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CIVIL ENGINEERING

A Computer Simulation Tool for Single-purpose Reservoir Operators

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Abstract. Variety of optimization techniques have been applied to solve various operational settings of reservoirs systems However, these complex procedures might not be easily adopted by the unsophisticated dam operators, which is the norm in most of the developing countries. This paper suggests a simple procedure designed to help dam operators develop and examine the operating rules necessary for the optimal operation of single use reservoirs which are quite popular in arid regions such as Saudi Arabia. The procedure involves first determining an optimal operating policy by stochastic dynamic programming (SDP), then examining the generated policy by a simulation model. Finally, once the operating rules are accepted, the model can be used as a computer-aided tool in real-time operation. A case study is also presented to demonstrate the use of the developed model, and to help compare the actual value of the objective function achieved through real time operation and the expected one obtained from SDP. This simulation model can be considered a useful user-friendly tool designed to insure a beneficial utilization of those often neglected reservoir systems in the developing countries.

Introduction

Reservoirs are important elements of water resources systems. Their main beneficial uses such as water supply for municipal, industrial and agricultural use, hydropower production; flood control; recreation; fish and wildlife habitat; and navigation show their significant value.

In Saudi Arabia, dams serving single or multiple purposes have been constructed throughout the country. However, most of the dams have been built with the main objective of storing flood water derived from rainfall and releasing it gradually to recharge the underlying aquifers and to meet the downstream demand as well. This demand includes a typical discharge requirement for irrigation or domestic water supply. Abha and Jizan dams, as examples, were constructed primarily for domestic water supply and controlled surface irrigation respectively.

The way these reservoirs are operated varies widely according to their importance. Accordingly, the majority of the small dams, on contrast of the large ones, are operated in a subjective manner. Gate operators normally release wateras downstream demand dictates. This demand is met as closely as possible through typical gated outlets provided at different levels on the dam body. They are manually regulated by the experienced operators attempting to control the amount released in accordance with the quantity of water in storage.

The proper operation of reservoirs in general is not an easy task, not only because of the high uncertainty of hydrology involved, but also because of the conflicts among its uses. For instance, these conflicts can arise between flood control and conservation purposes or among the conservation purposes themselves. Moreover, they could appear within the same beneficial use such as the temporal water shortage distribution. Thus, the process of reservoir operation should be treated as a multistage dynamic stochastic control problem.

As a solution for these conflicting management and operation problem, many mathematical models have been developed to devise an optimal operating policy. Among these mathematical models, optimization and simulation are perhaps the most popular quantitative tools.

As far as the optimization models are concerned, dynamic programming has been used extensively in reservoir operation. Little [1], Hall *et al.* [2], climinate Collins [3], Marino *et al.* [4] and many others reported various applications of dynamic programming. Stochastic dynamic programming (SDP) as an approach that can provide a solution for the hydrologic uncertainty involved in the operation problem, was used by Butcher [5,6], Dudly and Burt [7], Torabi and Mobasheri [8], Turgeon [9,10], and many others. Interestingly, a comparative study by Karamouz and Houk [11] has proven that SDP generated rules are more effective for the operation of small reservoirs compared to the one generated by other techniques such as deterministic dynamic programming. Coupling SDP with simulation for the sake of post optimality simulation has been reported by many authors. A study by Shim *et al.* [12] presented a generalized decision support system that utilizes a combined optimization-simulation approach for developing optimal operation policies for multipurpose reservoirs. A similar study was also presented by Fontane *et al.* [13] and was applied for the reassessment of Chungju reservoir in Korea. Lund *et al.* [14] presented a study in which implicit stochastic optimization coupled with simulation was used to develop operating rules for the main stem Missouri River reservoir system. The study concluded that simple data display and simulation modeling are found to be very effective for inferring and refining promising operating rules from deterministic dynamic optimization results.

In light of the above, literature has shown variety of studies in which optimization has been applied to solve various operational settings. However, these complex procedures might not be easy to be adopted by the unsophisticated dam operators, which is typical in most of the developing countries.

This paper suggests a simple procedure designed to help dam operators develop and examine the operating curves necessary for the optimal operation of single-purpose (typically small) reservoirs which are quite popular in Saudi Arabia. The procedure involves first determining an optimal operating policy by stochastic dynamic programming (SDP), then examining the generated policy by a simulation model. The examination process involves simulating the interval-by-interval operation of the reservoir based on deterministic inflow sequences for various time intervals, specified system characteristics and the operating rules determined by SDP. Finally, once the operating rules are accepted, the simulation model can be used as a computer-aided tool in real-time operation.

A case study was also presented to demonstrate the use of the developed model, and to analyze and compare the actual value of the objective function achieved through real time operation and the expected one obtained from SDP. This simulation model can be considered a useful user- friendly tool designed to insure a beneficial utilization of those uncared-for reservoir systems in the developing countries.

Model Description

This model is a typical simulation code designed to simulate the interval-by-interval operation of a reservoir with specified inflow for each interval, specified system characteristics and operating rules. It considers a single-purpose water supply reservoir only. Its use is to help the decision maker (operator) develop and examine the consequences of operating a reservoir system under a defined operating policies while trying to satisfy various water needs downstream. The model has been designed to handle two types of problems :

1. The independent inflow problem: In such a case the operating curves are developed using independent occurrence probabilities for the possible inflow levels. As a result, a unique operating curve for each stage will be generated and then adopted in the model.

2 The dependent inflow problem: In this type of problem the operating rules are developed by the use of conditional probabilities of the stream inflow in successive time intervals. In other words, the inflow during any time period is related to the preceding one by a conditional probability. In this case for each stage a group of operating curves depending on the preceding stage's inflow will be used.

In addition, the model is capable of adopting different types of operating policies, which are:

1. Target ending volume rule: This operating rule provides for each stage a prescriptioof the optimum ending storage for each possible discrete beginstorage and each possible previous stage's inflow level, in the case where conditional probability was used.

2. Target release rule: This policy defines the optimum release as a function of the existing storage volume, time of the year and, in case of conditioned probability, the preceding stage stream inflow.

Based on the type of problem to be analyzed and the operating policy to be adopted. the user will be asked to input an operating rule for each stage, a set of inflow sequences, bounds on storage governed by the physical features of the reservoir, demands, evaporation and infiltration rate coefficients, and initial storage volume. Besides that, the user needs to define a stage return equation in the stage return subroutine. The model, will then simulate the operation of the reservoir based on these inputs and display the results. The outputs of this model are presented in terms of optimal reservoir release during each stage (t), optimal ending volume, spillage, stage return, cumulative return and possible failures. Moreover, graphical presentations of the magnitude and time distribution of shortages, the adopted operating curves and the optimal ending storage can be displayed.

Theoretical Basis

This multistage reservoir simulation model is designed to deal with single-use reservoirs built to satisfy downstream water demand based on predetermined operating rules. However, the basic theory that governs reservoir operation in general is the water balance equation. This equation can be summarized in three groups of variables: (1) Inputs, which include stream inflow, catchment-inflow and water diversion. (2) Outputs, including water releases, spillage, evaporation, and seepage losses. (3) Storage which include maximum, minimum and active storage. The water balance equation and the operation policies for water supply are, [15]:

1. Invertible form: $$V(t+1) = V(t) + I(t) - E(t) - R(t) - SP(t) \tag{1}$$

2. Non-invertible form: $$R(t) = V(t) - V(t+1) + I(t) - E(t) - SP(t) \tag{2}$$

Where:

t = Number of stage.
$V(t)$ = Storage volume of the reservoir at beginning of stage (t).
$V(t+1)$ = Storage volume of the reservoir at the end of stage (t).
$I(t)$ = Inflow to the reservoir during stage (t).
$SP(t)$ = Spill from the reservoir during stage(t).
$R(t)$ = Release from the reservoir during stage (t).

While evaporation is computed by:

$$E(t) = \mathrm{Erate}(t)\,(a * V^{b}(t)) \tag{3}$$

Where:

$\mathrm{Erate}(t)$ = The evaporation rate for the stage t in $[m/m^2]$
a, b = Coefficients for converting reservoir volume to surface area.

The operating policies for water supply are:

1. IF $V(t+1)_{(calculated)} > \mathrm{Vmax}$, then

$$V(t+1) = \mathrm{Vmax}, \text{ and} \tag{4}$$

$$\mathrm{Spill}(t) = V(t+1)_{(calculated)} - \mathrm{Vmax}. \tag{5}$$

2. IF $V(t+1)_{(calculated)} < \mathrm{Vmin}$, then

$$V(t+1) = \mathrm{Vmin}, \text{ and} \tag{6}$$

$$R(t) = [V(t) + I(t) - E(t)) - \mathrm{Vmin}] \tag{7}$$

3. IF $R(t)_{(calculated)} < 0$, then

$$V(t+1) = (\, \mathrm{Vmin} - |R(t)| \,) \tag{8}$$

$$R(t) = 0 \quad \text{and} \quad \mathrm{failure}(t) = 1 \tag{9}$$

4. $$\%\ \mathrm{Failure} = \sum \mathrm{failure}(t) * 100 / \text{number of stages} \tag{10}$$

Where failure is defined as number of times the system failed to retain the minimum allowable storage.

On the other hand, the recursive equation, state transformation equation and constraints used to generate the operating policies used in the formulation of the stochastic dynamic program are:

1. Objective Function

   The objective functions employed here measures the deviation of a release from a target demand, so during operation water deficit or over supply will be minimized. The recursive relation is:

$$f_t(V_t) = \underset{V_{t+1}}{\mathrm{Min}} \sum_{k=1}^{K} [r_t(R) + F_{t+1}(V_{t+1})] * P_{tk} \tag{11}$$

2. Stage return functions:

$$r_t(R_t) = O_t \qquad \text{if } R_t > D_t \tag{12}$$

$$r_t(R_t) = S_t \qquad \text{if } R_t < D_t \tag{13}$$

$$O_t = R_t - D_t \tag{14}$$

$$S_t = D_t - R_t \tag{15}$$

3. State transformation equations (invertible):

$$R_t = V_t - V_{t+1} + I_{tk} - E_t - SP_t \tag{16}$$

4. Bounds on storage:

$$V\min < V_t < V\max \tag{17}$$

Where :

t = 1,2,..,12 number of stages.

k = 1,2,3 number of discrete values of possible inflow levels.

I_{tk} = value of stream inflow at stage t and discrete level k.

P_{tk} = independent occurrence probability of I_{tk}.

D_t = value of demand at stage t .

V_t , V_{t+1} and R_t are as defined earlier.

Case Study

To demonstrate the applicability and usefulness of the developed model, an actual water supply reservoir was investigated. The case study involved first developing the reservoir's monthly operating rules and then simulating its actual monthly responses based on those rules.

Site description

The reservoir system chosen for this case study was the Mangla reservoir on the Jhelum river in Pakistan with maximum storage volume of 7192 [MCM] and minimum storage of 500 [MCM]. Although the investigated reservoir is not small, it was considered because of the availability of its data. In addition, the reservoir is assumed to operate primarily as a storage facility for controlling water supply. Fifteen year hydrological records for the investigated reservoir were available on monthly basis. These records were first used in the development of the optimal operating rules and then applied in the real time simulation, see Table 1.

Table 1. Mangla Reservoir inflows (MCM)

	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug
1	2495	692	506	433	875	1250	1781	2448	5276	6061	7158	6032
2	2495	884	457	358	344	822	1761	1328	3092	5009	6029	5269
3	2068	940	442	347	315	506	608	932	2322	4032	5244	4928
4	3153	645	427	325	372	381	607	1048	2524	4716	5191	4898
5	2990	1076	504	574	730	1408	1441	2000	2880	3971	7175	8212
6	4153	992	606	635	1484	732	1519	1724	2086	4595	7502	8366
7	2966	854	526	502	821	540	1270	1905	2152	4679	7967	5933
8	3354	1015	595	451	416	441	615	1751	2383	3538	5939	7772
9	2133	1028	520	568	648	660	837	1365	2840	4642	5531	6388
10	5290	1441	670	619	637	994	1718	2265	3587	3800	9209	10119
11	3735	1390	602	527	572	1682	1671	2125	4046	3923	6507	6132
12	3389	1021	498	423	1278	1632	1486	1808	3709	6264	8975	7613
13	8376	1648	795	618	563	764	962	1209	2624	3584	4802	6130
14	2378	1087	561	437	546	704	1400	1695	2738	5056	6399	6223
15	3183	905	466	390	566	563	861	1649	2743	4696	6400	6290

Development of the operating policy based on SDP approach

The procedure used to derive the operating curves can be summarized as follows:

1. Carrying out a stream inflow frequency analysis. The results obtained were a set of monthly possible stream inflow levels (high, medium and low) and their corresponding independent occurrence probabilities. These results are summarized in Table 2.

Table 2. Monthly possible inflow levels and their associated probabilities

	High		Medium		Low	
Month	**(MCM)**	**Probability**	**(MCM)**	**Probability**	**(MCM)**	**Probability**
Sep	7325	7	5222	7	3119	86
Oct	1481	20	1147	40	812	40
Nov	732	7	611	33	488	60
Dec	768	7	591	33	414	60
Jan	1289	13	900	20	510	67
Feb	1465	27	1023	13	598	60
Mar	3200	7	2163	20	1126	73
Apr	2195	27	1690	40	1185	33
May	4744	7	3681	20	2618	73
Jun	5810	13	4901	47	3992	40
Jul	8475	20	7006	40	5537	40
Aug	9249	7	7509	27	5768	66

2. Calculating the monthly downstream water needs based on estimates of the monthly water use coefficients and the annual water demands. Table 3 summarizes the calculated average monthly demand pattern.

Table 3. Monthly demand pattern

Month	Demand (MCM)	Month	Demand (MCM)
Sep	3456	Mar	1107
Oct	1701	Apr	1512
Nov	1242	May	3159
Dec	972	Jun	4752
Jan	513	Jul	3942
Feb	1107	Aug	3564

3. Generating the operating policies using SDP. The optimization routine used was (CSUDP) developed by John Labadie [16] at Colorado state university. The operating policies developed were a set of 12 curves with long-term objective function value, that minimizes the total expected sum of deficit and excess deviations from target releases, of 4972 MCM. Each rule defines the optimal ending storage for each possible beginning volume. This kind of rules is very useful since they require prior knowledge of the initial volumes only, which are known, and do not depend upon the unknown current period's inflows. An example of these rules is shown in Fig. 1.

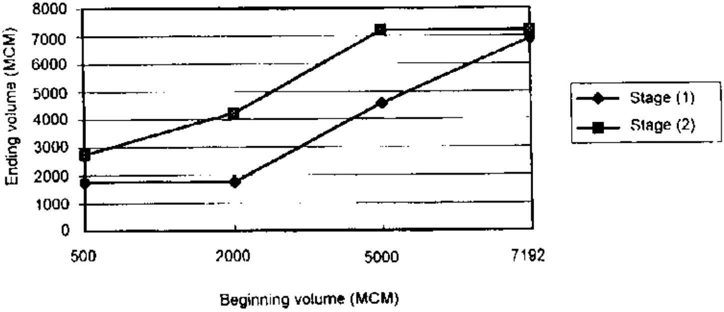

Fig. 1. Operating Rules for Stages 1 and 12.

Real time simulation

Once the operating rules are developed, the model will be used for both rules validation and real time simulation. Rules have been verified by first simulating the reservoir responses under 15 different scenarios of historical stream inflows representing both wet and dry years. Then comparing the actual value of the objective function achieved through simulation with the long-term expected one obtained from optimization. The validation process helps build a confidence in the produced operational policies in terms of how realistic they are for actual use. An example of the model's output for inflow set (1) is shown in Table 4 and Fig. 2. Also, the objective function values for all simulated inflows are listed in Table 5.

Table 4. Simulation results in (MCM) under inflow sequence (1)

Inflow sequence	Stage No.	Demand	Ending volume	Release	Spill	Stage return	Cumulative return
1	1	3456.0	6900.0	2787.0	0.0	669	669
1	2	1701.0	6039.1	1552.9	0.0	148	817
1	3	1242.0	6301.5	1243.6	0.0	2	819
1	4	972.0	4747.1	987.4	0.0	15	834
1	5	513.0	4671.1	950.9	0.0	438	1272
1	6	1107.0	4097.3	1823.9	0.0	717	1989
1	7	1107.0	4122.4	1755.9	0.0	649	2638
1	8	1512.0	3869.6	2700.8	0.0	1189	3827
1	9	3159.0	3296.7	5848.9	0.0	2690	6517
1	10	4752.0	2559.4	6798.3	0.0	2046	8563
1	11	3942.0	5000.0	4717.4	0.0	775	9338
1	12	3564.0	7192.0	3840.0	0.0	276	9614

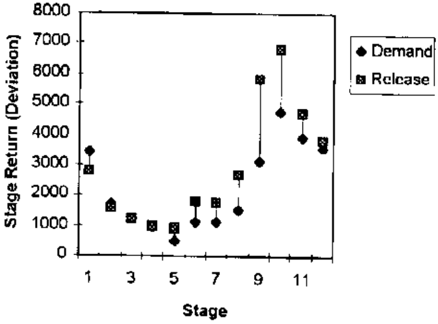

Fig. 2. Release vs. demand for inflow sequence (1).

Table 5. Actual objective function values(MCM)

Inflow sequence	Cumulative stage return
1	9614
2	4240
3	3510
4	5288
5	14370
6	8367
7	6468
8	4750
9	4488
10	15751
11	6068
12	11082
13	9547
14	3769
15	2358

Table 5 shows a wide variation in the actual annual returns for the 15 simulated deterministic inflow sequences from the expected long-term cumulative deviation of monthly releases from the monthly target demands (4972 MCM). However, the average value of these 15 actual cumulative returns (7308 MCM) should approximately equal to the expected return. This difference, which is relatively acceptable given the lack of data in most of the developing countries, will eventually fade with time as a larger sample size of examined inflows is collected and then simulated. In spite of that long records can be generated synthetically, the process is avoided to maintain the simplicity of the procedures.

Beyond rules validation, the model could be also used as a user-friendly tool to store, update and call these rules for day-to-day operation. The unsophisticated operator, would be just asked to simply input the date, beginning storage volume, and the required downstream demand. Based on these inputs, the model will retrieve the proper rule, interprets it and begins simulation. Finally, the user has the choice to display the results in either tabular or a graphical form. Based on his response a summary of the results will be displayed on the screen for prompt action.

Conclusion

The operating rules for a reservoir are tools to be used as a guide for water release for the achievement of maximum economic and efficient use of water. Based on these rules, the developed simulation model can help simulate the operation of water supply reservoirs to provide indications of realized outcomes of real time operation. It can be considered an useful management tool in the operational process of single-purpose (typically small) reservoirs.

Users with minimum knowledge of computers, which is the case with most reservoir operators in the developing countries should find this model very interactive and easy to use on site. The graphical capability of the model presents the calculation results in an interesting and brief form for the users.

The benefits of using the operating rules that provide an optimal return on the long run are not so obvious. In most cases, operators are more concerned about short term benefits, thus sacrificing the benefits of operating for the long run. Therefore, this simulation model might be a useful tool for showing the trade off between short and long term strategies.

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نموذج محاكاة لمشغّلي السدود ذات الغرض الوحيد

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قسم الهندسة المدنية ، كلية الهندسة ، جامعة الملك سعود ، ص.ب ٨٠٠ ،
الرياض ١١٤٢١ ، المملكة العربية السعودية

(استلم في ١٥/١١/١٩٩٧م ، وقبل للنشر في ٤/٥/١٩٩٨م)

ملخص البحث. تمّ تطبيق كثير من نماذج الأمثلية لحل الترتيبات التشغيلية المختلفة لأنظمة السدود. إلا أن هذه الإجراءات ليس من السهولة على مشغّلي السدود التقليديين استخدامها خاصة في الدول النامية. لذا فإن هذه الورقة تقترح إجراءات مبسّطة تمّ تصميمها لتساعد هؤلاء المشغّلين على بناء القواعد التشغيلية اللازمة للإدارة المثلى للسدود ذات الغرض الوحيد والشائعة في المناطق الجافة كالمملكة العربية السعودية واختبارها. وتشمل هذه الإجراءات أولاً تحديد سياسة تشغيل باستخدام البرمجة الديناميكية التوقعية. ومن ثم اختبار هذه السياسة بواسطة نموذج محاكاة صُمّم لهذا الغرض. وأخيرًا وفي حالة قبول هذه السياسة فإن نموذج المحاكاة يمكن استخدامه للتشغيل الآني للسد. إضافة إلى ذلك ، شمل البحث مثالاً يوضّح مدى فائدة نموذج المحاكاة وكذلك لمقارنة قيمة دالة الهدف الحقيقية والمتوقعة. وتخلص الدراسة في أن هذا النموذج يمكن أن يلعب دورًا مهمًا لمساعدة مشغّلي السدود للاستفادة المثلى من تلك السدود التي غالباً ما تكون مهملة وخاصة في الدول النامية.