A study of a real time adaptive closed-loop reservoir control algorithm

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ABSTRACT A comparison is made of a heuristic operating policy for the High Aswan Dam with that resulting from a steady state stochastic dynamic programming solution and that from a real time adaptive control formulation that used multi-lead forecasts of river flows. The objective is to minimize losses due to irrigation deficits, power production deficits and damages due to flooding. It can be concluded that performance is better with the steady state solution, and it is best using the adaptive formulation. Particularly, the use of forecasts and the adaptive formulation significantly reduces flood damages.

INTRODUCTION

Since the completion of the High Aswan Dam, many studies have been performed investigating its "optimal" release policy with respect to conservation storage, flood protection and hydropower generation. The problem is complicated due to the multi-objective nature of High Dam releases and to the lack of knowledge of future inflows to the High Dam reservoir, Lake Nasser. To cope with these complications, recent studies (Alarcon & Marks, 1979; El Assiouti et al., 1979) have utilized steady state stochastic dynamic programming algorithms. In these works, Lake Nasser inflows are characterized to be periodically stationary and the objective space is reduced by imposing lower and upper constraints on releases.

This study likewise utilizes stochastic dynamic programming techniques to derive High Dam release policies. However, two major modifications are incorporated. The first modification drops both lower and upper constraints imposed upon releases. Instead, the undesirability of very low and very high releases is described in the objective function, which will be discussed in a later section. Second, the stationarity assumption on Lake Nasser inflows is relaxed, and forecasted inflows for up to 12 months in advance are incorporated to characterize more accurately future unknown inflows. Release decisions will now be based upon forecasted inflows as well as the current reservoir elevation and the previous month's inflow. This is termed a "real time adaptive closed-loop" approach. Details for both the forecasting methodology and the real time adaptive control algorithm can be found in Curry & Bras (1980).

To test the performance of the adaptive release policy, a simulation model of the High Dam-Lake Nasser system is utilized. Using monthly streamflow data from 1912 to 1965, a comparison between the adaptive policy and two alternate operating policies is made for
several performance measures. The first alternate policy follows a set of rule curves proposed by Joint Research Project IMB/EXWAP, which tries to draw the reservoir level down to elevation 175 m by 1 August of each year. This is referred to as the heuristic policy (for more details, see Alarcon & Marks, 1979). The second alternate policy is derived from a steady state stochastic dynamic programming algorithm (i.e. without forecasting), similar (but not equal) to those used by El Assiouti et al. (1979) and Alarcon & Marks (1979).

SYSTEM PARAMETERS

Since some variables of the system under study are not well defined, certain assumptions must be mentioned prior to any analysis. The particular assumptions to be made concern water supplied to the system, water demanded, downstream degradation and the Toshka spillway.

First, Nile Basin data from 1912 to 1965 are used as input to the simulation model. For both the adaptive and the steady state dynamic programs, monthly distributions of flows at Wadi Halfa are used to describe Lake Nasser inflows. Sample statistics for Wadi Halfa, including the monthly means, variances and lag-one correlation coefficients, are given in Table 1.

<table>
<thead>
<tr>
<th>Month</th>
<th>Mean*</th>
<th>Std. dev.*</th>
<th>Lag-1</th>
<th>Xmax*</th>
<th>Xmin*</th>
<th>Nor/lognor</th>
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<tr>
<td>1</td>
<td>3.51</td>
<td>0.74</td>
<td>0.486</td>
<td>5.75</td>
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<td>2.45</td>
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<td>0.276</td>
<td>5.08</td>
<td>1.42</td>
<td>lognormal</td>
</tr>
<tr>
<td>3</td>
<td>2.28</td>
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<td>0.555</td>
<td>4.81</td>
<td>1.26</td>
<td>lognormal</td>
</tr>
<tr>
<td>4</td>
<td>2.04</td>
<td>0.69</td>
<td>0.640</td>
<td>4.54</td>
<td>1.05</td>
<td>normal</td>
</tr>
<tr>
<td>5</td>
<td>1.93</td>
<td>0.76</td>
<td>0.471</td>
<td>4.34</td>
<td>0.88</td>
<td>lognormal</td>
</tr>
<tr>
<td>6</td>
<td>2.07</td>
<td>0.78</td>
<td>0.270</td>
<td>4.52</td>
<td>1.00</td>
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</tr>
<tr>
<td>7</td>
<td>5.17</td>
<td>1.53</td>
<td>0.607</td>
<td>10.00</td>
<td>2.23</td>
<td>normal</td>
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<tr>
<td>8</td>
<td>19.45</td>
<td>3.36</td>
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<td>24.20</td>
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<tr>
<td>11</td>
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<td>0.929</td>
<td>12.20</td>
<td>4.14</td>
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</tr>
<tr>
<td>12</td>
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<td>0.87</td>
<td>0.874</td>
<td>7.06</td>
<td>2.99</td>
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</tr>
<tr>
<td>Total</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>= 87.20</td>
</tr>
</tbody>
</table>

Actual inflows to Lake Nasser must be reduced from the figures of Table 1 due to upstream abstractions in Sudan and to losses at Gebel Aulia reservoir. For this study, it is assumed that 16.5 x 10^3 m^3 are consumed annually by these two sources, following the monthly distributions given in Fig.1. The resulting annual average inflow to Lake Nasser is thus 70.7 x 10^3 m^3.

Irrigation demands downstream from the High Dam are taken to be
55.5 \times 10^9 \text{ m}^3 \text{ year}^{-1}. The monthly schedule of demands is given in Fig.1 in terms of percentage of total annual demands.

It was mentioned earlier that the dropping of lower and upper constraints on releases was a major modification incorporated in the study. However, it must be acknowledged that excessive reservoir releases will cause downstream degradation. Though figures in the literature range from 7.1 to 10.5 \times 10^9 \text{ m}^3, this study assumes releases of up to 7.6 \times 10^9 \text{ m}^3 \text{ month}^{-1} to be "safe" releases. Releases above 7.6 \times 10^9 \text{ m}^3 \text{ month}^{-1} are assumed to cause downstream degradation.

Further, it is assumed that the Toshka spillway is not operating, though it is understood that Toshka will, in fact, be ready to operate in the near future, and that further analyses should include Toshka.

Finally, using the above information, operating policies are derived for reservoir elevations 147-183 m. This is the portion of Lake Nasser originally designated to be live storage, amounting to approximately 137 \times 10^9 \text{ m}^3.

**OBJECTIVE FUNCTION**

The controlled releases at the High Aswan Dam give primary consideration to two objectives: meeting downstream irrigation demands and maintaining manageable reservoir storage volumes for flood control and downstream degradation purposes. A third objective, currently of lesser importance, is the maximization of electricity generated at the High Dam power plant.

The defined objectives cannot be met with absolute certainty over the infinite future, due to lack of knowledge of future Lake Nasser inflows. Further, these objectives are conflicting in nature with respect to releases, and due consideration must be given to the
importance in achieving each objective. The objective function utilized in this work takes the form:

\[ L_t = a(R - T_1^t)^b_1 + a_2(R - T_D^t)^b_2 + a_3(T_E^t - GN)^b_3 \]

where \( L_t \) are losses incurred from irrigation deficits, downstream degradation and power generation deficits during time period \( t (t = 1, 2, \ldots, 12); R_t \) is release \((10^3 \text{ m}^3 \text{ month}^{-1})\); \( T_1 \) is the irrigation target for time period \( t (10^3 \text{ m}^3 \text{ month}^{-1})\); \( T_D \) is the release above which channel degradation occurs \((10^3 \text{ m}^3 \text{ month}^{-1})\); \( T_E \) is the energy target during time period \( t (10^3 \text{ GWH} \text{ month}^{-1})\); \( GN \) is the energy generated during time period \( t (10^3 \text{ GWH} \text{ month}^{-1})\); \( a_1, a_2, a_3 \) are trade-off coefficients; \( b_1, b_2, b_3 \) are exponential coefficients; and \( a_1 = 0 \) if \( R > T_1 \), \( a_2 = 0 \) if \( R > T_D \), and \( a_3 = 0 \) if \( GN > T_E \).

The experiments performed in this work use the following values for the defined trade off and exponential coefficients:

\( a_1 = 10,000,000; a_2 = 10,000; a_3 = 1000; b_1 = b_2 = b_3 = 2 \). The trade off coefficients, although arbitrary, indicate a heavy preference for meeting the irrigation targets, a secondary preference for avoiding downstream degradation, and the least preference for maximizing energy. The exponential coefficients, all taken to be square terms, indicate an increasing marginal loss with each extra unit for which targets are not met.

**FORECASTING MODEL**

The model used for streamflow forecasting in this work was developed and discussed in detail by Curry & Bras (1980). Briefly, the model is of the form:

\[
\begin{bmatrix}
Y(k,i-1) \\
Y(k,i-2) \\
\vdots \\
Y(k,i-n_1(i))
\end{bmatrix}
= \begin{bmatrix}
\mathbb{I}_1 \\
\mathbb{I}_2 \\
\vdots \\
\mathbb{I}_{n_1(i)}
\end{bmatrix}
+ \begin{bmatrix}
U'(i) \\
V'(k,i)
\end{bmatrix}
\]

where

\[
Y(k,i) = \begin{bmatrix}
Y_1(k,i) \\
Y_2(k,i) \\
\vdots \\
Y_n(k,i)
\end{bmatrix}, \quad U'(i) = \begin{bmatrix}
U_1(k,i) \\
U_2(k,i) \\
\vdots \\
U_n(i)
\end{bmatrix}, \quad V'(k,i) = \begin{bmatrix}
V_1(k,i) \\
V_2(k,i) \\
\vdots \\
V_n(i)
\end{bmatrix}
\]

\[
V_j(k,i) = \sum_{m=1}^{n_O} C_{1}(j,m) W_{m}(k,i)
\]
In the above, $n_Q$ is the number of streamflow measuring stations considered in the basin and $Y_j(k,i)$ is the discharge at station $j$ in year $k$, month $i$. The vector $\bar{U}'(i)$ represents a periodic (period 12) mean streamflow and the vector $\bar{V}'(k,i)$ is a periodic (period 12) disturbance term. $W_m(k,i)$ is a white, uncorrelated noise of zero mean and unit variance. Notice that the elements of $\bar{V}'(k,i)$ are not necessarily uncorrelated and their variance is a function of time. These effects are introduced by the use of parameters $C_i(j,m)$ in the expression of $V_j(k,i)$. The coefficient matrix $\Pi_i$ is a function of month $i$. Calibration of this model requires estimating a coefficient matrix $\Pi_i$ for each month $i$, defining an autoregressive lag $n_1(i)$ for each month, determining the mean vector $\bar{U}'(i)$ and the corresponding residual $\bar{V}'(k,i)$. The procedure involves iterative use of generalized least squares techniques.

The forecasting model for the Nile River utilized eight different stations as illustrated in Fig. 2. Of interest to this work is the forecasting system for flows into the Wadi Halfa station (i.e. Lake Nasser).

It is important to emphasize that the nature of the forecasting equation is such that essentially there will be a different equation (different coefficients and variables) for each month's forecast into Wadi Halfa. Forecasts are possible up to a lead of 12 months.

FIG. 2  Schematic diagram of Nile River basin.
The accuracy of the forecast varies with lead and time of the year. For example, the dry month of April in Wadi Halfa can be forecasted in March (lead 1) with a variance reduction (as a measure of forecast accuracy) of 96%. The 12 month lead forecast of April in the same location has a variance reduction of 58%. On the other hand, the flood month of August at Wadi Halfa is forecasted with a 75% variance reduction at lead 1, but only a 1% variance reduction with a six month lead and 17% with a 12 month lead.

SIMULATION RESULTS

The simulation model used to compare the three operating policies is a simple water balance model. Over the 53 years of simulation, statistics on releases, reservoir elevations, power generation, spills, deficits and overall costs are tabulated on both a monthly and annual basis.

For this paper, results of one experiment are reported. The experiment consists of three simulation runs, one for each operating policy. Both the steady state and the adaptive release policies are derived using a monthly discount rate of 0.01.

First, the primary objective of the system, as indicated by the trade-off coefficients of the objective function, is to conserve water to ensure meeting present and future downstream demands. For both the steady state and the adaptive release policies, no irrigation deficits are incurred over the period of simulation (see Table 2). This is almost to be expected, given the huge reservoir storage capacity and the average annual excess of inflows over annual demands. The heuristic policy likewise incurs zero deficits. However, a major difference exists in the minimum monthly elevations occurring over the period of simulation with the heuristic policy dropping to significantly lower levels. The adaptive release policy yields much higher minimum monthly elevations, while the steady

<table>
<thead>
<tr>
<th>TABLE 2 Summary of simulation statistics* (discounted)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heuristic</td>
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<tr>
<td>-----------------</td>
</tr>
<tr>
<td>No. of irrigation deficits</td>
</tr>
<tr>
<td>No. of excessive releases†</td>
</tr>
<tr>
<td>Annual power generation (GWH)</td>
</tr>
<tr>
<td>Releases through turbines§</td>
</tr>
<tr>
<td>Releases bypassing turbines§</td>
</tr>
<tr>
<td>Total releases§</td>
</tr>
<tr>
<td>Evaporation (BCM§)</td>
</tr>
<tr>
<td>Annual costs</td>
</tr>
<tr>
<td>Years exceeding D/S demands</td>
</tr>
</tbody>
</table>

* For entries with "/" symbol, the left-hand number gives the mean value and the right-hand number gives the standard deviation.
† Releases above 7.6 x 10^9 m^3 per year.
§ 10^5 m^3 year^-1.
state policy produces slightly lower minimum elevations. These results indicate that both the steady state and the adaptive policies are more conscious of the undesirability of low reservoir elevations, and consequently attempt to avoid them.

The second most important objective is the avoidance of excessive (degradation causing) releases. Of particular interest are both the frequencies and the magnitudes of these releases. From Tables 2 and 3 it can be seen that the heuristic policy not only has the most excessive releases, but also the most severe. The steady state policy reduces both the frequency and the magnitude, while further improvement can be observed using the adaptive policy. Another interesting point to note is that, over the 53 years of simulation, the heuristic policy lowers the reservoir elevation to 175 m by

<table>
<thead>
<tr>
<th>Release*</th>
<th>Year</th>
<th>Release*</th>
<th>Year</th>
<th>Release*</th>
<th>Year</th>
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<td>7.66</td>
<td>5</td>
<td>7.68</td>
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</tr>
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<td>8.20</td>
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<td>6</td>
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<tr>
<td>7.65</td>
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<td>8.19</td>
<td>6</td>
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<td>8.91</td>
<td>23</td>
<td></td>
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<tr>
<td>10.00</td>
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<td></td>
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<td>53</td>
<td>7.65</td>
<td>53</td>
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</tbody>
</table>

* $10^3$ m$^3$ month$^{-1}$.

1 August every year. Conversely, the steady state and the adaptive policies lower the reservoir to 175 m by 1 August approximately 75% of the time, yet these two policies perform better in regard to excessive releases. For example, months 5-9 of 1964 have above average inflows. Simultaneously, all three simulations (heuristic, steady state, and adaptive) have mostly full reservoirs. Given this situation, the heuristic policy has large releases at the end of 1964 (months 11 and 12), in its effort to reach 175.0 m by the following August, and large costs are incurred. However, the other two policies allow reservoir levels to rise, releasing near to or well below $7.6 \times 10^3$ m$^3$ month$^{-1}$. When the first 6 months of 1965 have very high reservoir inflows (relative to their respective means given in Table 1), excessive releases are incurred by all simulations. However, the adaptive policy releases larger amounts of water in the first two months of 1965, foreseeing the above average inflows of the
The steady state policy, on the other hand, experiences more difficulties, as it lacks the knowledge of continued large inflows. The heuristic policy performs similar to the steady state policy for the year 1965, but it has already incurred large costs in the previous year of simulation.

The third objective concerns attaining monthly targets of hydropower generation. Two measures of performance for this objective are the annual average and the range of monthly average hydropower generated.

On an annual basis, the experiment shows the adaptive policy generating the most power, the steady state policy generating a little less, and the heuristic policy generating the least. Relative to annual generation, one might at first conclude that it is preferable to operate at higher elevations with corresponding lower releases (due to higher evaporation), rather than releasing higher quantities at low elevations. However, this cannot entirely be substantiated, as the steady state policy operates at the highest elevations and the resulting power generation is less than that of the adaptive policy. Seeking further explanation, one can point to the amount of water bypassing the turbines (see Table 2). Clearly, there is a direct relationship between the amount of water forced to bypass the turbines (due to turbine capacities) and annual hydropower generation. The adaptive policy, generating the most power, sends almost all water through the turbines, while the heuristic policy bypasses an average of almost $0.5 \times 10^9$ $\text{m}^3 \text{year}^{-1}$. Thus, the most influential factor on annual generation may not concern average reservoir elevations so much as the ability of the operating policy (over the long run) to avoid water bypassing the turbines.

Looking at the average monthly generation values, all simulations produce the most power in the month of July, and the least in December. Since monthly energy demands in Egypt are fairly uniform over the year, it might be considered preferable to have a corresponding uniform distribution of power production. The heuristic policy shows the tightest range of average monthly generation values, varying from 393 to 1061 GWH per month. The discounted adaptive policy likewise produces an average of 393 GWH in December, and has a maximum average power production of 1079 GWH in July. The other three policies generate relatively less in December and more in July, hence yielding a larger range. However, a closer look reveals that the higher values of power generation in December for the heuristic and the discounted adaptive policies are due to one or two very high releases, while the remaining December releases and corresponding generation are very similar to the other policies. The high December power generation of the heuristic and the discounted adaptive policies have corresponding high variances. It should also be noticed that these two policies, having the tightest ranges, also have the highest variances with respect to annual power generation (Table 2).

Aside from the stated objectives, a point of interest is the number of years during a simulation in which water in excess of downstream demands is released. As indicated by Table 2, the heuristic policy has the most years, ten altogether, in which excess
water is released, while the undiscounted steady state policy has the fewest with seven. Another way to say this is that there is water available solely for the purpose of power generation in fewer than two out of every 10 years. Of course, these results are dependent upon the set of statistics used to describe Lake Nasser inflows. However, it should also be recalled that Sudan abstractions and Gebel Aulia losses combined are taken to be $16.5 \times 10^9$ m$^3$ year$^{-1}$, while the Nile Water Agreement of 1959 allocated $18.5 \times 10^9$ m$^3$ year$^{-1}$ to upstream abstractions and losses. Increased future abstractions would further constrain the system, and the little leeway currently available for optimizing power production would probably be lost.

Finally, an overall measure of performance is the cost incurred as defined by the objective function. As is to be expected, the heuristic policy incurs the highest costs. This can be attributed to the non-optimizing nature of the policy. Both steady state policies show significant improvement in costs incurred, and the corresponding adaptive policies again perform the best. Since all simulations generate similar amounts of power, and do not experience irrigation deficits, the differences can be attributed to the frequency and magnitude of releases causing degradation (i.e. above $7.6 \times 10^9$ m$^3$ month$^{-1}$). The multi-objective nature of the system is thus handled well by optimization techniques. It also becomes evident once again that the incorporation of forecasted information is significant relative to the stated objectives.

**CONCLUSIONS**

From the experiments performed in this study, the following conclusions are made:

(a) The discounted steady state policies show significant improvement over the heuristic policy in operating the High Dam-Lake Nasser system relative to the stated objectives.

(b) The discounted adaptive policies show further improvement over their respective steady state policy counterparts.

(c) The benefits of forecasting can be seen mostly in the objective of avoiding high releases causing degradation.

(d) The use of forecasting results in higher minimum reservoir elevations, and lower maximum reservoir elevations.

(e) Maximizing annual power generation may depend mostly upon a policy's ability to avoid water bypassing turbines, which in turn requires avoiding excessive releases.

(f) Since at most 10 years of simulation released more than the downstream requirements among all simulations, there appears to be little leeway available for optimizing power generation for the given distribution and amount of demands.

(g) Discounting future losses appears to reduce the fear of future irrigation deficits, allowing improved performances in avoiding degradation causing releases by operating the reservoir at slightly lower elevations.

**ACKNOWLEDGEMENTS**

This study was sponsored by the MIT Technology
Adaptation Program, which is funded through a grant of the Agency of
International Development, US Department of State. The views and
opinions expressed are those of the authors and do not necessarily
reflect those of the sponsors. Work was performed at the Ralph M.
Parsons Laboratory, Department of Civil Engineering, MIT. The
cooperation of the Egyptian Ministry of Irrigation and our Cairo
University counterparts is gratefully acknowledged. The staff of
the MIT Technology Adaptation Program in Cairo and Cambridge,
Massachusetts, are thanked for their helpful administrative support.

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