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Hydropower Optimization for the Lower Seyhan System in Turkey using Dynamic Programming

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***Abstract**: Dynamic programming with successive approximation has been used in the past for optimizing multi-reservoir water resources systems. In this study, the State Incremental Dynamic Programming (SIDP) model is developed for energy optimization of multi-reservoir systems. A random file access method is used for reaching initial and intermediate data to cope with the curse of dimensionality of dynamic programming. A conventional dynamic programming method is used for each single reservoir to find the initial trajectory of the reservoirs. Then, the computer program developed in the study is applied to the multipurpose-multi-reservoir system in Lower Seyhan Basin, which has six reservoirs, some of which are serial and some parallel. First, extended historical flows were used to maximize firm energy in the critical period, and then total energy in the total flows. The program was run with 50-year long segments (20 flow scenarios) of the synthetic flow data generated by using the HEC-4 generalized computer program to take into account the stochastic nature of stream flows. An increment of approximately 20 percent in total energy was obtained by using the model for the Lower Seyhan System, as compared to that calculated previously by conventional methods..*

***Keywords**: reservoir optimization, reservoir operation, dynamic programming, water resources management, multi-reservoir optimization*

Introduction

A multi-reservoir system can have many objectives, decision variables, constraints, and risks associated with its operation. Commonly encountered benefits (objectives) include hydropower generation, water supply for domestic, industrial, or irrigation purposes, flood control, recreation, water quality, or other environmental uses. Considerable research effort has been directed at the development of techniques that are able to identify the optimum operating policies for reservoir systems. These include both simulation and optimization methods (Wurbs et al., 1985; Yeh, 1982).

Dynamic Programming (DP) is a mathematical technique for optimizing sequences of interrelated decisions, such as the release policy for a multipurpose reservoir. It was first introduced by Bellman (1957) and has since been modified and used for tackling various water resources management and reservoir operation problems (Larson, 1968; Heidari et al., 1971; Chow et al., 1975; Pradit and Askew, 1976; Turgeon, 1982; Bayazit and Duranyildiz, 1987; 1988). A comprehensive review of dynamic programming and its impact on water resources management are given by Yakowitz (1982), Stedinger, et al. (1984), and Yeh (1985). The main feature of the DP algorithm is that complete enumeration of solutions is avoided by decomposing a complex single problem into a series of much simpler problems (stages) that can be easily solved. At the start of each stage, the system can be in a number of states. A decision is required to indicate the state to transfer to the next stage. There is a cost or benefit associated with the transfer. The problem is usually solved by finding the optimum solution for the last stage first. Then, given the solution to that stage, the next-to-last stage is solved, and the process is repeated until the initial stage is reached. The principle of optimality (Bellman, 1957) ensures that this produces the overall optimum. The main problem associated with applying DP to a multi-reservoir system is to determine how to cope with the so-called "curse of dimensionality." Multi-reservoir system models, like many other models of the real world, tend to be very large, and therefore are computationally demanding and prohibitive. State Incremental Dynamic Programming (SIDP), introduced by Larson (1968), and Discrete Differential Dynamic Programming (DDDP), introduced by Heidari et al. (1971) were developed as a result of efforts to minimize and manage the dimensionality problem of the traditional DP.

Labadie (2004) assessed the state-of-the-art in reservoir system optimization models and considered future directions. According to Labadie's (2004) review, the keys to success in implementation of reservoir system optimization models were: 1) improving the levels of trust by more interactive involvement of decision makers in system development; 2) better ''packaging'' of these systems; and 3) improved linkage with simulation models which operators more readily accept. Labadie (2004) concluded that for the latter, increased application of heuristic programming methods was particularly important, which many system analysts had been slow to adopt because they lacked a strong scientific or theoretical foundation. The ability of genetic algorithms to be linked directly with trusted simulation models was a great advantage. In addition, past difficulties in inferring operating policies from implicit stochastic optimization models might be alleviated through applications of fuzzy rule-based systems and neural networks. The computational challenges of explicit stochastic optimization might also be overcome through judicious application of these heuristic techniques.

The purpose of the research presented in this paper has been to investigate the application of SIDP for multipurpose multi-reservoir hydropower system optimization and to optimize the hydropower of the Lower Seyhan System. When a system has more than two reservoirs, most DP methods have huge computer memory requirements. Some new approaches have been implemented to cope with the curse of dimensionality of DP in this study. A random file access method is used for reaching initial and intermediate data to cope with the curse of dimensionality of dynamic programming. Conventional dynamic programming method is used for each single reservoir to find the initial trajectory of the reservoirs.

A paper was published in Turkish from this study with the preliminary results from the old data and previous planning phase (Yurtal, 1993; 1995). Since then, some important changes have occurred in the structure and purpose of the Lower Seyhan Basin. A diversion weir was cancelled and municipality demand was added to the system. This study was conducted with the new planning phase.

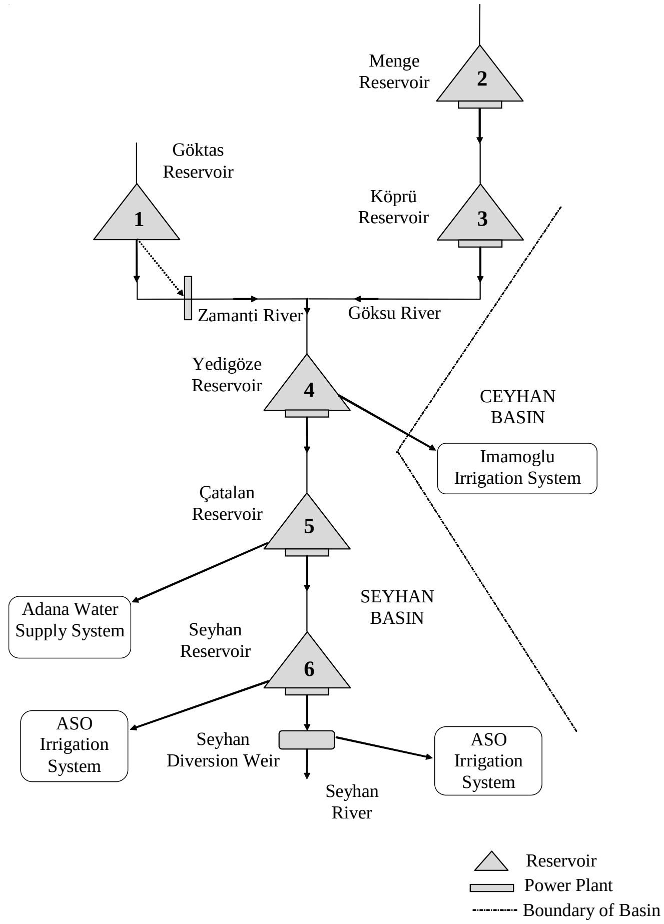

Figure 1. Lower Seyhan Basin Multipurpose Multireservoir System

Case Study

The catchment area of the Lower Seyhan Basin, which covers about 16,000 km² (the Seyhan River drains an area of 20,731 km²), is located in the southern part of Turkey, in the Eastern Mediterranean region. The multiple reservoir system consists of six (existing and planned) reservoirs shown in the schematic layout of the system in Figure 1. Details of the physical characteristics, including storage capacities, hydraulic structure characteristics, etc., of each reservoir of the Lower Seyhan River are given in Table 1. The data in Table 1 were collected and updated according

Table 1. Existing or planned reservoirs on the Seyhan River according to the Master Plan

	Goktas	*Menge*	*Kopru*	*Yedigoze*	*Catalan*	*Seyhan*
Dead Storage (10^6 m³)	84.5	61.99	54	207	550	276
Active Storage (10^6 m³)	24.7	242.10	206	448	1105	428
Flood Control Storage (10^6 m³)	-	-	-	-	471	220
Total Storage (10^6 m³)	109.3	304.09	260	655	2126	924
Spillway Capacity (m³/s)	4,078	4,965	5,305	9,193	10,055	3060
Irrigation Area (ha)	-	-	-	56400	-	186,000
Firm Energy (10^6 kWh)	660.1	125.35	248.6	413.8	271.4	108.9
Total Energy (10^6 kWh)	1,272.2	270.35	480.9	950.5	508.8	268.5

Table 2. Stream flow gauging stations used in the study (EIEI, 1952-91)

Station No.	*Station*	*Stream*	*Observed Years*	*Observed Duration (Year)*	*Annual Mean Flow (10^{-6} m^3)*	*Drainage Area (km^2)*
1801	Himmetli	Göksu	1936 - 1991	56	960.2	2,596.8
1805	Gökdere	Göksu	1939 - 1991	52	1,908.9	4,242.8
1806	Ergenusagi	Zamanti	1939 - 1979	41	2,177.8	8,698.0
1817	Arapali	Çakit	1964 - 1988	25	463.3	1,582.4
1818	Üçtepe	Seyhan	1961 - 1991	31	4,578.0	13,846.0
1820	Hacili	Körkün	1968 - 1991	22	449.8	1,441.0
1823	Emegil	Zamanti	1955 - 1988	34	358.2	2,756.0

to the publications of the State Hydraulic Works (DSI) in Turkey (Verbundplan-Romconsult-Temelsu, 1980; 1984; DSI, 1988; JICA, 1989).

Seyhan and Catalan are the largest reservoirs under operation within the system. Seyhan reservoir has been in operation since 1956 and Catalan reservoir since 1997. Yedigoze is presently being constructed while the other three reservoirs are waiting to be contracted. The system is operated to satisfy many objectives, including providing the water supply for municipal, industrial and agricultural uses, hydropower generation, and flood control (Verbundplan-Romconsult-Temelsu, 1980; 1984). The three planned reservoirs have mainly an energy-generation purpose. Each of the reservoirs, except Goktas, has a hydroelectric power plant next to the dam. The Goktas power plant will be constructed 16 km downstream from the reservoir (JICA, 1989).

Inflow Data

Historical monthly flows from 1936 through 1991 were used in this study. These flows were obtained for the six reservoirs by transferring from selected streamflow gauging stations in the basin using their catchment area ratios. These gauging stations were selected based on their proximity to the reservoirs, the length of record and the accuracy of recorded flows (Table 2). As shown in Table 2, gauging station No. 1801 has the longest flow record (56 years). The streamflow length of each gauging station was extended to 56 years using the HEC-4 streamflow generation and reconstruction program, which was developed by the U.S. Corps of Engineers (U.S. Army Corps of Engineers, 1971).

HEC-4, Monthly Streamflow Simulation, is one of the generalized computer programs developed by the Hydrologic Engineering Center of The U.S.Army Corps of Engineers (HEC, 1971). This program analyzes recorded monthly streamflows at a number of interrelated gauging stations, preferably in the same basin, and it computes generated synthetic data again in monthly values for any desired length. The program initially reconstitutes missing data of the short-record stations based on multiple regressions among stations using the recorded data of those longer-record stations. The multiple regression uses the current and preceding monthly flows of the other stations in the group and the preceding monthly flow of the station itself as independent variables.

Taking the recorded monthly flow data at the gauging stations in Seyhan Basin in Table 2, and using them as input to HEC-4, 1,000-year long synthetic monthly flow series with 50-year-long segments were generated. The historical monthly flow series and simulated series were compared in Figure 2 and Figure 3 for the first and second 50-year-long segments of generated series, and in Figure 4 for all segments. Transferring the monthly flow data to the axes of each of the six dams with the help of the formu-

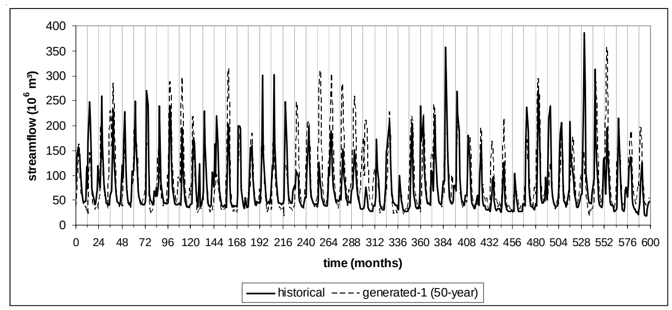

Figure 2. Historical and generated (first 50-year of 1000-year) monthly streamflows using HEC-4

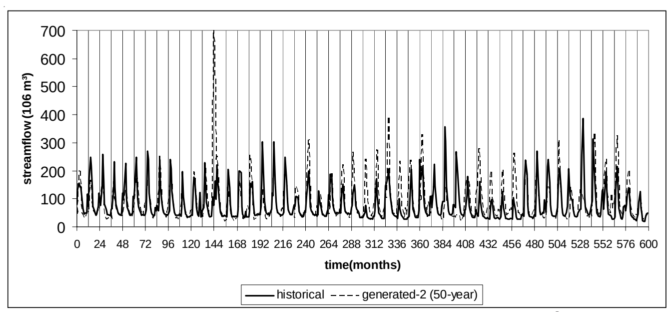

Figure 3. Historical and generated (second 50-year of 1000-year) monthly streamflows using HEC-4

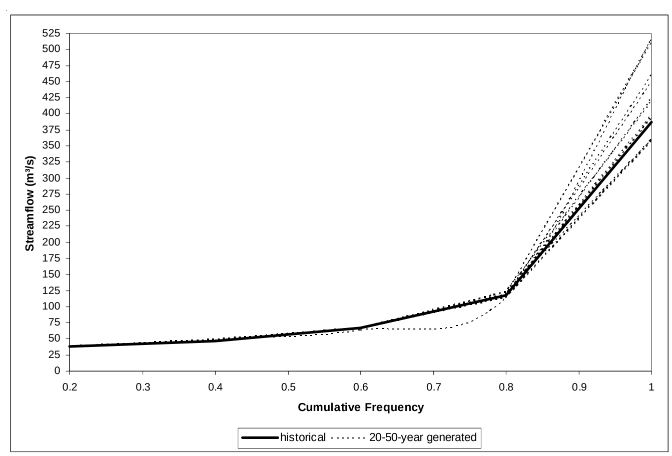

Figure 4. Historical and generated 20 non-overlapping 50-year monthly flow segments using HEC-4

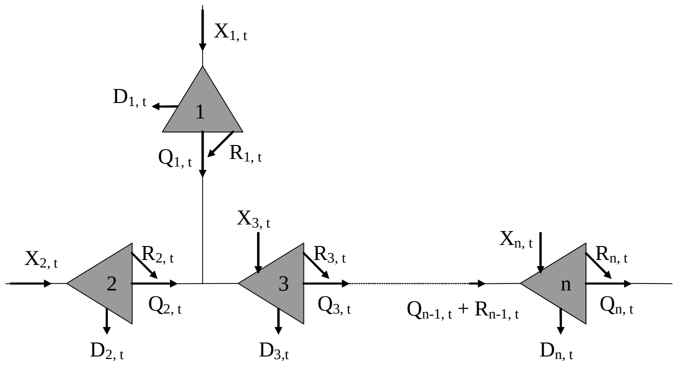

Figure 5. Schematic diagram of a multi-reservoir system

lae suggested by Yurtal (1993), twenty non-overlapping 50-year monthly flow segments were obtained for each sub-basin of the six dams in basin. Twenty flow scenarios with 50-year-long segments of the synthetic flow data have been used with the program developed for SIDP to take into account the stochastic nature of the streamflow.

Storage-Elevation and Storage-Area Relationships for Reservoirs

In order to incorporate evaporation loss from the reservoir surface and to compute the head for hydropower generation, regression equations were obtained using the Storage-Elevation and Storage-Area curves.

Evaporation

There are many stations measuring daily evaporation in the basin through type A Pans. The most suitable ones for this study were chosen according to their elevation, observation duration, and distance from the reservoirs. Monthly recorded pan evaporation values were converted to the evaporation values from the reservoir surface by multiplying the original values by a pan coefficient (0.70) according to the standards of the State Hydraulics Works (DSI) in Turkey. DSI uses the same pan coefficient (0.70) for monthly evaporation values from the lake.

Irrigation and Domestic Water Demands

Seyhan reservoir supplies irrigation water to the fields in the Lower Seyhan plain (ASO Irrigation system). However, these demands are separated into two categories, direct and indirect, since some water is taken directly from the reservoir while the rest of the total irrigation demand is supplied from the weir downstream of the dam. Yedigoze reservoir will supply water for irrigation to the fields in the Kozan-Kirmit plain (Imamoglu Irrigation system). Catalan reservoir will supply domestic water to Adana City. Irrigation and domestic water demand values were obtained from the State Hydraulic Works (DSI). The demands to be released for irrigation and domestic waters from Seyhan and Catalan reservoirs are taken as the mean monthly values of the last six years. A minimum flow of 10 percent of the yearly average inflows is taken as a fixed low-flow augmentation requirement for environmental purposes.

Modeling a Multi-Reservoir System

Multi-reservoir System Model for SIDP

The configuration of a multi-reservoir system can be defined as shown in Figure 5. The continuity equation of the system represents one of the main system constraints and may be given as

$$S_{i,t+1} = S_{i,t} + X_{i,t} + \sum_{j=0}^{j=k_i} Q_{j,t} + \sum_{j=0}^{j=k_i} R_{j,t} - Q_{i,t} - D_{i,t} - R_{i,t} - Ev_{i,t} \qquad \begin{cases} i = 1,2,...,n \\ t = 1,2,...,m \end{cases} \qquad (1)$$

where $S_{i,t}$ is storage in reservoir *i* at the beginning of time period *t*; $X_{i,t}$ is the local (or total for the most upstream reservoir) inflow in reservoir *i* in time period *t*; $D_{i,t}$ is the direct demand at reservoir *i* in time period *t*; $R_{i,t}$ is spilled water from reservoir *i* in time period *t*; $Ev_{i,t}$ is evaporation from reservoir *i* in time period *t*; *k* is the number of reservoirs upstream of a particular reservoir (if k_i equals 0, then there is no upstream reservoir and this reservoir is the most upstream on a river or a tributary); *n* is the number of reservoirs in a system; and *m* is the total time period.

The following expression is obtained if Equation 1 is rearranged to give *Q* from reservoir *i* in time period *t*

$$Q_{i,t} = S_{i,t} - S_{i,t+1} + X_{i,t} + \sum_{j=0}^{j=k_i} Q_{j,t} + \sum_{j=0}^{j=k_i} R_{j,t} - D_{i,t} - R_{i,t} - Ev_{i,t} \qquad (2)$$

Evaporation ($Ev_{i,t}$) is calculated as

$$Ev_{i,t} = A_{i,t} \times Ep_{i,t} \qquad (3)$$

$$A_{i,t} = a \times (S_m)^b \qquad (4a)$$

$$A_{i,t} = a + b \times S_m + c \times (S_m)^2 + d \times (S_m)^3 \qquad (4b)$$

$$S_m = \frac{S_{i,t} + S_{i,t+1}}{2} \qquad (5)$$

where $Ep_{i,t}$ is the corrected pan-evaporation values of reservoir i in the time period *t*; $A_{i,t}$ is the average surface area of reservoir *i* in the time period *t*, which is determined from Equations 4a or 4b; coefficients *a*, *b*, *c*, and *d* are the exponential or polynomial fit coefficients; and S_m is average reservoir storage during time period *t*.

If $S_{i,t}$ and $S_{i,t+1}$ are equal to the $S_{i,max}$, maximum storage of reservoir *i*, and $Q_{i,t}$ is greater than the maximum capacity of power tunnel(s), then $R_{i,t}$ is calculated from Equation 6 and must be less than the maximum spillway capacity of reservoir *i*, $R_{i,max}$

$$R_{i,t} = Q_{i,t} - Q_{i,\max} \qquad (6)$$

After the discharge from the power tunnel(s) is determined, power and energy generation is calculated according to Equations 7 and 8

$$P_{i,t} = \eta \times g \times Q_{i,t} \times h_{i,t} \quad (7)$$

$$E_{i,t} = P_{i,t} \times T \quad (8)$$

where g is the gravity acceleration (9.81m/s^2); η is the overall hydropower plant efficiency, $h_{i,t}$ is the net head of reservoir i in time period t; T is time in hours; $P_{i,t}$ and $E_{i,t}$ are power and energy generated from reservoir i in time period t (kW and kWh).

The net head, $h_{i,t}$, for reservoir i in time period t is given as

$$h_{i,t} = hg_{i,t} - hl_{i,t} \quad (9)$$

where $hg_{i,t}$ is the gross head; and $hl_{i,t}$ is the total head loss for reservoir i at time t. Manning's equation is used for head loss calculations because of the standard of DSI (State Hydraulic Works of Turkey), which is the foundation having authority for development of water resources of Turkey. If D is the diameter of a power tunnel, and Manning's roughness coefficient is assumed as n= 0.014, the following expression for the total head loss is derived

$$hl_{i,t} = \frac{0.00202 \times (Q_{i,t})^2}{D^{16/3}} + hm \quad (10)$$

where hm is the minor loss, which is assumed constant (hm=2 m) in this study.

The gross head of reservoir i in time period t is given as

$$hg_{i,t} = El_{i,t} - Tw_i \quad (11)$$

where $El_{i,t} = a \times (S_m)^b$ or (12a)

$$El_{i,t} = a + b \times S_m + c \times (S_m)^2 + d \times (S_m)^3 \quad (12b)$$

where $El_{i,t}$ is the water elevation in reservoir i at the beginning of time period t; Tw_i is the tail water elevation of reservoir i; hm is a minor loss, which is assumed constant in this study (2 m); and a, b, c, and d are the exponential or polynomial fit coefficients.

Objective Function

Two objective functions are defined for the firm and the total energy maximization

$$E_F = Max\left(\min_{t=1,2,\dots,m} \sum_{i=1}^{n} E_{i,t} \right) \quad (13)$$

$$E_T = Max \sum_{t=1}^{m} \sum_{i=1}^{n} E_{i,t} \quad ; \quad \left(\sum_{i=1}^{n} E_{i,t} \geq E_F \quad , \quad t = 1,\dots,m \right) \quad (14)$$

where E_F and E_T are firm and total energy of the system; and $E_{i,t}$ is energy for t^{th} time period of i^{th} reservoir.

Constraints

For maximization of firm energy, the following constraints must be satisfied.

Storage constraint:

$$S_{\min_i} \leq S_{i,t} \leq S_{\max_i} \quad (15)$$

where $S_{\min_i}$ is the minimum storage of reservoir i, and $S_{\max_i}$ is the maximum storage of reservoir i.

Power tunnel constraint:

$$Q_{i,t} \leq Q_{\max_i} \quad (16)$$

where $Q_{\max_i}$ is the maximum capacity of the power tunnels.

Spillway constraint:

$$R_{i,t} \leq R_{\max_i} \quad (17)$$

where $R_{\max_i}$ is the maximum spillway capacity of reservoir i. In the program implementation, $R_{\max_i}$ if is set to zero, then this constraint will be ignored.

Channel constraint:

$$W_{\min_i} \leq Q_{i,t} + R_{i,t} \leq W_{\max_i} \quad (18)$$

where $W_{\min_i}$ and $W_{\max_i}$ are the minimum and maximum capacity of downstream river reach.

Firm energy constraint:

$$E_{i,t} \geq E_{F_i} \quad (19)$$

where E_{F_i} is the firm energy maximized in the previous DP stage for reservoir i.

Computer Algorithm of SIDP Model

The SIDP model developed for the Lower Seyhan Project (Yurtal, 1993; 1995) is used for hydropower system optimization (Figure 6). The program uses random access files as the record number of the reservoir number, which is updated at each iteration of the successive approximation algorithm, to cope with the dimensionality problem. The program consists of six modules as shown in Figure 6. The *MainProg* module reads in the reservoir index number, inflows to the reservoirs, evaporation data, regression coefficients for storage-elevation and storage-surface area curves, and other physical characteristics such as spillway capacity, power tunnel capacity, flood control storage, dead storage, total storage, etc. Then the

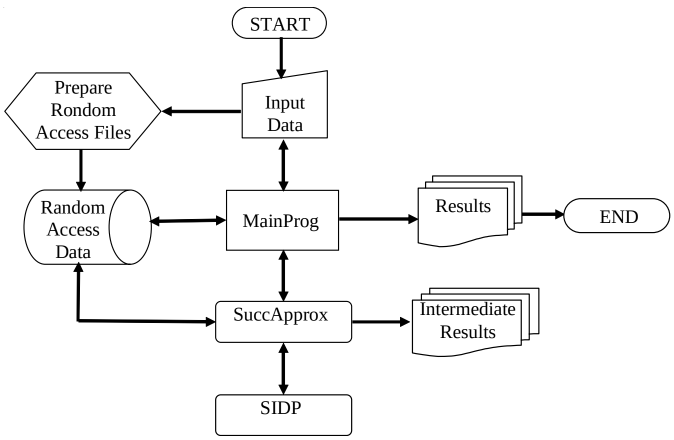

Figure 6. SIDP model for hydroelectric optimization of multi-reservoir systems

module creates the necessary random access files in terms of the reservoir index number. These indexed files are used by the *SuccApr* module that updates the files with new policies and releases that are obtained throughout the iterative process. The IDP module is an Incremental Dynamic Programming subroutine introduced by previous research (Larson, 1968; Turgeon, 1982; Bayazit and Duranyildiz, 1987; 1988). This module prints the intermediate results if needed. An initial trajectory is very important for the IDP method both to obtain the results in fewer iterations and to cope with the divergence problem. In this study, General Dynamic Programming method is used for single reservoir operation with the possible minimum state numbers (10 to 15) obtained with the trial and error approaches to find the initial trajectory of each reservoir. The procedure is repeated by starting with the first (most upstream) reservoir until it converges with the same total energy value in the last iteration. The IDP model starts the iterative process from the most upstream reservoir and carries on towards the most downstream reservoir. While it searches for the optimum policy for a reservoir, the initial policies of other reservoirs are considered constant. After finding the optimum trajectory, it creates the indexed data files that are then used in the following iterations, and repeats the procedure for the next indexed reservoir (downstream). When the computations for the last reservoir is completed, the procedure is repeated by starting from the first (most upstream) reservoir until it converges with the same total energy value in the last iteration.

Results

The approach used in this study has been employed to maximize the firm and total energy of the Lower Seyhan project by using SIDP. The critical period was used for maximizing the firm energy, and the total period was used for maximizing the total energy. All the analysis was performed using monthly flows, which is common practice. After maximizing the firm energy of the system, these firm energy values were used as a constraint for the second step in maximizing total energy.

First, the SIDP program was applied to the multi-reservoir system using the Master Plan data to compare the results of the SIDP model and the conventional methods. Then, the SIDP program was applied using updated and extended historical flows and 20 generated flow segments of 50-year-long for the new planning phase and data. The results obtained are shown in Table 3. The values in the first row of the table were taken from the Master Plan of Lower Seyhan Basin (DSI,1988; JICA, 1989; Verbundplan-Romconsult-Temelsu, 1980; 1984). The values in the second row of Table 3 were found with the SIDP model using the actual Master Plan Report data to compare with the conventional methods. The third row values were obtained using the SIDP model with the updated and extended historical streamflow data and the purposes and dimensions of the new planning phase. In the last row, values were obtained using the new planning phase dimensions and purposes as the mean value of the results of the twenty 50-year generated streamflow segments. A sampling distribution was then applied to the firm and the total energy values obtained in the second step for a confidence level of 95 percent. The confidence intervals of the mean value of firm energy and total energy obtained with generated streamflow data were calculated with statistical methods (Table 4).

As can be seen from the first two rows of Table 3, the SIDP model provided us an increase of approximately 19 percent in firm energy and 20 percent in total energy. The results have emphasized the importance of the operation method and the system approach. When the report results in Table 3 are compared with the mean values of the generated streamflow data results from Table 4, it can be seen that the lower limit of the confidence interval of the firm and total energy values are about 25 percent and 21

Table 3. Firm and total energy generation values for the system obtained by using SIDP (GWh)

	Firm Energy (GWh)	*Total Energy (GWh)*
Report results	1,589.5	3,563.7
SIDP results with Report data	1,885.5	4,282.1
SIDP results with Historical Monthly Flows	1,962.4	4,343.2
SIDP results with Generated Monthly Flows	1,985.0	4,322.5

Table 4. Confidence intervals of means of energy values for generated flows with a confidence level of 95%

	Firm Energy (GWh)	*Total Energy (GWh)*
Sample size	20	20
Mean	1,985	4,323
Variance	21,638	80
Standard deviation	141	9
Median	1,972	4,325
Degrees of freedom	19	19
Confidence level	95%	95%
Confidence interval	1,919-2,051	4,318-4,327

percent greater than the results of the traditional method, respectively. Additionally, with the new planning phase the firm energy and the total energy values will increase.

Discussion and Conclusions

A State Incremental Dynamic Programming (SIDP) model was developed for energy optimization of multi-reservoir systems. A random access method was used for reaching initial and intermediate data, and Conventional Dynamic Programming method was used for each single reservoir to find the initial trajectory of the reservoirs to cope with the curse of dimensionality of Dynamic Programming. The computer program developed in the study is applied to the multipurpose-multi-reservoir system in Lower Seyhan Basin. First, extended historical flows are used to maximize firm energy in the critical period and then total energy over the entire period of flow records. The program is run with 50-year long segments (20 flow scenarios) of the synthetic flow data generated by using the HEC-4 generalized computer program to take into account the stochastic nature of streamflows.

The increase of the firm energy of 24 percent and of the total energy of 21 percent has shown the importance of the system approach and the mathematical programming technique in multi-reservoir optimization in a basin. The increase of the firm energy of the Lower Seyhan Reservoir System is about 296 GWh with the report data compared with the original report results, according to Table 3. This value is greater than the firm energies of the Seyhan, Catalan, Kopru, and Menge reservoirs, although there is no new reservoir or no change in capacity of the existing reservoirs in the system. This result is obtained from the system approach and using dynamic programming technique.

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