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Optimal energy production in the Yeşilirmak River Basin

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ABSTRACT

Optimal planning and operation of water resources are depend on a complex structure and process that include country economics and life standards. Currently, sustainable use and development of water resources to maximize possible benefits are the two big challenges to be overcome and efficient use of hydro power forms a significant component of this., A water resources system with multi-reservoirs is described in this study. It is considered to three scenarios in the system. The system is set up on the optimization model for the long term planning. The method of the dynamic programming with successive approximations is used in the model. Objective function in the optimization model has two stage, maximization of firm and total energies. The model is applied to the system with multi-reservoirs presented successively on the main and secondary line of the Yeşilirmak River in the Yeşilirmak River Basin. Results are evaluated to the maximization of the energy production. Accordingly, the firm energy obtained from the optimization model is presented approximate the value determined by empiric equations, and also the average energy in the model is % 32 better than the value obtained by empiric equations. Additionally, it is observed that the optimization process of the reservoirs with the highest operational storage was controlled and managed.

Keywords: Multi-Reservoirs System, Optimal Energy Production, Dynamic Programming, Yeşilirmak River Basin

1. INTRODUCTION

Water resources planning integrated with the country economics and the suggested life standards is complicated process and a multi-dimensional. Water resources planning and management have to cover all of activities to provide optimal uses of water resources, in presented targets direct and in the frame of the suggested critics. Compatibility with the general economical criteria, environmental protection, and social factors must be observed while optimal solutions are investigated for various purposes such as energy generation, irrigation and flood protection. In the long term planning of multi-reservoir and multiple objectives systems, optimization and simulation methods can be used

in combination to determine solutions which take into account the stochastic nature of the produce optimal benefits and hydrological events under certain risks. A similar approach can be used for a more detailed optimization of the expected benefits and for the control of the events like droughts and floods, where the risks must be decreased to a minimum, in short term planning and real-time operation of the system [1].

Optimization and simulation models for optimum operations of water resources systems have been developed since the early 1960s [2]. Results of such studies are used in the planning and management of reservoirs. Reservoir operation rule curves in decision making are widely used to guide the system operators for long term reservoir operation [3]. A rule curve can be defined as the

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set of target end-of-period storage (or elevation) values in a reservoir [4]. Past studies on management of reservoir operations either use heuristic approaches or mathematical programming based optimization approaches when deriving the rule curves. The choice depends on the complexity of the objective and the structure of the reservoir system.

Water resources systems are described examples of modeling, nonlinear programming, linear programming, dynamic programming, simulation and operation models in the technical case study [5]. It has been conducted important work in water resource systems on the application of optimization models [6]. In optimization models, they describe components such as input parameters, unknown decision variables and constraints. When a hopper system is operated; evaluations are based on the ability of the system to meet existing water demands that change over time. In a reservoir system, the aim of the hopper operating system is to maximize the benefits under the mass balance equations and other constraints, to minimize the costs, to meet the variable water demands' [7].

Dynamic programming was developed firstly [8]. Dynamic programming (DP) can effectively deal with the sequential decision making of optimization problems in a water resources system consisting of reservoirs. Lagrange multipliers and sequential approach techniques were suggested for optimization of multidimensional systems with dynamic programming [9]. They have also attempted to improve computational simplicity by reducing the number of transactions and by developing discrete dynamic programming (DDP) [10].

Deterministic optimization methods for optimization of reservoir operations can be exemplified by, nonlinear programming (NLP), linear programming (LP), deterministic dynamic programming (DDP), or network flow optimization (NFO), the last being more suitable for multi-reservoir systems [4 and 11]. The first study of deterministic dynamic programming appears to have been used only in the operation of a reservoir [12 and 13]. It was used reservoir volume as a state variable [13]. It was applied Dynamic Programming with Successive Approximation (DPSA) algorithm to a hypothetical four reservoirs system. The proof of

convergence for DPSA was provided [14]. Incremental Dynamic Programming (IDP) was proposed and applied to water resource problem [15]. Discrete Differential DP (DDDP) was suggested and was implemented to the same hypothetical reservoir system [16] adopted [17]. Incremental DPSA (IDPSA) was applied to a reservoir system, performed by Tennessee valley authority [18]. It was used the DPSA technique together with the simulation methods to maximize the energy production of the Sakarya Basin in the study of optimal sizing and operation of a series hydroelectric plant on a river [19]. DPSA have also been implemented in the Lower Colorado River Dam System to assist in the planning of optimal hourly hydropower units [20]. It has been prepared a study that maximizes hydroelectric energy production, which analyzes the sensitivity and effectiveness of the model with a linear programming approach [21].

A multiple reservoirs system serving various objectives like irrigation, energy production and flood control have been operated [22]. In this study, multiple reservoirs were optimized to maximize energy generation and to meet the irrigational needs. A NLP was utilized. This technique was applied to a project named Koyna Hydro-Electric in Maharashtra. Three different dependable inflow scenarios were considered to solve the NLP model to maximize energy generation under different policies of operation. In this study, similar optimum rule curves were obtained for different inflow scenarios. The optimum operation of a large scale of hydropower plants in Yangtze River Basin in China was performed. An improved decomposition-coordination and discrete differential dynamic programming (IDC-DDDP) have been used under the objective of maximizing total power generation [23]. This study showed that IDC-DDDP has satisfactory and vying performances in total energy production and convergence speed, compared to the other methods that can be used for large scale of hydropower systems.

The efficient implicit stochastic optimization (ISO) is widely studied for the derivation of optimal rule curves for the long-term planning of the single-reservoir and/or the multi-reservoir systems [24]. When deriving the rule curves for reservoir operations, past studies consider a variety of objectives. A common objective is maximizing the hydropower generated from the

reservoir. Rule curves were developed for China’s Qing River cascade hydroelectric reservoirs with the objective of decreasing annual energy generation. A simulation model was developed to investigate the dynamic behavior of a multi reservoirs system [25]. This model was developed using the principles of SDs and an object-oriented simulational environment is constructed for the model. Specifically, the tail water level change is considered in the developed model in detail by deriving tail water curves. The results demonstrated that in the operational decision taken by one reservoir would affect the whole system of reservoirs.

Approaches in operating systems were investigated in reservoir systems; classical optimization models, simulation modeling, optimization simulation combined optimization, fuzzy set theory, evolutionary algorithm and artificial neural networks (ANN) [26]. A stochastic evolutionary algorithm was operated to maximize the optimal size of the hydropower plant section for maximum energy and economic benefit [27]. deterministic and stochastic models were analyzed for maximizing profits from the sale of electricity produced in reservoirs [28]. ANN was used for long-term water level estimates [29]. It has been dealt with the optimum design, control and operation of small hydropower plants with the honey bee optimization algorithm [30].

A water resources system with multi-reservoirs is described in this study. It is considered to three scenarios in this system. The system is set up on the optimization model for the long term planning. The method of the dynamic programming with successive approximations is performed for the model. Objective function in the model has two stage, maximization of firm and total energies. The model is implemeted to a water resources system with multi-reservoirs presented successively on the main and secondary line of the Yeşilirmak River in the Yeşilirmak River Basin.

2. MATHEMATICAL MODEL

“The optimization model is comprised of four parts: (1) statement of constituent equations, (2) formulation of constraints, (3) specification of objective function, and (4) optimization technique. It may be noted that the model is for long term

planning and operation of a multi-reservoir system. Therefore, a monthly time scale is appropriate and monthly flows are used as input to the system. The system output to be optimized is represented in the objective function. Each part is now expressed in what follows.

Constituent equations: A multi-reservoir system can be represented as a series of reservoirs, each with a storage capacity, a power production unit, inflows from upstream and releases downstream, as shown in Figure 1.

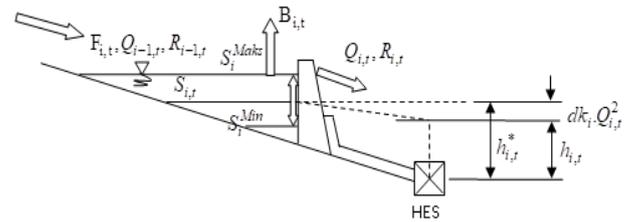


Figure 1. Variables related to t-time operation in any i-res

Taking $i = 1, 2, \dots, N$, where N is the number of reservoirs, and $t = 1, 2, \dots, M$, where M is the number of time intervals (months), the basic constituent equations of the system are the water balance relations of each reservoir for each time interval (for all i and t):

$$S_{i,t+1} = S_{i,t} + F_{i,t} + Q_{i-1,t} + R_{i-1,t} - Q_{i,t} - R_{i,t} - L_{i,t} \quad (1)$$

where $S_{i,t}$ is the water stored in the reservoir; $F_{i,t}$ is the inflow into the reservoir from its sub-drainage area; $Q_{i,t}$ is the water released for energy production from the reservoir; $R_{i,t}$ is the spilled water from the reservoir; and $L_{i,t}$ is the water loss through evaporation and seepage from the reservoir.

The other constituent equations for power generation are expressed as:

$$P_{i,t} = k_i \cdot Q_{i,t} \cdot h_{i,t} \quad (2)$$

$$h_{i,t} = h_{i,t} - h_f^i \quad (3)$$

$$h_f^i = \frac{8}{\pi^2 g} f^i J_e^i \frac{Q_{i,t}^2}{d^{i5}} \quad (4)$$

$$\alpha^i = \frac{8}{\pi^2 g} f^i J_e^i \frac{1}{d^{i5}} \quad (5)$$

$$l_e^i = l^i + \frac{d^i}{f^i} \sum K^i \quad (6)$$

$$h_{i,t} = h_{i,t} - \alpha^i \cdot Q_{i,t}^2 \quad (7)$$

where $P_{i,t}$ is the power generation from the reservoir; $h_{i,t}$ is the net turbine head for the reservoir; k_i is the average power generation coefficient for the reservoir; $h_{i,t}$ is the water height in the reservoir (measured from turbine level); h_f^i is the total energy loss; f^i is the friction coefficient; l_e^i is the equivalence pipe length; d^i is the pipe diameter; l^i is the pipe length; K^i is the local coefficient of energy loss; α^i is the average head loss coefficient for the reservoir; and $h_{i,t}$ will be obtained as a function of the average storage volume (at the beginning and end of the time interval):

$$h_{i,t} = h \left(\frac{S_{i,t} + S_{i,t+1}}{2} \right) \quad (8)$$

The total power generation of the system at time t is given as

$$\sum_{i=1}^N P_{i,t} = \sum_{i=1}^N k_i \cdot Q_{i,t} \cdot h_{i,t} \quad (9)$$

The system constraints are related to the storage capacity, power generation capacity and water usage (for energy production, irrigation, and other purposes)” [1].

3. OPTIMIZATION MODEL FOR LONG TERM PLANNING

“Specification of constraints: The constraints to be expressed are for storage capacity, power generation, energy production, water spill, and total water release.

1. The constraint on the storage capacity an be expressed as

$$S_i^{Min} \leq S_{i,t} \leq S_i^{Max} \quad (10)$$

where S_i^{Min} and S_i^{Max} are the minimum and maximum storage capacities of the reservoir.

2. The constraints for power generation can be expressed as

$$0 \leq P_{i,t} \leq P_{k_i} \quad (11)$$

where P_{k_i} is the installed power generation capacity for reservoir.

3. The constraint on releases for energy production can be expressed as

$$Q_i^{Min} \leq Q_{i,t} \leq Q_i^{Max} \quad (12)$$

where Q_i^{Min} and Q_i^{Max} are the minimum and maximum releases for reservoir. Obviously, Q_i^{Max} is related to the installed power generation capacity P_{k_i} , while Q_i^{Max} is related to the minimum required release downstream D_i^{Min} such that

$$Q_i^{Min} = D_i^{Min}, \text{ when } R_{i,t} = 0 \quad (13)$$

4. The constraint on the spill of water can be written as

$$0 \leq R_{i,t} \leq R_i^{Max} \quad (14)$$

where R_i^{Max} is the maximum spillway capacity for reservoir.

5. The constraints on the total water release can be written as

$$D_i^{Min} \leq (Q_{i,t} + R_{i,t}) \leq D_i^{Max} \quad (15)$$

where D_i^{Min} is the minimum release for pollution control or navigation, and D_i^{Max} is the maximum safe discharge for downstream of the reservoir.

Objective function: The primary objective is to maximize energy production, encompassing the maximization of firm energy and secondary energy (or the total energy production). For the maximization of firm power, the critical dry period within the observed monthly flow series must be selected and using the critical period flow series (Sert et al. 1982), the objective function may be stated as:

$$\max P_F = \max \left[\min \sum_{i=1}^N P_{i,t} \right] \quad (16)$$

where N is the total number of months in the critical period (is observed as 12 months).

For the maximization of total energy, average monthly flows may be used, and the already maximized firm power $P_{F_{max}}$ will be imposed as a parametric constraint:

$$\sum_{i=1}^N P_{i,t} \geq P_{F_{max}} \quad (17)$$

$$\max \left[\sum_{t=1}^M \sum_{i=1}^N P_{i,t} \right] \quad (18)$$

which is equivalent to maximizing the secondary energy $\sum_t \sum_i (P_{i,t} - P_{F_{max}})$, since $P_{F_{max}}$ is a parametric constant.

Optimization method: In the dynamic programming with successive approximations, equations between 1 and 18 represent the “stage transformation equations” where time periods (t) are “stages” and storage levels in each reservoir ($S_{i,t}$) are “states.” Thus, the releases from a reservoir ($Q_{i,t}, R_{i,t}$) appear as the basic decision variables. However, it must be noted that the spilled water release $R_{i,t}$ will only take place when the storage and turbine release capacity constraints of the reservoir are violated, otherwise it will be zero. Thus, $R_{i,t}$ is a dependent variable and the real decision variable is $Q_{i,t}$.

The DPSA technique has an advantage over other types of dynamic programming in terms of reduced calculated time and computer memory requirements. There are three variables in DPSA: state, decision and stage variables. The group of their values related to some constrains is called system politic. The criterion which determines the effect of this system politic is also expressed as an objective function.

Optimization by DPSA was programmed using MATLAB (Mathematic laboratory, the language of technical computing). This program has one main program and four sub-programs as shown in Figure 3.

In general, the objective function describes the benefit functions that depend upon the water stored in each reservoir and the releases from the reservoir. These functions are usually non-linear relations and the solution by optimization becomes complicated when more than one expected benefit of storage or release is taken into account at a given time. The optimization is done using a dynamic programming with successive approximations (DPSA) technique, which divides the problem with multi-decision variables into sub-problems with one decision variable, and then solve the problem while taking decision variables one by one. A schematic view of the state-decision-stage variables in DPSA of a reservoir is shown in Figure 2.

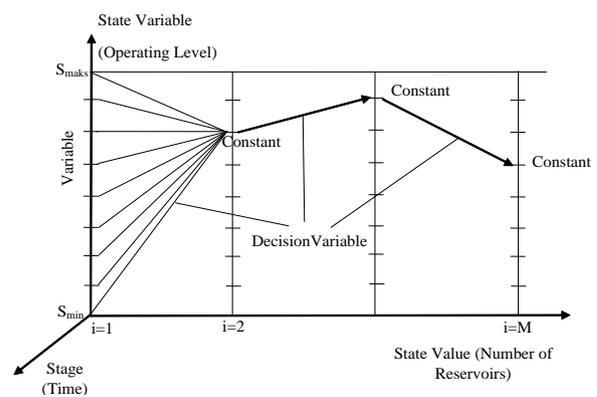


Figure 2. Schematic representation of state value and state-decision variable at any stage in dynamic programming

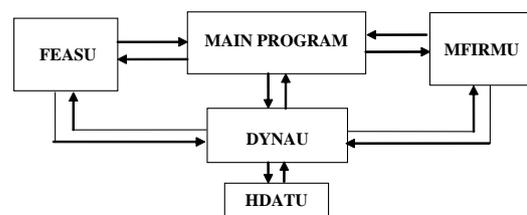


Figure 3. View of the relations between the main program and the sub-programs

In the main program, first, the beginning policy of optimization process is designated. This beginning policy is important to reach the optimal solution and reduce the computer operational time. Second, in subprograms, the optimization process with this politic is started and meanwhile, as the operational level in the current reservoir is

taken as variable successively, the objective function of the system is implemented to realize by using values of the beginning policy in the operational levels of the others and these solutions obtained are kept in the memory of the model. Third, the values of the system parameters generated from these solutions are continuously controlled by taking into consideration the system constraints at each stage of the optimization process. Finally, the operational process to integrate these solutions is started and the optimal solution is reached. In this optimization process, using the beginning policy, the optimal solution can be reached. Solutions should be sought using other beginning policies. These sub-programs are DYANU, FEASU, MFIRMU and HDATU as explained below:

DYANU is a sub-program which evaluates the values of state and decision variables in the objective function one by one for each stage variable. FEASU is a sub-program which decides whether double of the state-decision variables is possible or not for each stage variable. MFIRMU is a sub-program which helps select an optimal solution among optimal solutions for each stage-state-decision variable. HDATU is a sub-program which is used to calculate the reservoir operation level with the selected volume for each stage-state-decision variable” [1].

4. APPLICATION

Data: The Yeşilirmak River Basin, Turkey, as shown in Figure 4, was selected as a study area.

There are seven successive and nonsuccessive reservoirs situated on the Yeşilirmak River (at the central of the Black Sea) for energy production. The basic characteristics of seven reservoirs in the system are shown in Table 1 [DSI]. The variation of reservoir storage volume with height over turbines is given in Table 2. When these data are illustrated, it is shown that Hasan Uğurlu and Kılıçkaya Reservoirs have large storage, Hasan Uğurlu Reservoir have large installed power and Ataköy Reservoir have small storage and installed power. Values of the energy production of the system (such as average and total energies) by using these data and Equations 8 and 9 given for reservoirs are determined. In the model, inflows into the reservoirs are taken from one reservoir to the other reservoir.

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Figure 4. Schematic view of Yeşilirmak Basin

Table 1. Basic characteristics of reservoirs in the system.

Reservoirs	Gölova	Kılıçkaya	Çamlıgöze	Almus	Ataköy	Hasan U.	Suat U.
Drainage Area (km ²)	727	8251	8251	2353	2353	35900	36100
Objective	Irr.+En.	En.+Flood	Energy	Irr., Flood+En.	Energy	Energy	En.+Irr.
Installed Power (MW) (Upper limits)	19	124	33	27	5,5	500	69
Dam Height (m)	26	134	37,5	95	26	175	51
Maximum operational level (m)	1294	850	751,5	804,5	736,9	190	61,5
Minimum operational level (m)	1280	821	745	767,37	733,5	150	58,5
Maximum Volume (10 ⁶ m ³)	70,28	1400	60,15	950	1,93	1018,37	182,5
Minimum Volume (10 ⁶ m ³)	12,6	367	30,02	151,54	0,82	382,3	154,4
HPP Elevation (m)	1274,7	750	723,3	731,6	715	61,5	28
Spillway Capacity (m ³ /sn)	70	3000	3000	2243		11000	11000
Energy Production Capacity (m ³ /sn)	105,6	133,1	125,6	39,7	26,9	417,5	221,0
Monthly Maximum Inflow (m ³ /sn)	15,51	290,52	329,17	110,61	114,47	831,02	835,66
Monthly Minimum Inflow (m ³ /sn)	1,83	1,89	5,75	0,04	3,90	51,23	51,50
Monthly Mean Inflow (m ³ /sn)	5,88	51,96	55,81	17,99	21,85	191,59	192,48

Table 2. Volume-height relationships for reservoirs ($h=a.S^2+b.S+c$, $h(m)$, $S (10^6 m^3)$)

Reservoirs	a	b	c	R ²
Gölova	-0.0021	0.4375	1.9776	0.9849
Kılıçkaya	-0.0001	0.131	22.478	0.9004
Çamlığöze	-0.0011	0.4066	2.46	0.9856
Almus	-0.0001	0.1356	6.9936	0.971
Hasan U.	-0.0001	0.2034	19.61	0.9592
Suat U.	-0.0006	0.2855	4.2783	0.9812

Monthly mean flows into the reservoirs from sub-drainage areas are shown in Figure 5 and monthly inflows into reservoirs during the drought period from sub-drainage areas (2001) are shown in Figure 6. This system is set up on the optimal operation model for the long term planning. The technique of the dynamic programming is used for this model.

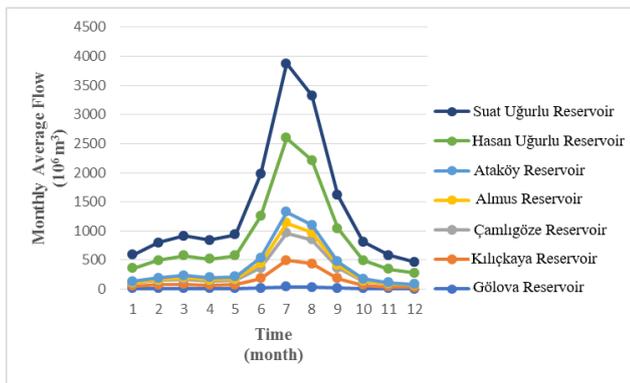


Figure 5. Monthly average flows from the basin to the reservoirs

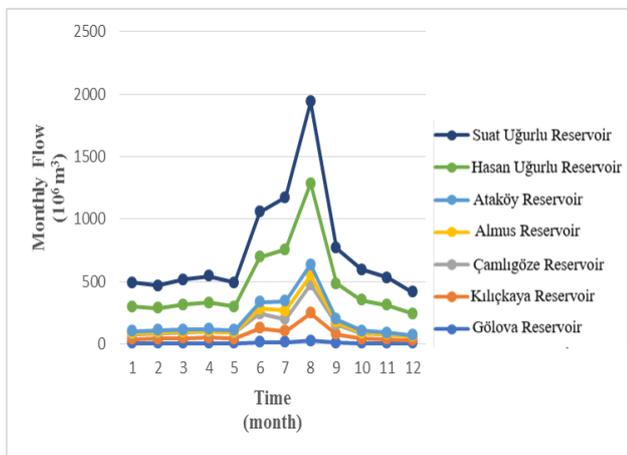


Figure 6. Monthly flows from the basin to the reservoirs in the critical period

Scenarios: In this study, the model is applied to a water resources system with multi-objective and multiple reservoirs presented successively on the

main and secondary line of its river in the Yeşilirmak River Basin. It is considered to three scenarios on this system as shown Figure 7:

Scenario 1: Operation of reservoirs with 2 and 3 lines together and then re-operation of reservoirs by adding 1 line.

Scenario 2: Operation of reservoirs with 1 and 2 lines together and then re-operation of reservoirs by adding 3 line.

Scenario 3: Operation of reservoirs with 1 and 3 lines together and then re-operation of reservoirs by adding 2 line.

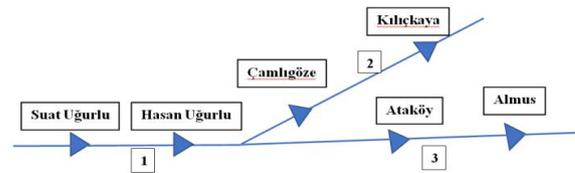


Figure 7. Reservoirs on the main and secondary lines of the model

The flows are $10^7 m^3$ and $10^6 m^3$, the time dimension is month. The operational curve (minimum operational levels) of the system using drought period flows will be determined to maximize the firm power. The normal operational levels of the system will be determined by maximizing the total energy generated using average flows (at the same time providing the maximization firm power). Thus, firm energy and total energy optimizations are made for the system and operating policies are determined

5. RESULTS AND ANALYSIS

In the optimization model, first the beginning policy of optimization is designated by using monthly inflows of the dry period and monthly mean inflows. The optimization process with this policy is started for each scenario. Through optimization, the maximized firm power of the system and monthly minimum operational levels

of the reservoirs are obtained. Then, by using the maximized firm power in the model and using the monthly mean inflows, the total energy of the system is maximized. In this manner, the maximized total energy of system and the normal operational levels of the reservoirs are obtained.

The energy optimization results were obtained in two steps for each scenario. First, the primary objective was the maximization of the firm power (with the critical period monthly flows shown in Figure 8). The firm power in the first and second scenarios were obtained as 114,600 MW and the third scenario's firm power was also 119,140 MW. Second, the primary objective value was used to maximize the total energy by using the average monthly flows, and the average total energy for the system was thus determined. The average total power in the first, second and third scenarios were 412,810 MW, 419,730 MW and 411,230 MW respectively. The power values in each scenario were compared and maximum firm power and maximum average total power were selected. We applied the DSI empiric equation to a water resources system with multi-reservoirs in the Yeşilirmak River Basin of Turkey. From the empiric equation, the firm power and the average total power were determined as 119,720 MW and 317,26 MW respectively. As a result, the model produced approximate value firm power and 32% greater average total energy than did the empiric equation.

Monthly minimum and normal operational levels obtained from model are shown in Figures 8 and 9, respectively. When monthly minimum operational levels were considered, it was observed that levels in the Hasan Uğurlu Reservoir changed from $1018,37 \times 10^6 \text{ m}^3$ to $382,30 \times 10^6 \text{ m}^3$ and levels in the Kılıçkaya increased from $1400 \times 10^6 \text{ m}^3$ to $367 \times 10^6 \text{ m}^3$. As a result, it was clearly seen that Hasan Uğurlu reservoir was controlled and managed using optimization with the incorporation of large variations in the operational levels. In addition, Hasan Uğurlu reservoir was planned only for energy production, but Kılıçkaya reservoir was planned for energy production and flood control.

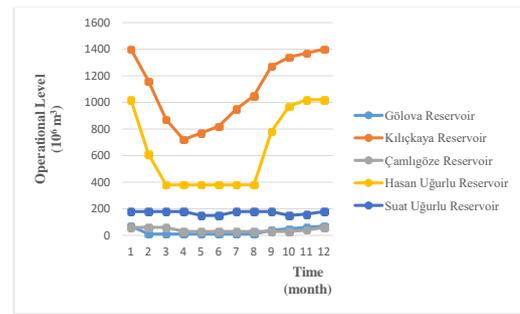


Figure 8. Monthly minimum operational levels at reservoirs

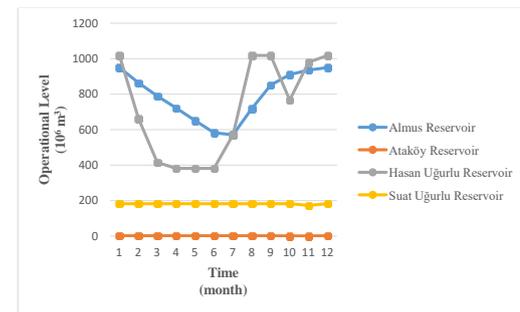


Figure 9. Monthly normal operational levels at reservoirs

6. CONCLUSIONS

Optimization model of the method of the dynamic programming with successive approximations is developed for long term planning and management and more particularly for maximizing the energy production from a multi-reservoir system. The model is performed to a reservoir system in the Yeşilirmak basin, Turkey. Results of energy production and power generation are compared with the results of the empiric equations. It is found that the proposed model yield 32 % greater average total energy than does the empiric equations. It is shown that reservoirs with large storage control and manage the optimization process.

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