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Derivation of Operation Rule for Ilisu Dam

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ABSTRACT

Tigris River water that comes from Turkey represents the main water resource of this river in Iraq. The expansion in water river implementations has formed a source of trouble for the workers in the water resources management field in Iraqi. Unfortunately, there is no agreement between Iraq and Turkey till now to share the water of this international river. Consequently, the optimal operation of water resources systems, particularly a multi-objective, multi-reservoir, is of the most necessity at the present time.

In this research two approaches, were used the dynamic programming (DP) approach and simulation model to find the optimal monthly operation of Ilisu Dam (from an Iraqi point of view) through a computer program (in Q. Basic language) to find the optimum monthly release and storage by adopting an objective function that minimizes the release and storage losses (penalty). The historical inflow data of 588 months from (Oct. 1961 to Sep. 2009) formed the input data to the optimization models. Storage rule curves for the reservoir at (lower, mean, upper) of (10%, 50%, and 90%), respectively, were found according to the results of the optimized operation. A simulation model was developed to operate the system using these rule curves.

Key Words: Ilisu dam, dynamic programming, rule curve, simulation, etc.

اشتقاق منحنيات التشغيل لسد اليسو

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الخلاصة

ان مياه نهر دجلة القادمة من تركيا هي المصدر الاساس لمياه هذا النهر ضمن الاراضي العراقية. ان التوسع في استخدامات مياه النهر في دول الاعالي تشكل مصدر قلق للعاملين في حقل ادارة المياه في العراق وعدم وجود اتفاق بين العراق وتركيا لحد الان من اجل قسمة المياه بينهما لهذا النهر الدولي. وعليه يعد التشغيل الامثل لنظام الموارد المائية ، خاصة متعددة الاهداف ومتعددة الخزانات، من الامور المهمة في الوقت الحاضر.

في هذا البحث استخدم اسلوبان للتشغيل هما البرمجة الديناميكية وبرنامج المحاكاة لإيجاد التشغيل الشهري الامثل لسد اليسو (من وجهة النظر العراقية) عن طريق عمل برنامج حاسوب لإيجاد الاطلاق الشهري الامثل والخزين الامثل من خلال تبني دالة هدفيه لتقليل خسائر كل من الاطلاق والخزين. لغرض الحصول على التشغيل الامثل تم استخدام البيانات التاريخية لمدة 588 شهراً من تشرين الاول 1961 الى ايلول 2009 شكلت بيانات الادخال لنموذج الامثلية . تم استنباط منحنيات مستويات الخزين (storage rule curve) الادنى والمعدل والأعلى عند 10% و 50% و 90% من الوقت او اكثر على التوالي من

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خلال النتائج التي تم التوصل اليها من تشغيل النموذج الامثل ، وبالاعتماد على منحنيات التشغيل تم اعداد نموذج محاكاة تشغيل المنظومة.

1. INTRODUCTION

Operation and management of water resources systems are one of the most difficult problems. Water resources systems have the capability of providing a number of water-related benefits. These benefits may be for human consumption, agricultural, industrial, domestic uses, flood control, hydroelectric power generation, water quality improvements, recreation, fish, and wildlife maintenance and navigation. Reservoirs are the man-made mechanism built on a stream or river on purpose to control the stream or river flow to meet the demand. The excess water is stored in the reservoir and will be delivered for various purposes during the time of deficit, **Fadhil, 1990.**

Iraq suffers from the problem of water resources in the last ten years and there are many researchers expected that there will be problems between the riparian states, particularly in the Middle East, including the Arab world as in the case of disagreement between Iraq and Syria on one hand, Iraq and Turkey on the other on water quality and quantity in the Tigris and the Euphrates Rivers which constitute the most important water resources in those countries. Turkey constructed additional reservoirs such as Ilisu reservoir on Tigris River, this reservoir reduces the quantity of water which arrives at the Iraqi border.

Ilisu Dam is a major component of an integrated water development scheme planned in the 1970’s for the upper Tigris watershed. The goal of this scheme is to provide economic development within the region through the generation of electricity and large-scale irrigated agriculture. The Dam is a single purpose hydroelectric facility; it will also increase the water available for irrigation by storing seasonal runoff that will be released to form the inflow to the planned Cizre Dam.

Optimization of water resources systems is the subject of several investigations throughout the world. The dynamic programming has been one of the most widely used methods due to its natural characteristics of being able to deal with discrete dynamic models and no limitations on the types of equations governing the system, constraints, or cost functions. The dynamic programming, although is very useful, has its shortcomings in the amount of storage and time consumed in a digital computer simulation. The successive approximation discrete differential dynamic programming (DDDP) is used to reduce the computer time and memory requirements. The DDDP is an iterative technique in which recursive equation of dynamic programming is used to search an optimal operation. The DP and simulation models are used in this study. The most of important advances made in water resources engineering are the evolvement and application of mathematical techniques for planning, design, and management of complex water resources systems. The choice of methods depends on the characteristics of the reservoir system, the availability of data, and the objectives and constraints specified, **Fadhil, 1990.**

Al-Delewy, 1995, applied DP formulation and DDDP models for the operation of a multi-reservoir, multi-objective water resources system, taking the Diyala River system which comprises two extra-large dams as a case study. The application considered eight objectives: flood control, domestic use, pollution control, irrigation, hydropower generation, and the problems of spilling beyond irrigation demand, spilling beyond hydropower-generation capability, and evaporation loss. The daily inflow raw-data recorded at two main gauging stations on the Diyala River was considered. The data for 32 water years (11688 days) was processed and analyzed to yield the adopted inflow historic-series. An appropriate, genuine, total objective function that considered the encountered objective, was established. A new convergence criterion was introduced. The model was run on a monthly basis for one year, starting in May.

Teixeira and Marino, 2002, developed a DP model to solve the problem of two reservoirs in parallel supplying water for irrigation districts. In the model, forecasted information including crop evapotranspiration, reservoir evaporation, and inflows is updated, which allowed application of the model for real-time reservoir operation and generation of a more precise irrigation schedule.

2- Simulation (as the nontraditional methods): is one of the most efficient ways of analyzing water resources systems, which is based on physical relations accompanied by a series of operational rules attempting to simulate a phenomenon as close as possible to reality and the system behavior under a specified policy. A simulation model is applied to find the suitable rule curves. The model is straightforward and applicable for both simple and complex systems, **Hossein, et al., 2007.** The simulation process is a trial and error technique rather than an analytical process that converges to a global optimum solution, **Al-Delewy, 1995.**

Hussain, 2010, found that optimum monthly releases from Al- Tharthar reservoir to Euphrates and Tigris rivers, by using DDDP with inflow data of Tigris river for 26-years from (1979-2004) considered as the input data, to minimize the total penalty of monthly releases and storage of Al- Tharthar reservoir. The simulation model is developed to operate the system depending on the rule curves. The quantity and quality mathematical model has been prepared based on governing equation to calculate discharge and salt concentration.

2. OBJECTIVES OF THE STUDY

The main objectives of this study are summarized as follows:

a. Application of the dynamic programming (DP) to develop rule curves for Ilisu reservoir by using a modified monthly inflow data.
b. Developing a simulation model for the historical period (1961-2009) for Ilisu reservoir depending on the rule curves of the reservoir in order to estimate monthly releases, water level, storage, and power, thus satisfying the water requirements.
c. Find the optimal operation of Ilisu dam.

3. METHODOLOGY AND PROCEDURE

3.1 Dynamic Programming (DP)

The Dynamic Programming (DP) approach solved by the Discrete Differential Dynamic Programming technique is applied to determine the optimal operation of reservoirs on Ilisu dam in Turkey.

3.1.1 The Objective function of the operation

The objective of the operation can be defined as follows: Minimize the sum of penalties or losses associated with deviating from the ideal operation, **Houck, 1982.**

Multiple objective systems must be operated under variable constraints in order to achieve the optimal operation. One of the important constraints during the operation period is the storage level, which should be within two limits, maximum design, and minimum operation storage. The second important constraint is the releases from the reservoir through various outlets such as turbines, bottom- outlets and spillways, which should be maintained within the assigned limits and do not violate maintaining the minimum and maximum capacity of the flow downstream of the dam. The third important constraint is that generating power should be operated within the capacity of the turbines and power plant capacity in order to achieve the target of the power demand. The total penalty represents the losses associated with releases and storages and should be minimized. The other side of the total benefit represents that the power generation should be maximized.

The objective function for release, storage and power will be written as follows:

A) The objective function of release :

The objective function of the release aims to minimize the losses associated with deviating from the demands during drought period or the capacity of the river during the flood period. Therefore, the optimal release should be equal to or greater than the demands and less than the capacity of the river. This may be formulated as follows:

$$Min.\ Penalty = \sum_{i=1}^{N} \sum_{j=1}^{12} Loss(R(i,j)) \tag{1}$$

where: i=serial number denoting year, i=1, 2,…, N.; j=serial number denoting month, j=1, 2,…,12.

Min. Penalty= The total minimum penalty due to release.

Loss R(i,j)=The loss functions of the release in an ith year and jth month.

The following equations were used to define the release loss function:

If $R(i,j) < Dem(j)$ then $Loss\ R(i,j)=a * (R(i,j) - Dem(j))^2$ (2)

If $R(i,j) < MF$ then $Loss\ R(i,j)=b* (R(i,j) - MF)^2$ (3)

And, if $Dem(j)\leq R(i,j) \leq MF$ then $Loss\ R(i,j)=0$ (4)

where: R(i,j)= The total release of water during the ith year and jth month (m^3/s).

Dem(j)=The total water requirements during the jth month (Irrigation + Industrial + Environmental + Fish + Thermal power+ Forest +Domestic) (m^3/s).

MF= The maximum permissible flow, which represents the capacity of the river for flood (m^3/s).

a, b = Constants which represent weighting factors that reflect the effect of violating the constraints of irrigation deficiency and flood control in the river, respectively. Their values depend on the consideration of the decision maker. Values of (a) and (b) in this study have been both taken to be equal to (one).

B) The objective function of storage

In the optimum operation of any reservoir, the storage should be less than the maximum design level during the flood periods and not less than the minimum operating level during the drought periods. This may be formulated as follows:

$$Min.\ Penalty = \sum_{i=1}^{N} \sum_{j=1}^{12} Loss(S(i+1,j)) \tag{5}$$

where: Min. penalty= the total minimum penalty due to storage.

Loss(S(i+1,j))=The loss functions of the storage at the end of ith year and jth month, which could be expressed as follows:

If $S(i+1,j) < MOS$ then $Loss(S(i+1,j))=c * (S(i+1,j) - MOS)^2$ (6)

If $S(i+1,j) < DOS$ then $Loss(S(i+1,j))=d * (S(i+1,j) - DOS)^2$ (7)
And, if $MOS \leq S(i+1,j) \leq DOS$ then $Loss(S(i+1,j))=0$ (8)

where: S(i+1,j)= The storage at the end of the ith year and jth month (million m^3/s).
MOS= The minimum operation storage (million m^3/s).
DOS= The maximum operation storage (million m^3/s).
c, d: Constants which represent weighting factors that reflect the effect of violating the constraints of DOS and MOS. Their values depend on the consideration of the decision maker. Values of (c) and (d) in this study have been both taken to be equal to (one).

The objective function of the optimization of the whole system can be formulated as follows:

$$Min.\ Penalty=F=Minimize = \sum_{i=1}^{N} \sum_{j=1}^{12} (Loss(R(i,j))+ Loss(S(i+1,j))) \tag{9}$$

C) The objective function of power generation

The objective function of the operation of the reservoir is to maximize the power generation (PW); it is a function of flow released and head at the reservoir during the specific period of operation.

$$PW=f (\gamma, Q, \Delta H)$$

$$PW(j)= \gamma * Q * H \tag{10}$$

$$PW(j)=\eta * \gamma * H(j) * R(j) \tag{11}$$

where: PW(j)= The power generation from the reservoir during the jth month (KW).
H(j)= The average effective head during the jth month (m); R(j)= Average monthly release through the turbines of the power plant of the reservoir (m^3/s); γ= The unit weight of water which (KN/m^3).
the η = The overall efficiency of the turbine, which is assumed to be 95%, **Ilisu Dam and HEPP, 2005-b.**

$$PW(j)=9.81 * \eta * H(j) * R(j)$$

When PW(j) is in MW and using release in (million m^3/s), then Eq. (11) reduces to:

$$PW(j)= K * H(j) * R(j) \tag{12}$$

where: K = 0.0036

$$\text{Max. benefit} = PW = \sum_{i=1}^{N} \sum_{j=1}^{12} K * H(i,j) * R(i,j) \tag{13}$$

The power plant of the Ilisu reservoir must be operated within the limit of its capacity. The power plant capacity of the reservoir is 1200 MW.

3.1.2 The Constraints

The maximization and minimization problem is subjected to the constraints. The constraints in the dynamic program (DP) are divided into storage constraints, release or outflow constraints, continuity constraints and additional constraints for the power generation, as follows:

A) Storage constraints

The storage quantities in the reservoir at the beginning of the first month should be known, while the storage in the other months should be within the set of admissible storage which is already defined as:

$$S_{min} \leq S(i,j) \leq S_{max} \tag{14}$$

where: $S(i,j)$=The storage of the reservoir during the ith year and at the beginning of the jth month (million m^3/s).
S_{max} = The maximum allowable storage of the reservoir (million m^3/s).
S_{min} = The minimum allowable storage of the reservoir (million m^3/s).

B) Release (outflow) constraints

The water released from the reservoir in any system during any ith year and jth month should be within the feasible limits:

$$Dem(j) \leq R(i,j) \leq MF \tag{15}$$

$$R(i,j) \leq Rt(i,j) + Rs(i,j) \tag{16}$$

$$Rt(i,j) \leq Rt\ max \tag{17}$$

$$Rt\ max \leq Ds \tag{18}$$

$$Rs(i,j) \leq Ds \tag{19}$$

where: R(i.j) = The total average monthly release from the reservoir during the ith year and the jth month (m^3/s).
Rt(i.j) = The average monthly discharge through the turbines of the reservoir during the ith year and the jth month (m^3/s).
Rs(i.j) = The average monthly discharge through (spillway) outlet of the reservoir during the ith year and the jth month (m^3/s).
Dem(j) = The monthly water requirement during the jth month (m^3/s).
MF = The permissible flow for the reservoir (m^3/s).
Rt max = The maximum discharge capacity through the turbine of the reservoir (m^3/s).
Ds = The maximum discharge capacity of the other outlet (spillway) of the reservoir (m^3/s).

C) Continuity constraint

Continuity constraint is one of the physical constraints of dynamic programming that should include contents of the reservoir from the beginning of one period to the next. This constraint represents the input variable (inflow activity) and the outputs variable (outflow activity) which can be written as follows:

$$S(i,j+1) = S(i,j) + I(i,j) - R(i,j) - EVP(j) \qquad (20)$$

where: S(i,j+1) = The storage of the reservoir at the end of the jth month (million m^3/s).
S(i,j) = The storage of the reservoir at the beginning of the jth month (million m^3/s).
I(i,j) = The average monthly inflow to the reservoir during the jth month (million m^3/s).
R(i,j) = The average monthly release from the reservoir during the jth month (million m^3/s).
EVP(j) = The average monthly net amount of water lost from or added to the reservoir during the jth month (million m^3/s).

D) Additional constraints

These constraints define the limits of the head and power generation of the power plant of the reservoir which can be written as follows:

$$MOL \leq H(i,j) \leq DOL \qquad (21)$$

$$Pmin \leq PW \leq Cap \qquad (22)$$

where: DOL = The maximum design operation level of the power plant of the reservoir (m).
MOL = The minimum operation level of the power plant of the reservoir (m).
PW = The total power generation from the power plant of the reservoir (MW).
Cap = The maximum capacity of the power plant of the reservoir (MW).
Pmin = The minimum capacity of the power plant of the reservoir (MW).

To obtain the economic objective, the resource systems must be operated efficiently. In the present case study, the objective function is to find the optimal operation for the reservoir of the system under study.

3.1.3 Procedure of running the mathematical model DDDP

The DDDP algorithm adopted in the solution of the operation problem of any reservoir system was programmed in (Q. Basic) language. The flow chart of DDDP program is shown in **Fig.1**. The application of the proposed DDDP involves the following steps:

1- Reading input data I(j), EVP(j), Smax, Smin, Dem(j), MF, Wmin (i=1, 2,…, N : j=1, 2,…,12).
Where: Wmin = The minimum flow for the reservoir (m^3/s).

2- Determining initial trajectory by using Eq. (23).

$$S'_{(n,i)} = (Smax(i) - Smin(i))/2 + smin(i) \qquad (23)$$

3- Computing the maximum storage increment allowed from the initial trial trajectory (initial corridor width, by using Eq. (24) for the first cycle).

$$S_{(n,i)} = S'_{(n,i)} + (Z-2) * Delta(i) \quad ; \quad Z = 1,2,3 \qquad (24)$$

$$Delta(i) = (Smax(i) - \mathrm{Smin(i))/\ x} \qquad (25)$$

where: Delta(i) = the maximum deviation allowed from the initial state in the reservoir (i).
x = a factor that specifies the initial increment Delta (i).

A value of X = 8 has been found to minimize the computer time required to reach an optimal trajectory, **Ali, 1978.**

4- Setting iteration equal to one, and then constructing a corridor around the trial trajectory for the first operational period (i.e., first month and searching the state of the system maximum of the objective function). There are only three possible states of the system in the first period.
5- Using the continuity equation Eq. (20), the decision variable (release from the reservoir, R(i)) during the first month could be obtained.
6- After calculating the decision variable R(i), the program proceeds to the objective function for checking whether this policy in this month satisfied the system constraints then computes power due to the operation of the system in this period.
7- For all other months, the foregoing computational procedure becomes more complicated because the number of possible decisions increases to 9 in the i^{th} period.
8- The procedure must be carried out for all other stages (i.e. i=2,3,…N) and the total maximum power or minimum penalty associated with this iteration is computed by DP recursive equation Eq.(9) and Eq.(13), then the optimum trajectory within a given corridor and its return are determined by DP methodology.
9- After completing each iteration, it should be checked whether the convergence criterion has been satisfied or not. A new iteration is needed if the convergence criterion is not satisfied. This new iteration starts from the optimum trajectory that has been obtained from the previous iteration and the procedure is repeated until the pre-specified convergence criterion is satisfied.

In this research, the case is for computing the water requirements and power generation. The DDDP computer program runs 178 cycles in this case.

3.1.4 Results of DP model and analysis

The results of operating the DP indicated that the requirements for water (demand) from the reservoir are greater than maximum outflow, therefore, the optimal operating is when the reservoir satisfied just 56.4% of these requirements. The remaining of the requirements for water can be met from other sources such as Euphrates River and Diyala River.

Fig. 2 shows optimum average monthly outflow and demand for the dam. Maximum monthly outflow is 680 m^3/s in July (1961-1968), while minimum outflow is 310 m^3/s in December and January (1983-1986) and average monthly outflow is 464 m^3/s, while the average of demand is 415 m^3/s, and maximum deficit in satisfying the demand is 15 m^3/s. Outflow from spillway is 0 m^3/s. Average annual flow at the Iraqi-Turkish borders (before implementation of Ilisu Dam) is 637 m^3/s. Average annual flow at the Iraqi-Turkish borders after implementation of the dam will decrease with the consideration of water requirements of Turkish from 637 m^3/s to 432.6 m^3/s, while this flow will decrease with the consideration of water requirements of Turkish and Syrian from 637 m^3/s to 384.6 m^3/s. The maximum water level is 525.0 m in May and June (1969), and the minimum water level is 486.1 m in October (1987, 2002, 2009) and September (2002) and the average monthly water level is 507.5 m.

Fig. 3 shows optimum average monthly storage. Maximum operation storage is 10637 million m^3/s in June (1969) while minimum operation storage is 2950 million m^3/s in November (1987, 2002, 2009). Average minimum and average maximum storage occur during the months of November and June with the storage value of 5506 million m^3/s and 7420 million m^3/s, respectively, and average monthly storage is 6309 million m^3/s. The storage of reservoir is between minimum and design operation storage of 2950 million m^3/s and 10612.5 million m^3/s, respectively. Average annual evaporation from the reservoir is 3.8 m^3/s. Monthly power production ranged between 255MW in November (2002) and 766 MW in July (1969), while annual power production ranged between 394 MW and 515 MW with an average of 455 MW. The total maximum power generated with maximum reservoir release amounts to 6247MW, while the total minimum power generated with minimum reservoir release amounts to 4656 MW. Outflow from a power outlet is equal to outflow from the dam due to outflow from spillway is 0 m^3/s. The results of the DP model are summarized in **Table 1**.

3.2 Rule Curves

A rule curve is a guideline for reservoir operation and is generally based on a detailed sequential analysis of various critical combinations of hydrologic conditions and demand. Operation according to design rule curve considered as optimal operation, henceforth, this operation will be referred to as "theoretical" operation**, Fadhil, 1990**.

The rule curves or guide curves (GC) are commonly used in the reservoir operations. These rule curves define the release decision according to the present reservoir storage. They are usually constructed from the data in the critical period. They give a confidence to the reservoir operators that the reservoir will have enough water to meet the future demand provided that the reservoir inflow must not be less than the past. Once the reservoir operators, knowing the present state of the system can make a release decision according to the rule curves and their experiences, **Vudhivanich, 1986**.

Young, 1967, first initiated to derive rules using simple linear regression or multiple linear regressions from the deterministic optimization results. He derived regression equations using inflows and storages to find optimal releases.

He proposed the multiple hedging rules which divided the reservoir storage into 3 zones. The rules indicated the release at 90, 50 and 10% of the demand according to the reservoir storage in zone 1 (high storage), 2 (medium storage) and 3 (low storage). The multiple hedging rules could reduce the overall deficit index.

The formulated DP model has been solved by DDDP approach to determine an optimal operation of the reservoir. The rule curves (upper, average, and lower) should fall between the minimum and design operation storage, the computer program is written in (Q.Basic) language to determine these rule curves.

Six statistical models namely, normal, log- normal type II, log- normal type III, Pearson type III, log- Pearson type III and Gumbel type I distribution has been used to determine the rule curves of Ilisu reservoir using historical streamflow records for 588 months (from 1961 to 2009). The average rule curve is determined by averaging the values of the storage obtained by the model over the considered period, whereas the upper and lower rule curves have been derived depending on the non-exceeding probability values of (10 %, 90%) of the probability distribution of the optimal storage to represent the upper and lower rule curves, respectively**, Mark, 1992**. The model results are accepted or not by using the measures, standard error (SE), root mean square error (RMSE), bias and chi-squared test (X^2) were used to obtain the best fit. The smallest values of these measures lead to the best fit, **Nasser, 2002**. Table 2 shows the results of these measures. The normal distributions are the best among the above types of distributions and used to determine these rule curves. The results of optimal operation rule curves are tabulated in table 3 and shown schematically in **Figs. 4 and 5**, respectively.

$$SE= [(\Sigma(EL_O - EL_C)^2/(N-M))]^{0.5} \tag{26}$$

$$RMSE= \Sigma[(EL_O - EL_C)/EL_O]^2 \tag{27}$$

$$BIAS= \Sigma[(EL_O - EL_C)/EL_O] \tag{28}$$

$$X^2 = \Sigma[(EL_O - EL_C)^2/EL_O] \tag{29}$$

where: N= The sample size; EL_O= Observed water level; EL_C= Computed water level.
M= The number of parameter distribution.

3.3 Simulation Model

Simulation is a descriptive technique. A simulation model incorporates the quantifiable relationships among variables and describes the outcome of operating a system under a given set of inputs and operating conditions. Most simulation models do not contain algorithms for seeking optimal solutions. However, such models usually permit far less drastic simplification and approximation of the real problem than is required when using an analytic optimization model, **Meta System Inc. 1975**.

3.3.1 The Monthly operation procedure by the simulation model

The real-time monthly operation of the Ilisu reservoir has been obtained by using the historical monthly inflow data for the period (October 1961 to September 2009) that represent the input data to the model. The outputs of the model are the reservoir storage, outflow from the reservoir, outflow from power outlet and spillway, reservoir water level, the output of power generation and the energy power potential. The procedure of simulation model involves the following steps:

1- The input data are inflow, evaporation, precipitation, demands, power capacity, and the rule curves of the Ilisu reservoir.
2- Estimating the initial storage of the reservoir which is equal to the average of the upper and lower rule curves at the first month.
3- Calculating the storage which should be within the operation rule curves range and be neither more than the design operation storage nor less than the minimum operation storage of the reservoir.
4- Determining the amount of water (outflow) that should be neither more than the maximum permissible flow nor less than the minimum permissible flow of the downstream channel.
5- Determining the water level which, as formerly mentioned, is a function of the reservoir storage and then comparing it with the rule curves; if it exceeds the rule curves, then the computed storage and the water level are readjusted.
6- Calculating the outflow from the power outlets which should not exceed the capacity of the power outlets, and then storing the remaining release in the reservoir. The minimum operation level represents the minimum level for operating the power generators.
7- Calculating the head (H) on the power generation units which, as formerly mentioned, is a function of the storage.
8- Determining the output power production from the reservoir power station, this depends on the flow passing through the power outlets and the rated head and then calculating the output power by Eq. (12).
9- Determining the energy potential which is calculated by the following Eq.(30):

$$PPw = 9.81 * Rt * H * Eff * 24 * 30/1000000 \tag{30}$$

where: PPw= Energy potential (GWh); Eff: The efficiency of the power generation which is (95%) in this research.

3.3.2 Results of simulation model and analysis

Fig. 6 shows optimum average monthly outflow and demand for Ilisu dam. Maximum monthly outflow is 1044 m^3/s in May (1993), while minimum monthly outflow is 67 m^3/s in December, and average monthly outflow is 460 m^3/s, while the average of demand is 415 m^3/s, and without a deficit in satisfying the demand. Outflow from spillway is 0 m^3/s. Average annual flow at the Iraqi-Turkish borders (before implementation of Ilisu Dam) is 637 m^3/s. Average annual flow at the Iraqi-Turkish borders after implementation of the dam will decrease with the consideration of water requirements of Turkish from 637 m^3/s to 428.6 m^3/s, while this flow will decrease with the consideration of water requirements of Turkish and Syrian from 637 m^3/s to 380.6 m^3/s. The maximum water level is 520.3 m in June, and the minimum water level is 501.8 m in November (2009), and while the average monthly water level is 514.3 m.

Fig. 7 shows optimum average monthly storage. Maximum operation storage is 9208 million m^3/s in June, while minimum operation storage 5078 million m^3/s in November (2009) and average monthly storage is 7680 million m^3/s. Average minimum and average maximum storage occur during the months of November and June with the storage value of 6566 million m^3/s and 8764 million m^3/s, respectively. The average annual evaporation from the reservoir is 5 m^3/s. Monthly power production ranged between 61.8 MW in December (1990) and 1117.8 MW in May (1993), while the annual power production ranged between 414 MW and 576.9 MW with an average of 475.4 MW. The total maximum power generated with maximum reservoir release amounts to 7779.5 MW, while the total minimum power generated with minimum reservoir release amounts to 4927.9 MW. Outflow from a power outlet is equal to outflow from the dam due to outflow from spillway is 0 m^3/s. Monthly energy potential from the reservoir ranged between 46 GWh in December (1990) and 831.6 GWh in May (1993), while annual energy potential ranged between 302.7 GWh and 421.5 GWh with an average of 347.4 GWh. The results of the simulation model are summarized in **Table 4**.

4. CONCLUSIONS

The major objective of this research is to find the optimal operation of Ilisu Dam. The optimization process was attained by applying Dynamic Programming solved by the Discrete Differential Dynamic Programming technique, and by monthly simulation models. The available monthly inflow for 49 years from (Oct. 1961 to Sep. 2009) has been considered as the basic input data to the system to find the optimum monthly release, water level, storage, and generation capacity of the reservoir.

Since rule curves are necessary guides for long-term reservoir operation, the monthly elevation, storage rule curves, that were determined by an optimization model, were used in this study to develop the monthly simulation model to estimate the release, water level, storage, and generation capacity. A simulation model is adopted to achieve an operation as much close to the optimum operation as possible and to keep the storage and release within their targets. The following conclusions are obtained:

4.1 Conclusions of DP model:

1- The results of operation indicated that the release satisfied just 56.4% of the water requirements.

2- The maximum monthly release was 680 m^3/s, the minimum monthly release was 310 m^3/s, the average monthly release was 464 m^3/s, and maximum deficit in satisfying the demand was 15 m^3/s. Average monthly release in DP model was higher than in simulation model during November, December, January, and February.

3- Average annual flow at the Iraqi-Turkish borders (before implementation of Ilisu Dam) was 637 m^3/s. When Ilisu dam was operated in the DP model, average annual inflow to Iraq will be decreased with the consideration of water requirements of Turkish and Turkish and Syrian to 67.9% and 60.4 %, respectively.
4- Average annual evaporation from the reservoir was 3.8 m^3/s.
5- Average annual generation power was 455 MW, the total maximum generated power with maximum reservoir release amounts was 6247 MW, and the total minimum generated power with minimum reservoir release amounts was 4656 MW. The DP model shows that Ilisu reservoir can be operated at half of the capacity during April, May, June, July, August, and less than half capacity during the remaining months of the year.

4.2 Conclusions of Simulation Model:

1- The maximum monthly release was 1044 m^3/s, the minimum monthly release was 67 m^3/s, the average monthly release was 460 m^3/s, and without a deficit in satisfying the demand.
2- Average annual flow at the Iraqi-Turkish borders (before implementation of Ilisu Dam) was 637 m^3/s. When Ilisu dam was operated in the simulation model, average annual inflow to Iraq will be decreased with the consideration of water requirements of Turkish and Turkish and Syrian to 67.3 % and 59.7 %, respectively.
3- Average annual evaporation from the reservoir was 5 m^3/s.
4- Average annual generation power was 475.4 MW, the total maximum generated power with maximum reservoir release amounts was 7779.5 MW, and the total minimum generated power with minimum reservoir release amounts was 4927.9 MW. The simulation model shows that two third of the capacity of Ilisu reservoir is utilized during April, May, June, July, while a half or less than half of the capacity is utilized during the remaining months of the year.

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NOMENCLATURE

a, b, c, d = constants, dimensionless.
Cap = the maximum capacity of the power plant of the reservoir, MW.
Delta(i) = the maximum deviation allowed from the initial state in the reservoir (i), million m^3/s.
Dem(j) = the monthly water requirement during the jth month, m^3/s.
DOL = the maximum design operation level of the power plant of the reservoir, m.
DOS= the maximum operation storage, million m^3/s.
Ds = the maximum discharge capacity of the other outlet (spillway) of the reservoir, m^3/s.
EL_C= computed water level, m.
EL_O= observed water level, m.
EVP(j) = the net monthly water losses from Ilisu reservoir during the jth month, million m^3/s.
H(j)= the average effective head during the jth month, m.
I(i,j) = the average monthly inflow to the reservoir during the jth month, million m^3/s.
M= the number of parameter distribution, dimensionless.
MF= the maximum permissible flow, m^3/s.
MOL = the minimum operation level of the power plant of the reservoir, m.
MOS= the minimum operation storage, million m^3/s.
N= the sample size, dimensionless.
Pmin = the minimum capacity of the power plant of the reservoir, MW.
PW = the total power generation from the power plant of the reservoir, MW.
R(i,j) = the average monthly release from the reservoir during the jth month, million m^3/s.
Rs(i.j) = the average monthly discharge through (spillway) outlet of the reservoir during the ith year and the jth month, m^3/s.
Rt max = the maximum discharge capacity through the turbine of the reservoir, m^3/s.
Rt(i.j) = the average monthly discharge through the turbines of the reservoir during the ith year and the jth month, m^3/s.
S(i,j) = the storage of the reservoir at the beginning of the jth month, million m^3/s.
$S'_{(n,\, i)}$ = the initial trial trajectory for the System, m^3/s.
S_{max} = the maximum allowable storage of the reservoir, million m^3/s.
S_{min} = the minimum allowable storage of the reservoir, million m^3/s.
Wmin= the minimum outflow of Ilisu reservoir, m^3/s.
x = factor, dimensionless.
γ= the unit weight of water, KN/m^3.
η =the overall efficiency of the turbine, dimensionless.

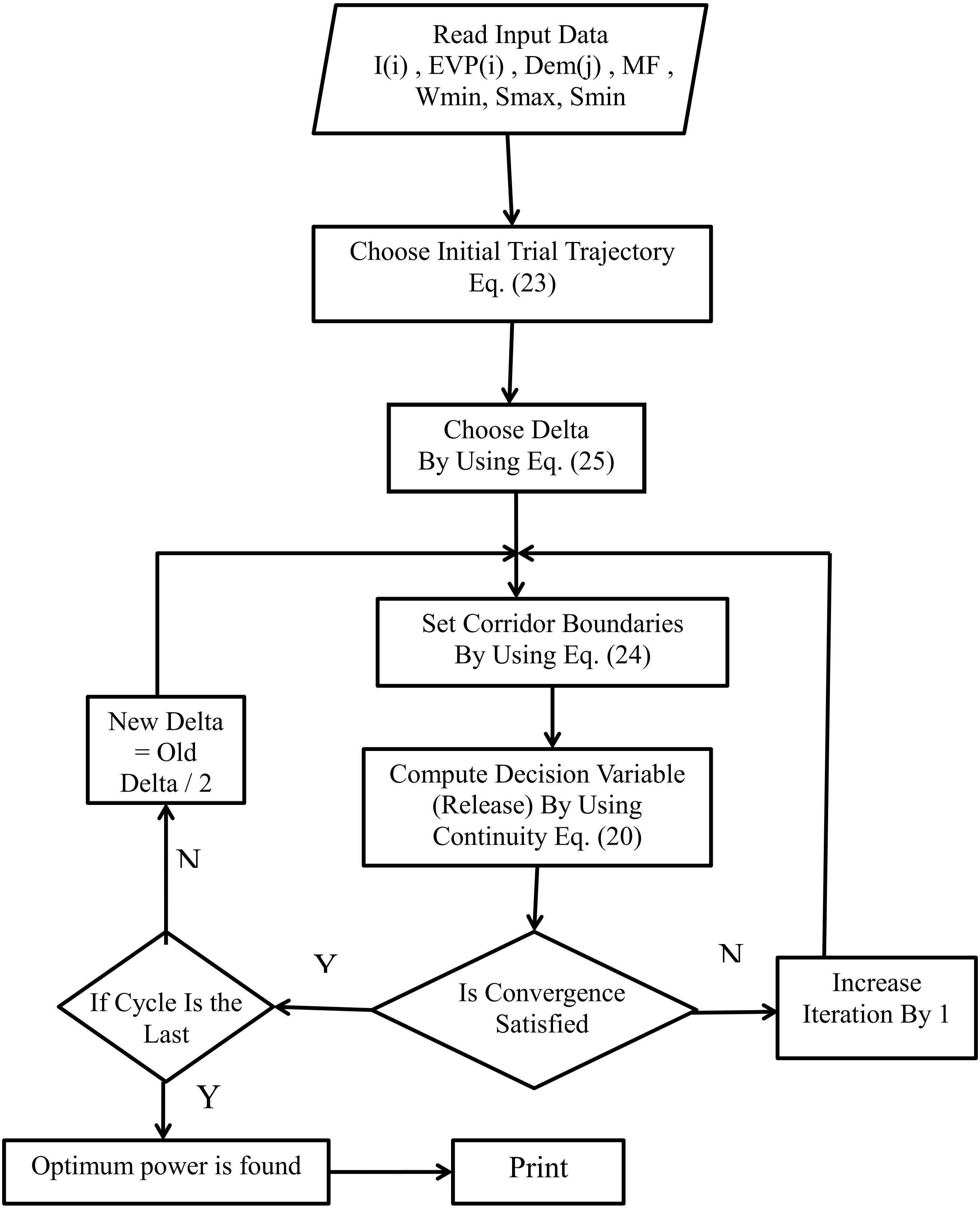

Figure 1. Flow Chart for Multi-Purpose Reservoir Operation by Using DDDP Program.

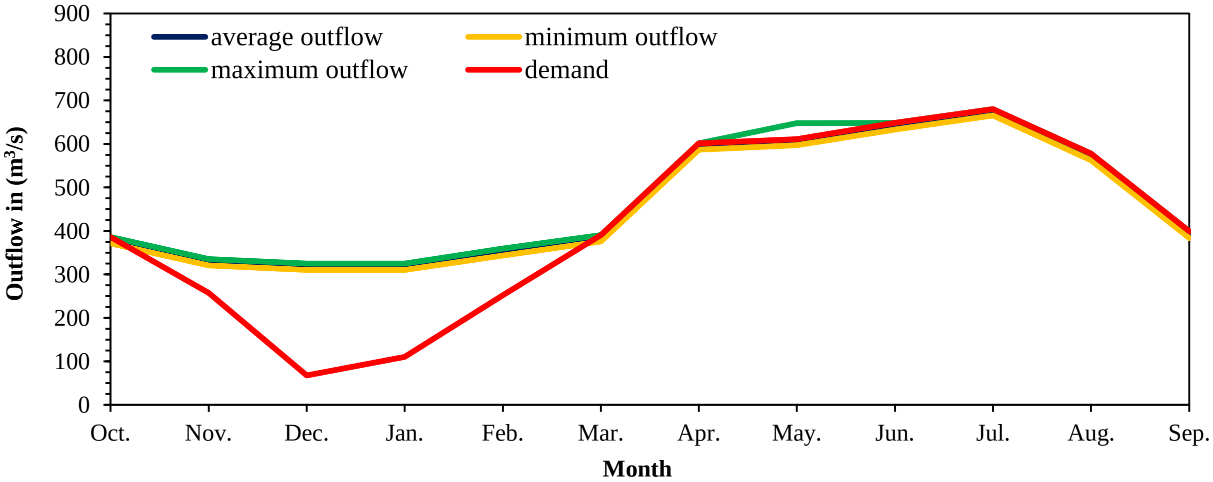

Figure 2. Optimum average monthly outflow and demand of Ilisu dam using DP model.

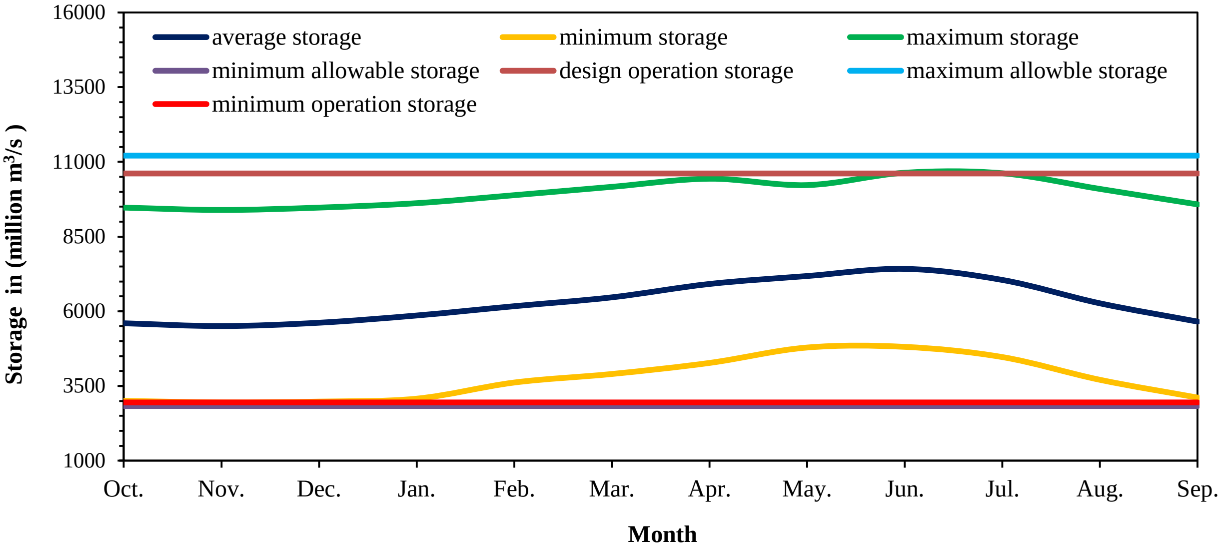

Figure 3. Optimum average monthly storage of Ilisu dam using DP model.

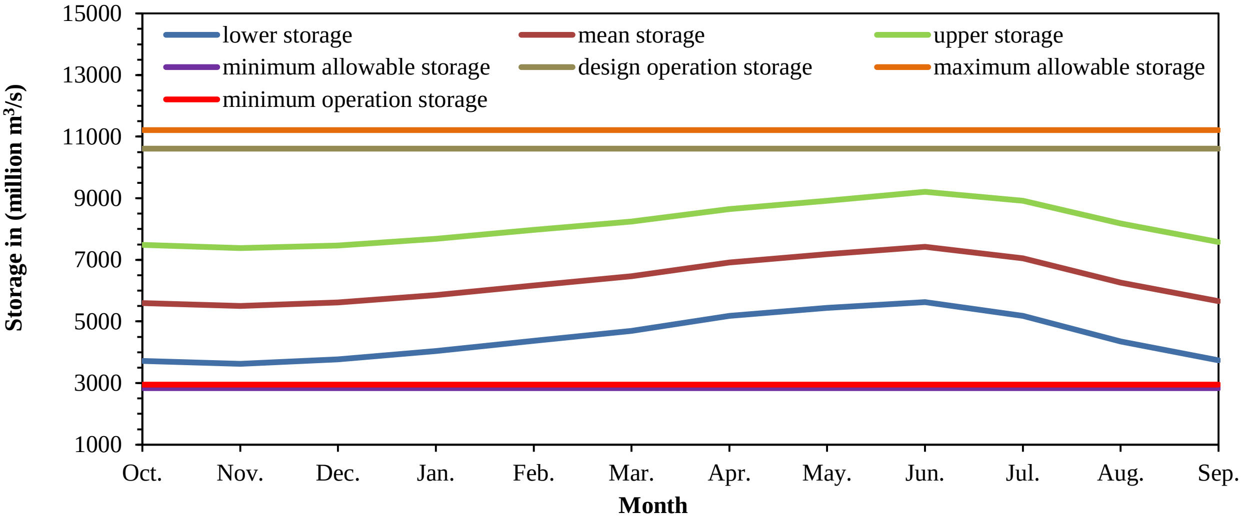

Figure 4. Optimum operation storage rule curves for Ilisu Dam.

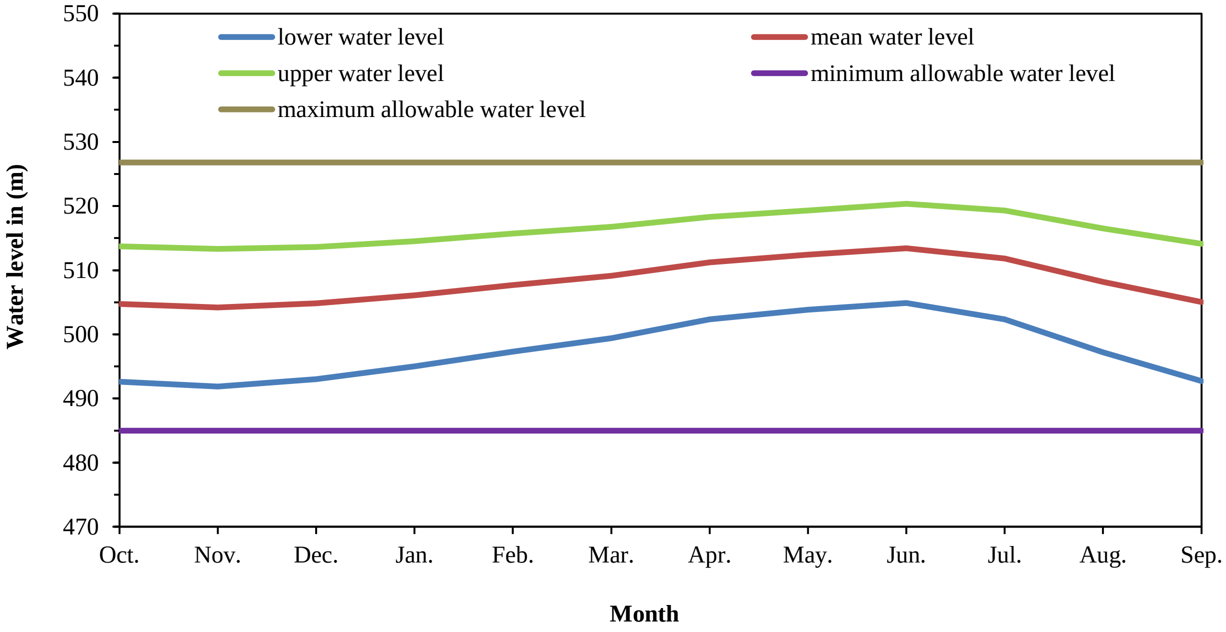

Figure 5. Optimum operation elevation rule curves for Ilisu Dam.

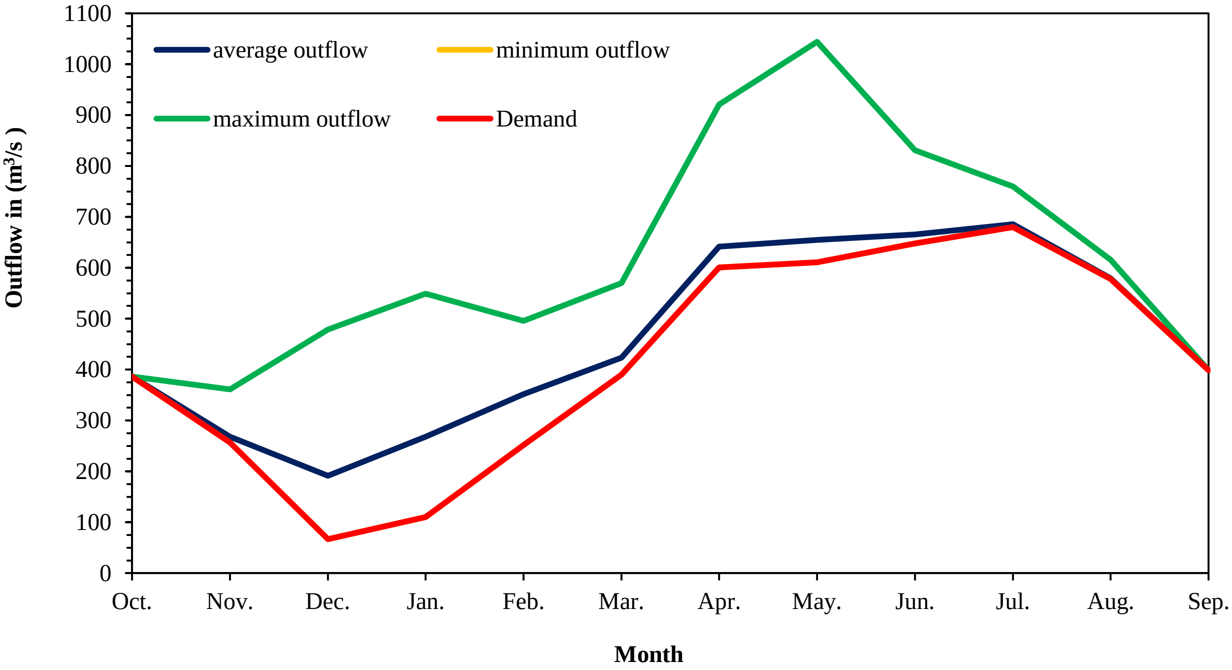

Figure 6. Optimum average monthly outflow and demand of Ilisu dam using simulation model.

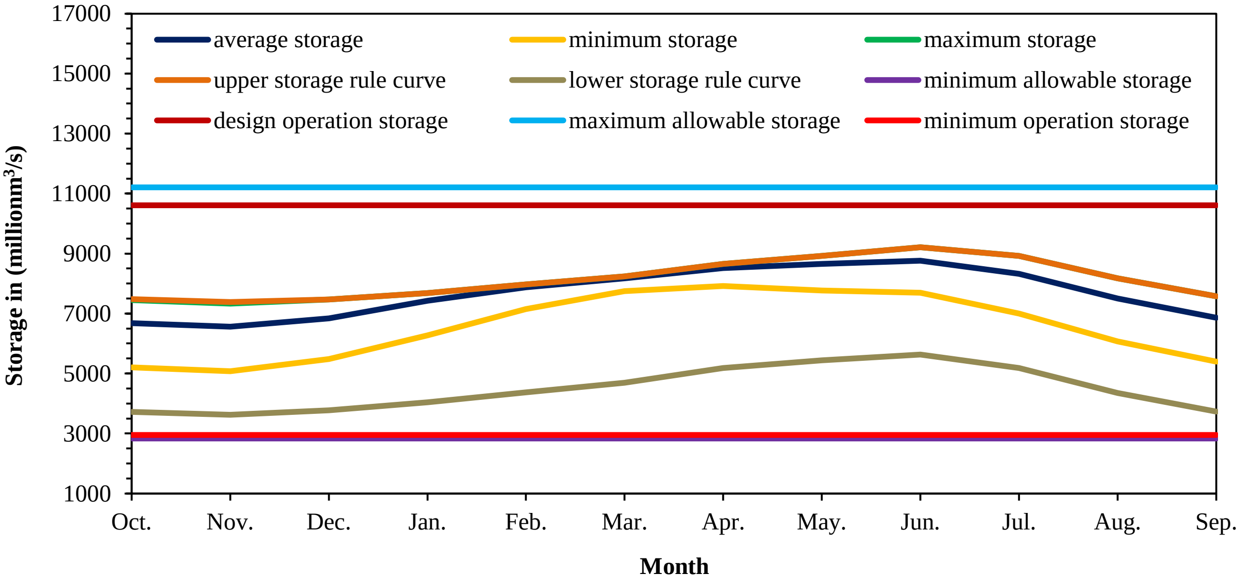

Figure 7. Optimum average monthly storage of Ilisu dam using simulation model.

Table 1. Results of DP model for Ilisu dam for the period (1961-2009).

Item	Unit	Monthly		The monthly average for the year		
		Min	Max	Min	Max	Average
Inflow	m^3/s	336	1162	346	704	466
Storage	million m^3/s	2950	10637	5506	7420	6309
Water level	m	486.1	525.0	503.3	513.0	507.5
Outflow	m^3/s	310	680	318	674	464
Outflow from spillway	m^3/s	0	0	0	0	0
Outflow from power outlets	m^3/s	310	680	318	674	464
Power outlets	MW	255	766	306	669	455

Table 2. Values of standard error (SE), root mean square error (RMSE), bias and chi-squared test (X^2) of six statistical models.

Type	SE	RMSE	BIAS	X^2 calculated	X^2 table	X^2 result
Normal	1.050	0.153	0.824	8.789	11.1	OK
Log-normal type II	1.128	0.182	0.839	10.150	11.1	OK
Log-normal type III	1.079	0.155	0.930	9.279	11.1	OK
Pearson type III	1.173	0.148	0.907	10.966	11.1	OK
Log- Pearson type III	1.335	0.175	0.913	14.204	11.1	NOT OK
Gumbel type I	2.224	1.191	2.491	76.870	11.1	NOT OK

Table 3. Values of optimum rule curves of Ilisu Reservoir.

Month	Rule curves based on the storage (million m^3/s)			Rule curves based on the water level (m)		
	Upper	Average	Lower	Upper	Average	Lower
Oct.	7483	5600	3717	514	505	493
Nov.	7387	5506	3625	513	504	492
Dec.	7465	5618	3771	514	505	493
Jan.	7682	5860	4039	515	506	495
Feb.	7972	6171	4371	516	508	497
Mar.	8239	6467	4695	517	509	499
Apr.	8652	6915	5179	518	511	502
May	8919	7180	5442	519	512	504
Jun	9208	7420	5632	520	513	505
Jul.	8920	7049	5178	519	512	502
Aug.	8177	6265	4354	517	508	497
Sep.	7577	5655	3733	514	505	493

Table 4. Results of a simulation model for Ilisu dam for the period (1961-2009).

Item	Unit	Monthly		The monthly average for the year		
		Min	Max	Min	Max	Average
Outflow	m^3/s	67	1044	191	686	460
Water level	m	501.8	520.3	509.5	518.7	514.3
Storage	million m^3/s	5078	9208	6566	8764	7680
Outflow from power outlets	m^3/s	67	1044	191	686	460
Outflow from spillway	m^3/s	0	0	0	0	0
Power production	MW	61.8	1117.8	192.3	720.2	475.4
Power potential	GWh	46	831.6	143	535.8	347.4