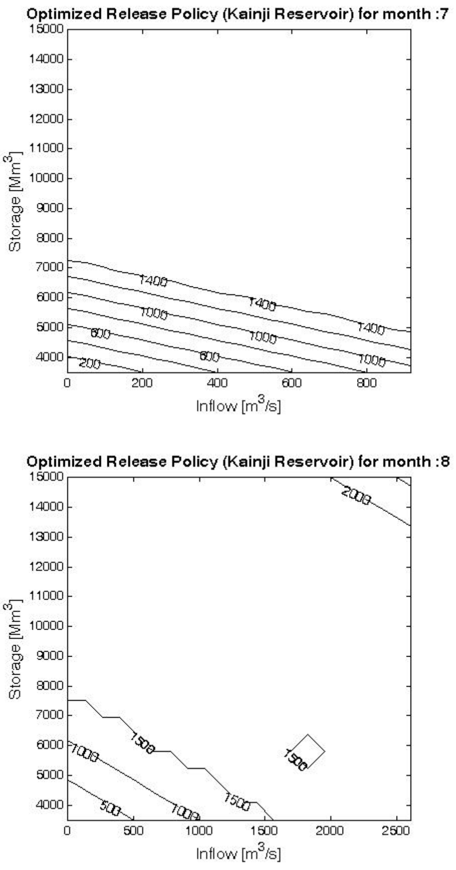


Fig. 4(a). Optimized release policy for Kainji Reservoir in January – June.



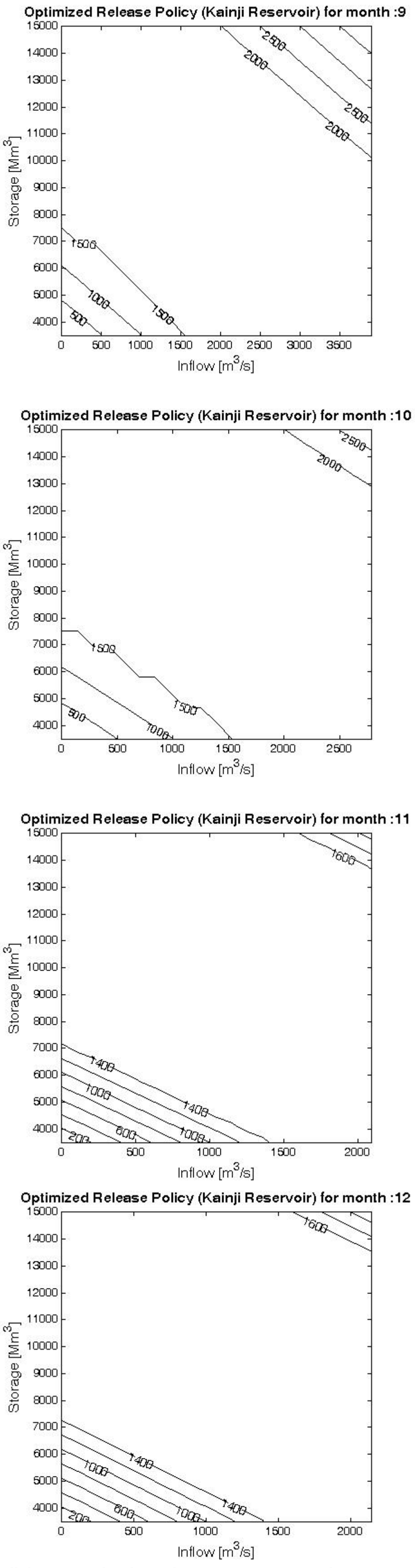
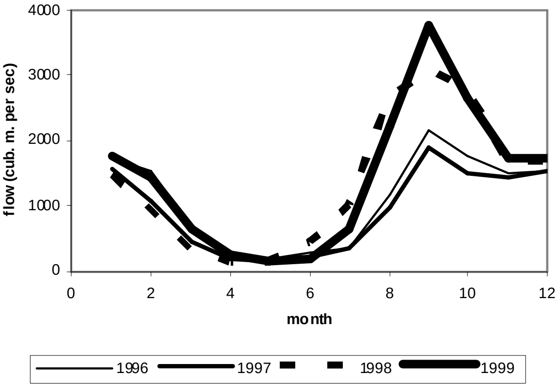
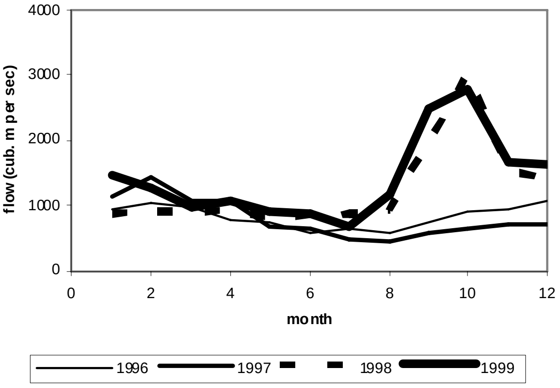


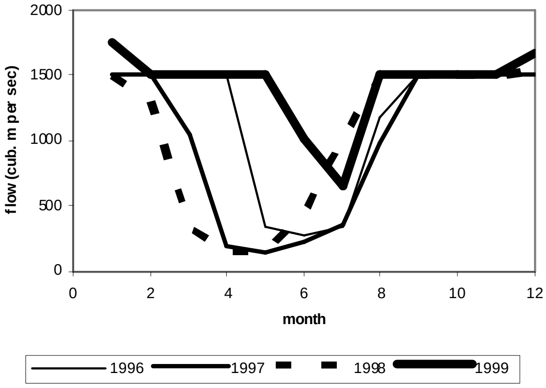
Fig. 4(b). Optimized release policy for Kainji Reservoir in July – December.



(a) Inflow.



(b) Outflow as operated by managers.



(c) Optimised release.

Fig. 5. Operation of Kainji Reservoir between 1996 and 1999.