Aswan High Dam Reservoir management system
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ABSTRACT

The Aswan High Dam Reservoir management system was developed to simulate dam operation under varying boundary conditions taking as example climate change and Millennium Dam construction, and analyze the optimal operation rules of the reservoir taking into account a large number of objectives, including hydropower production and water supply for irrigation purposes. The developed system runs on Windows platforms and comprises three basic modules: a user-friendly graphical interface managing all graphic features, a computational engine where all the algorithms are implemented, and a database and files module managing hydrological and operational data. The developed model was calibrated. The future hydrologic scenarios developed have been used to assess the expected impacts of potential climate change (baseline and three periods with two global emission scenarios) and the Millennium Dam. The new operation rules were used for scenarios analysis. It was concluded that overall applying the new operation rules will decrease the percentage of occurrence of minimum water levels. Also, the Millennium Dam will increase the percentage of occurrence of minimum water levels. Finally, the period III (2070–2099) for the two global emission scenarios is very critical for the dam operation.

Key words | climate change, dam operation, decision support systems, operation rules, scenario analysis, water resource management

INTRODUCTION

Successful integrated management of water supply systems requires the effective use of Decision Support Systems (DSS) able to support managers to make key decisions. According to a structural definition (Sprague 1983; Reitsma et al. 1996), a DSS can be defined as a computer-based tool comprising three subsystems: the modeling subsystem, the database subsystem and the user interface subsystem, interconnected with each other. Numerous researchers have developed computer-based DSS for the management and operation of reservoirs and river systems (e.g., Simonovic & Savic 1989; DeGagne et al. 1996; Koutsoyiannis et al. 2002). Currently, the vast majority of reservoir system planning and operation is undertaken using simulation and optimization models (Lund & Guzman 1999). To date, these have focused primarily on the physical aspects of the system (Reitsma 1996). They are frequently based on simple engineering principles for dam operation, such as keeping reservoirs full for water supply or empty for flood control. As such, they provide a great deal of flexibility in the specification of system operations under various flow, storage and demand conditions. Many rules are based on largely empirical or experimental success, determined either from actual operational performance, performance in simulation studies or optimization results. These experimentally-supported rules are common for large multi-purpose projects.

Georgakakos (2006) describes four scales at which DSS can improve reservoir network management by improving decision making:

• long term infrastructure planning and construction;
• interannual and seasonal operational decisions for over-year storage and water contracts;
• 1–3 month operational decisions for dry period conservation or flood management; and
• daily releases for water allocation or hydropower operation. Decision support at the first scale is used in a planning capacity, where the decisions are for changes or improvements in infrastructure.

The operational decisions associated with the other three scales are primarily reservoir release schedules. DSS can help operators make releases which best meet the objectives of the project: meeting user demands, suitable deficit allocations during drought periods, and most importantly a release schedule which appropriately balances the present demands with the value of storage for future demands.

Climate change can have an impact on water resources systems resulting in changes in both, the hydrologic cycle and water availability (IPCC 2007). Since the magnitude of local climate change depends on the rate of change of weather conditions, precipitation and temperature, some regions have already begun investigations into the potential impact on local water systems, particularly in areas of multipurpose use of water and reliance on water supply facilities such as reservoirs (Wood et al. 1997; Hamlet & Lettenmaier 1999; Payne et al. 2004; Simonovic & Li 2004; Van Rheenen et al. 2004). In a geographic region that, by its nature, depends on effective management of the water resources by the storage reservoirs, a study of potential climate change impacts on reservoir operation is justified. The reservoir not only provides water for basic needs, but also stores the surplus of water during high flow season to provide protection of downstream area from flooding. Reservoir systems, designed and operated using historical data, are unlikely to have management contingencies for the effects of climate change. To fill that research gap, scientific work is being done on the impact of climate change with an attempt to define the risks associated with current reservoir operation practices (Nemec & Schaake 1982; Klemes 1985; Burn & Simonovic 1996; Yao & Georgakakos 2003). Brekke et al. (2009) developed a risk assessment framework and applied it to California’s Central Valley Project and State Water Project systems. They used a total of 97 scenarios based on emissions and General Circulation Models (GCMs) provided by the Intergovernmental Panel on Climate Change (IPCC). A weighting was assigned to each scenario, for risk-based planning approach, to study how the risk outlined is sensitive not only to selected climate scenarios but also to analytical design choices such as weight projections. In much of the existing and quite limited research only current reservoir operating rules are used to determine how water systems will respond to climate change.

Many studies including the Aswan High Dam Reservoir (AHDR) simulation and optimization models have been conducted, but the availability of reliable data and economic and human resources burdens the implementation of complex models for the management of water (Alarcon & Marks 1979; WMP 1979; Gueriso et al. 1981; Sadek & Aziz 2005; Soliman et al. 2007; Shafie et al. 2008). Also these studies have taken into account a stationary climate that is increasingly considered inadequate for sustainable water resources management. Few studies have taken into consideration climate change impact on the Aswan High Dam (AHD) such as Mobasher & Ostrowski (2010) for reservoir systems, climatic variability and the related hydrologic uncertainty are major sources of vulnerability. This is especially true in West Africa where the already high interannual variability is exacerbated by trends associated with climate change (Dow 2005; Hellmuth et al. 2007). DSS can reduce these vulnerabilities by improving water resource management in the face of climate variability and change (Yao & Georgakakos 2003; NRC 2008), including systems in Africa (McCARTNEY 2007).

This study attempts to develop a DSS for managing the AHDR operation for adaptation to climate change. The system has several important characteristics. We develop a tool of analysis that is easy to use and easily accepted by managers who have little training in quantitative analysis, and that corresponds as closely as possible to the way in which water release decisions were made historically. Of course, the overriding goal is to design decision rules that significantly improve on previously practiced rules, especially in the event of extreme hydrological conditions such as flooding or drought and climate change scenarios. The manager can easily use the DSS on a monthly basis, to quickly analyze the impact of several different alternative courses of action (such as water release schemes) on the relevant objectives and other quantities of interest (such as electricity generation and reservoir storage). The system is a scenario-driven decision support tool for incorporating climate change into new operating rules for the AHDR. Therefore, the DSS proposed in this study can be used to determine reservoir operation rules that adapt to new conditions whenever information is available (for example updated GCM output).
CASE STUDY DESCRIPTION

Construction of the AHD on the River Nile in southern Egypt began in 1960 and was completed in 1972. The dam is in fact the core of all production in Egypt. It is the foundation upon which the country's contemporary industrial, agricultural and economic revival depends. The intended purposes of the project are irrigation, hydropower generation and flood control. With regard to its relative economic importance, the dam project has a unique position among the big irrigation projects in the world. AHDR, known as Lake Nasser, is a reservoir formed as a result of the construction of the AHD. It is located on the border between Egypt and Sudan (see Figure 1).

The reservoir has a large annual carry-over capacity of 168.90 BCM (billion cubic meters) that corresponds to a lake surface area of 6,540 km², length of 500 km and an average width of 12 km. The ratio between storage capacity and the corresponding surface area or the storage mean depth for the

![Figure 1](https://iwaponline.com/jh/article-pdf/15/4/1491/387205/1491.pdf)
AHD is 24.82 m. About 300 km of its length lies within the Egyptian borders, while 200 km are within Sudanese territory. The total storage capacity of the reservoir is allocated as follows: 90 BCM as live storage capacity between levels 147 and 175 m (meters above sea level, MASL), 31 BCM as dead storage for sediment deposition, and 41 BCM as a flood control buffer between the levels of 175 and 182 m (MASL). The reliable water supply from the AHDR is estimated as 55.5 BCM yr$^{-1}$, based on the average natural flow of 84 BCM yr$^{-1}$, reservoir evaporation losses of 10 BCM yr$^{-1}$ and an allocation of 18.5 BCM yr$^{-1}$ for the Sudan. The hydroelectric power station consists of 12 units with a capacity of 175 MW each, i.e., a total capacity of 2,100 MW, producing on average 7 billion kWh of energy annually. Each turbine is under a head range of 60–76 m, while the water level in the reservoir upstream of the turbines ranges between 175 m at the beginning of the water year in August and 165 m or less in the drought seasons. The height of the turbines is 108 m, so the head on the turbines can be calculated as $175 - 67 - 108 = 6$ m in the normal operation case for a corresponding range of discharges between 270 and 345 m$^3$ s$^{-1}$. Associated with the generating units are emergency low-level outlets for releasing water when downstream needs exceed the flows that can be handled by the turbines (Abu-Zeid & El-Shibini 1997). The design criteria for the AHDR are shown in Figure 2.

The reservoir satisfies the multiple roles of water conservation, flood protection and hydropower generation. The releases from the dam are designed to meet irrigation requirements, which vary markedly from one season to another and hydropower is generated as a secondary benefit. In addition, the reservoir is operated to control the annual flood by drawing down the reservoir to a predetermined level on a specified date each year. Additional constraints on the operation of the reservoir are imposed by the need to limit the magnitude of releases so as to avoid downstream degradation and/or hindrance to navigation. During low flood years, the water released for different uses, in Egypt and Sudan, is reduced according to a sliding scale in order to avoid reservoir emptying. The amount of monthly releases, therefore, is determined by the amount of the flood and essential requirements. The reservoir reached its lowest storage level of 150.62 m in July 1988, but fortunately, the large flood of 1988–1989 allowed the reservoir to rise again and reach a level of 168.82 m in December 1988. In the 1990s, the reservoir continued to rise until it reached the highest level of 181.60 m in November 1999 (Sadek 2002).

Egypt’s water demand might rapidly increase due to the population growth and the improvement of living standards as well as to achieve the government policies in order to reclaim new lands and to encourage development in the industrial sector. The major water consuming sectors are agriculture, municipalities and industries. On the other hand, yield supply related to rainfall and evaporation, and subsequent changes of inflow into the reservoir must be taken into consideration. These supply scenarios are stochastic and vary year by year. Drivers are global warming and related climate change which will determine these variables. The natural Nile flows are very sensitive to relatively small changes in rainfall. Nile River discharge has a very great variation due to the variety of the different characteristics of the Nile basin. The Nile flood can be as high as 150 BCM yr$^{-1}$ (1878–1879) and as low as 42 BCM yr$^{-1}$ (1913–1914). Nile River floods can be classified according to the following five categories (Sadek & Aziz 2005):

- Very low flood with an average flow of 52 BCM yr$^{-1}$;  
- Low flood with an average flow of 70 BCM yr$^{-1}$;  
- Average flood with an average flow of 92 BCM yr$^{-1}$;  
- High flood with an average flow of 110 BCM yr$^{-1}$;  
- Very high flood with an average flow exceeding 110 BCM yr$^{-1}$.

Studies of climate change impact on the Nile River show that the basin is extremely sensitive to temperature and precipitation changes (Strzepek & Yates 2000). An increase of

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Figure 2 | Design criteria for the AHD.
10% in average annual precipitation would lead to an average increase in annual flow of 40%. Similarly, a decrease in 10% in precipitation would lead to a reduction of the annual flow of more than 50% (Ministry of Water Resources and Irrigation 2005). Beyene et al. (2007) assessed the potential impacts of climate change on the hydrology and water resources of the Nile River basin using a macroscale hydrologic model driven by 21st century simulations of temperature and precipitation downscaled from runs of 11 GCMs and two global emissions scenarios (A2, corresponding roughly to unconstrained growth in emissions, and B1, corresponding to elimination of global emissions increases by 2100) archived for the 2007 IPCC report. The results show that, averaged across the multimodel ensembles, the entire Nile basin is expected to increases in precipitation early in the century (period I, 2010–2039), followed by decreases later in the century (period II, 2040–2069 and period III, 2070–2099) with the exception of the easternmost Ethiopian highlands which might experience increases in summer precipitation by 2080–2100. Averaged over all models and ensembles, annual streamflow at the AHD for scenario A2 was predicted to increase to 111% of the 1950–1999 mean during 2010–2039, but then to decrease to 92 and 84% of the 1950–1999 mean during 2040–2069 and 2070–2099, respectively. For scenario B1, the corresponding numbers were 114% (increase) during 2010–2039, and decreases to 95 and 87% of the 1950–1999 mean for 2040–2069 and 2070–2099, respectively.

Another varying boundary condition is the Grand Ethiopian Renaissance Dam (formerly known as Project X or the Grand Millennium Dam) that Ethiopia announced in April 2011 over the Blue Nile (Figure 3). This huge dam will flood 1,680 km² of forest in northwest Ethiopia, near the Sudan border, and create a reservoir that is nearly twice as large as Lake Tana, Ethiopia’s largest natural lake. While there are no known studies about the dam’s impacts on the river’s flow, filling such a huge reservoir (it will hold up to 67 BCM of water, and likely take up to 7 years to reach capacity) will certainly impact Egypt, which relies almost totally on the Nile for its water supply. Climate change could increase the project’s many risks. If it fills in 3 years (from 2014 to 2017), it will save 21 BCM every year, so only 27 BCM will come into Egypt instead of 48 BCM, in other words, a 21 BCM decrease in Egypt and Sudan’s share. After completion of the dam construction, and assuming that it operates only 10 pumps from 15 and that the capacity of each pump is 4.3 BCM then Egypt would receive only 43 BCM instead of 48 BCM, a loss of 5 BCM divided between the Egyptian and Sudanese share (Zewde 1997; BCEOM 1998; Waterbury 2002; World Bank a,b; Berhane 2011).

Due to the enormous importance of the reservoir, special and national consideration must be given to the reservoir operation and development. Operation of the AHDR might face different challenges in the 21st century due to potential changes of the demand-supply conditions. The management of the AHDR is one of the most important issues related to water resources studies in Egypt. The developed model will be used to analyze future development of water resources yield and demand, and related modifications of the infrastructure and operation. It is designed as a comparative analysis tool. A base case is developed and then alternative scenarios are created and compared to this base case. Therefore, this paper objective is to
develop ‘easy to use’ computing tools in order to perform these scenario analyses studies and to improve the management of the High Aswan Dam Reservoir under climate change.

**ASWAN HIGH DAM RESERVOIR MANAGEMENT SYSTEM (AHD RMS)**

The developed management system is a computer-based tool comprising three subsystems: the modeling subsystem, the database subsystem and the user interface subsystem, interconnected with each other. Computer software was developed, using Visual Basic, by the author and it is named ‘Aswan High Dam Reservoir Management System (AHD RMS)’. The capabilities of the developed system help in understanding a given problem, explore the consequences of different alternatives and facilitate sensitivity analyses. One of the main objectives of this study was to determine the possible scenarios of climate change and then incorporate this information into the system in order to determine the impact that climate change is likely to have on the natural availability of the water resources in the river basin.

The database subsystem

**Figure 4** shows the input database of the developed software and it contains the following modules.

![Figure 4](https://iwaponline.com/jh/article-pdf/15/4/1491/387205/1491.pdf)
Operation rules

This includes the top of the buffer, Toshka spill, max daily release, minimum daily release, beginning of water year storage and Aswan emergency spill zone.

The irrigation requirements

Irrigation demands downstream from the High Dam are taken to be 55.5 BCM yr\(^{-1}\) (MWRI 2005). The monthly schedule of demands is given in a table from the database in terms of percentage of total annual demands, following the monthly distributions.

The hydropower requirements

This includes the energy demand, tail water elevation, max turbine flow, generating efficiency and working turbine hour.

The monthly evaporation rates

The annual evaporation losses from the reservoir are divided between the months, the highest evaporation rates from the reservoir occur in May–October, while the lowest values occur in the period December–February.

The modeling subsystem

In this study, the modeling subsystem is based upon a simulation model that operates on the basic principle of water balance accounting, where both the engineered and biophysical components of a water system are represented to facilitate multi-stakeholder water management dialogue for reservoir operations and hydropower generation, Typically AHDRMS is applied by configuring the system to simulate a recent ‘baseline’ year, for which the water availability and demands can be confidently determined. The model is then used to simulate alternative scenarios (i.e., plausible futures based on ‘what if’ propositions) to assess the impact of different development and management options. This model is considered to be unique because it is developed based on mass balance hydrologic routing equations, hydropower, discharges, and head relationships with special conditions relating to the nature of the location and the special complicated nature of the problem since the storage volume can reach up to 162 BCM yr\(^{-1}\) with a length of about 500 km and the existence of many types of outflows (point and non-point outflows) at different locations. The conceptual presentation of the modeling subsystem is shown in Figure 5.

Input module

Inflow – Historical data were considered for water inflow discharge input. These historical data are measured at Dongla gauging station (750 km U.S. HAD) from 1971 to 2001 (NRI 2010). These data are used as input to the simulation model as shown in Figure 6.

Sudan Abstraction – According to an agreement with Egypt signed in 1959, Sudan’s share of the water available from the Nile is 18.5 BCM yr\(^{-1}\). This allocation is based on an average natural inflow into the reservoir of 84 BCM yr\(^{-1}\) (period 1900–1959) and an estimated 10 BCM yr\(^{-1}\) of reservoir losses. However, the actual use of Nile water by Sudan during the past period was about 14.5 BCM yr\(^{-1}\) (NWRP 2005). This module is based on the historical data available for Sudan abstraction during different conditions (Abdel-Latif & Mansour 2011). So we will include Sudan intake in our model from Table 1.

El-Sheikh Zayed Canal – El-Sheikh Zayed Canal conveys water discharge from Lake Nasser to the newly cultivated lands in the national project of El-Sheikh Zayed, constructed 1998/1999. The huge pump station (on Lake Nasser left bank) is used to elevate water from Lake Nasser to the El-Sheikh Zayed Canal. The station has been designed to have a maximum static lifting of about 52.5 m to ensure its operation when the water level in Lake Nasser reaches its lowest level of storage, which is 147 m above (MASL). The designed maximum discharge of the pumping station was estimated to be about 300 m\(^3\) s\(^{-1}\) (25 million m\(^3\) d\(^{-1}\)). The expected annual water discharges from the lake into the canal are estimated to be 5 BCM (El-Sammany 2002). The canal has a length of 60 km, bed width of 30 m, side slopes with 2:1 gradient and is lined to prevent seepage from the canal. Table 2 presents the monthly intake of this project if it operates to its full capacity.
Figure 5 | Aswan High Dam Reservoir management modeling subsystem.

Figure 6 | The annual water inflow of the historical data at Aswan 1971–2010.

Table 1 | Sudan’s monthly discharge

<table>
<thead>
<tr>
<th>Month</th>
<th>Aug</th>
<th>Sep</th>
<th>Oct</th>
<th>Nov</th>
<th>Dec</th>
<th>Jan</th>
<th>Feb</th>
<th>Mar</th>
<th>Apr</th>
<th>May</th>
<th>Jun</th>
<th>Jul</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sudan FLOW (BCM)</td>
<td>1.81</td>
<td>2.01</td>
<td>2.62</td>
<td>2.18</td>
<td>2.03</td>
<td>1.67</td>
<td>1.11</td>
<td>1.03</td>
<td>0.69</td>
<td>0.69</td>
<td>0.97</td>
<td>1.67</td>
<td>18.5</td>
</tr>
</tbody>
</table>
Operation rules restriction module

This module monitors both the upstream water level and the outflow downstream dam. The task of this module is to ensure that the maximum water level upstream of the dam is not exceeding the maximum limit during any time step and, also, to avoid increasing of the outflow discharge downstream of the dam higher than the safe limits if possible. Lake Nasser operation policies were determined by the Ministry of Water Resources and Irrigation (MWRI) according to different restrictions to ensure dam safety and suitable water management. These restrictions can be summarized as follows:

1. Maximum water level upstream of the AHD should not exceed 182.00 m at any time.
2. The released discharge downstream of the dam should not exceed the safe discharges to avoid damage to the river bed, banks and hydraulic structures.
3. The water level at the beginning of the water year (August 1) should be kept, if possible, at 175 m to account for coming floods. Any water in excess of this discharge program is evenly distributed in the months with the lower water requirements in such a way that the peak monthly discharges during the peak summer months remain unchanged. The months with the lowest requirements receive a greater volume of the excess water in order that all months in which any additional water is spilled have the same total discharge.
4. Daily and monthly water released should be compatible with water requirements. The monthly discharges from the AHD follow a fixed pattern of releases.
5. The simulation model uses the sliding scale for reduction which the MWRI suggested for coping with a series of low floods. The reductions in withdrawals should come into being if the reservoir content in the live storage zone was less than 60 BCM on July 31. It is worth noting that if there are successive high floods and the water level in the lake exceeds 178 m, the excess water is diverted to a free spillway and then to Toshka depressions. In more emergency cases, when the flood capacity exceeds the Toshka spillway capacity, the West Bank spillway operates to ensure that the upstream reservoir elevation does not exceed 183 m. When the level is not higher than 182 m, the water will be stored in the Toshka depression with a maximum discharge of 250 million m³ d⁻¹ (Sadek 2002).

Simulation submodule

The AHDR simulation model has been conceptualized and should perform the following operations:

1. Prepare the input data, which should include the inflow, initial storage, evaporation, and water demands, beside the operation rules of the reservoir. The initial storage of the reservoir for the first month of the operation period was assumed. The inflow at Dongola is discounted by the losses and abstractions from Sudan and El-Sheikh Zayed Canal on a monthly basis.
2. The demand will be calculated on a monthly basis based upon the monthly irrigation water requirements and should be neither more than the maximum nor less than the minimum permissible flow of the river.
3. The difference between the inflow and the demand will be calculated in order to obtain the new stored volume (with reference to the volume of the previous month), on a monthly basis.
4. Based on this new stored volume, the new surface area of the lake and the new water elevation upstream of the dam will be calculated (monthly average), based on the available historical series of data and/or formulas presently used by the Nile Sector. The resulting storage should be within the operation rules range and be neither more than the design operation storage nor less than the minimum operation storage of the reservoir. If it exceeds the rule, then the computed storage and water level are readjusted through readjusting the release.
5. The calculation of evaporation losses and seepage losses will be operated based on the surface area and the water level.
level (monthly average), based again on available historical data and/or formulas used by the Nile Sector. The calculation of flow to Toshka spillway and Aswan spill was calculated based on operation rules restrictions.

6. Calculate the outflow from the power generating outlets, \( Q_p \), which should not exceed the capacity of the power outlets. The minimum operation level represents the minimum level for operating the power generators.

7. Repeat the respective steps for the following months.

The operation of a reservoir is described by the water balance equation under various constraints concerning storage volume, outflow from the reservoir and water losses. The water balance equation applied on a monthly basis has the following form:

\[
\frac{dS(t)}{dt} = \sum_{j=1}^{n_i} Q_{\text{in},j} - \sum_{j=1}^{n_o} Q_{\text{out},j} \tag{1}
\]

\[
S(t + dt) = S_t + I_t - R_t - L_{\text{evp}} - L_{\text{seep}} - L_{\text{abs}} - Q_{\text{out}} - Q_{\text{emg}} - Q_{\text{southvalley}} \tag{2}
\]

where \( S(t + dt) \): storage at time \( (t + dt) \) \((m^3)\); \( S_t \): storage at time \( t \) \((m^3)\); \( I_t \): mean inflow to the storage in month \( t \) \((m^3)\); \( R_t \): water discharged from the storage in month \( t \) downstream the dam \((m^3)\); \( L_{\text{evp}} \): mean mean storage evaporation from the storage reservoir in month \( t \) \((m^3)\); \( L_{\text{seep}} \): seepage losses from the storage reservoir in month \( t \) \((m^3)\); \( L_{\text{abs}} \): bank storage absorption losses \((m^3)\); \( Q_{\text{out}} \): water released from Toshka spillway in month \( t \) \((m^3)\); \( Q_{\text{emg}} \): water released from the emergency spillway in the dam in month \( t \) \((m^3)\); \( Q_{\text{southvalley}} \): the water demand for (South Valley) in month \( t \) \((m^3)\).

Volume elevation (million \( m^3 \), \( m \)) empirical relation is given by:

\[
H = 79.9734 + 0.0369801V + 8.87056\ln(V) \tag{3}
\]

\[
A = -3, 164.28 + 25.4914V + 1, 092.92\ln(V) \tag{4}
\]

The constraint concerning storage volume \( V_t \) is:

\[ V_{\text{min}} < V_t < V_{\text{max}} \]

where \( V_{\text{min}} \) = dead storage volume = 31.60 BCM corresponding to the minimum power pool level (147 m); and \( V_{\text{max}} \) = maximum storage volume = 162.30 BCM corresponding to the maximum power pool level (182 m).

The mean monthly outflow discharge \( Q_t \) during month \( t \) must satisfy the constraint:

\[ Q_{\text{min}} < Q_t < Q_{\text{max}} \]

where \( Q_{\text{min}} \) = minimum releases = 3.2 BCM \( \text{yr}^{-1} \); and \( Q_{\text{max}} \) = Maximum releases = 7.5 BCM \( \text{yr}^{-1} \).

Output module

Hydropower module – The general equation which presents hydropower generation is a function of several factors such as discharge through the turbines, water head on turbines, the specific weight of water and the turbine’s efficiency. The general equation is given by Eshra (2009):

\[
P = \frac{\eta \gamma Q H}{1,000} \tag{5}
\]

where \( P \) = generated electric power output in \((\text{kW})\), \( Q \) = water flow through the turbine (Discharge) in, \( m^3 \text{ s}^{-1} \), \( H \) = net head of water in \( m \) (the difference in water level between upstream and turbine downstream), \( \eta \) = station (turbine & generator) efficiency factor, and \( \gamma \) = specific weight of water \((9,810 \text{ N m}^{-3})\).

Toshka and Aswan outflow computation module – The Toshka spillway (260 km upstream HAD) is in the Western desert, at the end of Toshka Khor with a width of 700 m and a crest level of 178 m constructed 1998/1999. The spillway is an un gated canal without a regulator. Excavation works started in 1978 and completed in 1982. It was constructed to release the excess water when water level reaches 178.00 m (MASL). The excess water is discharged to a natural depression located at the western side. This flow will help in limiting the outflow behind the dam to values ranging from 350 to 400 million \( m^3 \text{ d}^{-1} \) which are the discharge values that cause no harm to the Nile bed. The connecting canal from the spillway to the downstream depression area has an inlet width of 500 m and an outlet width of 275 m with a total length of 20.5 km. The outlet
weir of the canal has a crest level of 176.00 m and the canal slope is 14.6 cm km\(^{-1}\). The lowest level of the depression is 150 m (MASL) while the highest level is 190 m (MASL). The surface area of the depression is about 6,000 km\(^2\) and it can contain about 120 x 10\(^9\) m\(^3\) (Ismail & Aziz 2005). This module is based on the computations of the proposed project outflow hydrograph. The following equation for Toshka demands is used by Thompson (1981):

\[
Q = 19 \left(H - 178\right)^{3/4} \times 30.41,000 \quad \text{where } H > 178, \text{ otherwise } 0
\]

where \(Q\) = Toshka spill (BCM/month) and \(H\) = lake water level (m). Toshka spill cannot exceed 6 BCM/month. Aswan spill = max release if \(H > 182.6\) m or \(S > 162\) BCM.

**Losses computation module** – The major Lake Nasser losses are evaporation and seepage losses. They are both incorporated in the model by this module. The MWRI in Egypt for many years adopted the figure of 7.5 mm d\(^{-1}\) as the annual mean evaporation which corresponds to an evaporation rate of 2.70 m yr\(^{-1}\) (Whittington & Guariso 1983). A later review of previous literature data established a large range for evaporation from AHDR between 1.7 and 2.9 m yr\(^{-1}\). Based on water balance, energy budget and modeling techniques, a narrower range of 2.1-2.6 m yr\(^{-1}\), with an average of 2.35 m yr\(^{-1}\), was calculated by Sadek et al. (1997). In a 2002 technical report, based on the available data at the Nile Forecasting Center in Cairo, it was estimated that the annual evaporation from the AHDR varied between 12 and 12.6 BCM yr\(^{-1}\) which correspond to an evaporation rate of 2.0-2.1 m yr\(^{-1}\) (Delft Hydraulics 2002). Hassan et al. (2007) computed the evaporation losses from the reservoir and found that the yearly average of the daily evaporation rate is 6.33 mm d\(^{-1}\) and the average volume of the annual water lost by evaporation is about 12.5 BCM. In this simulation analysis, evaporation is calculated monthly as a function of the surface area of the AHDR and fixed monthly coefficients as in Table 3, and is calculated by the following equation (Mobasher & Ostrowski 2010):

\[
\text{Evaporation loss } L_{evp} = \left((A_t + A_{t-1})/2\right)C_t \times 1,000
\]

where \(A_t\) = reservoir area at beginning of month \(t\) (km\(^2\)), \(A_{t-1}\) = reservoir area as at the end of month \(t\) (km\(^2\)), and \(C_t\) = evaporation coefficient pertaining to month \(t\) (mm).

For the seepage losses, the empirical regression functions for seepage losses and water levels used for this part are as follows (Eshra 2009):

\[
\text{Monthly seepage } S = 0.038 \left( H - 110 \right)
\]

where \(S\) = the flow in BCM/month to the ground water in Lake Nasser, and \(H\) = the storage level in meters.

**Outflow hydrograph generation module** – The proposed outflow hydrograph downstream the AHD is computed using this module. The module computations are based on the water requirements for different months, the restrictions of the allowable maximum outflow downstream of the dam, and the maximum allowed water levels upstream of the dam. So the basic outflow hydrograph is composed from the historical data and water demand and water discharges and levels restrictions. Over the 30 years of simulation, releases, reservoir elevations, power generation and spills are tabulated on both a monthly and annual basis.

**Optimization module**

This consists of the specification of a pre-defined algorithm, described for example, by a set of ‘if-then’ rules or a decision matrix. These determine which control actions are to be taken for each of the possible states of the system. To find an appropriate set of rules, often a trial-and-error procedure is applied, supported by appropriate simulation tools (Schutze et al. 2002). Besides computational efficiency, this approach also has the advantage of greater clarity in the decision-finding procedure.

A scenario analysis tool has been embedded into a DSS that allows a choice of the best scenario between some

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</tr>
</thead>
<tbody>
<tr>
<td>Evap (m)</td>
<td>0.18</td>
<td>0.14</td>
<td>0.11</td>
<td>0.15</td>
<td>0.19</td>
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<td>0.5</td>
<td>0.32</td>
<td>0.3</td>
<td>0.27</td>
<td>0.22</td>
<td>2.70</td>
</tr>
</tbody>
</table>
defined possible scenarios for reservoir operation rules modification for adaptation to climate change. The controlled releases at the AHD give primary consideration to two objectives: meeting downstream irrigation demands and 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. The objective function utilized in this work takes the form:

\[ L_t = \sum_{t=1}^{N} \left( \left( \frac{R_t - T_t^1}{T_t^1} \right)^2 + \left( \frac{T_{E_t} - G_t}{G_t^2} \right)^2 \right) \]  

where \( L_t \) = losses incurred from irrigation deficits and power generation deficits during time periods \( t \) (\( t = 1, 2, \ldots, 12 \)), \( R_t \) = release (BCM), \( T_t^1 \) = irrigation target for time period \( t \) (BCM), \( T_{E_t} \) = energy target for time period \( t \) (10^3 GWH/month) and \( G_t^2 \) = energy generated for time period \( t \) (10^5 GWH/month).

The suggested new operation rules for optimum operation are based upon reductions in agricultural water use and crop pattern changes during droughts, or application of a rising scale to handle the large number of reservoir excess releases due to high floods.

**The interactive process and the user interface subsystem**

The AHD RMS interface was designed using the Visual Basic programming language. It was designed to be used interactively through message boxes that pop up according to user clicks. Initially, the user enters the database including the reservoir operation rules, irrigation requirements, power requirements and the monthly evaporation rates. Second, the user clicks on simulation to run the model and to choose the optimum operation rule. The calculated reservoir storage, water level, release, hydropower and evaporation are shown in tables and graphically as shown in Figures 7 and 8.
Suggested scenarios

The climate change scenarios generated by Beyene’s study (Beyene et al. 2007) will be used as a multiplier to the historical natural series (1971–2001) to the model for simulating future inflows to the reservoir. First, the future hydrologic scenarios developed have been used to assess the expected impacts to potential climate change and basin development scenarios. The operation policies which were determined by the MWRI were used for the scenarios analysis in the simulation model of the AHDR. Second, the proposed operation rules were used to control these impacts for optimum operation of the reservoir in the case of climate change to satisfy the preset objective function of minimum irrigation deficit and maximum power production. Finally, the effect of the Millennium Dam will be included in this scenario in addition to climate change. The assessment results are summarized relative to the following criteria: water supply releases; reservoir level variations; hydropower production; and evaporation losses.

MODEL RESULTS AND ANALYSIS

Model calibration

The developed model was calibrated using actual measurements. The calibration was performed to study the effect of numerical approximation on model results. The calibration is also required to determine the accuracy of losses, seepage and evaporation estimations. All months through years from 1971 to 2001 were measured and calculated, and were used for calibration. Figure 9 shows the calibration result for these years. It can be concluded that the calibration process for water levels upstream of the AHD show close relationships between the model computed results and the actual readings.
For different years the maximum difference between computed and measured water levels did not exceed 4 m or 2% error which is acceptable.

**Optimum operation rules versus historical operation**

By applying the model to 2 years of high flood period (1998–1999) and inspecting the difference in initial storage, final storage, hydropower, release and water level by applying the new operation rules. The objective to increase the hydropower and get use of the excess water surplus by using the new operation rule the hydropower increases to 5%. By applying the model to 10 year drought period (1979–1988) and inspecting the difference in initial storage, final storage, hydropower, release and water level by applying the new operation rules. The level of U.S. High Dam had dropped from 173.03 m in August 1979 to 150.62 m in July 1988, and about 72.8 BCM were taken from reservoir to fulfill the irrigation requirements. This amount represents almost 1.3% of the yearly consumption of Egypt, which is 55.5 BCM.

This emphasizes the need to apply new operation rules to the reservoir in order to cope with such drought periods. Therefore, by using the suggested new operation rules of the developed system, the level of U.S. High Dam had dropped from 173.03 m in August 1979 to 153 m in July 1988 and about to 68 BCM were taken from the reservoir to fulfill the irrigation requirements and is less compared with the case of applying the traditional operation rules of the reservoir.

**Future scenarios for reservoir operation**

The future hydrologic scenarios developed have been used to assess the expected impacts of potential climate change (baseline and three periods with two global emission scenarios A2 (B1)) and Millennium Dam effect. The new operation rules suggested were used for the scenarios analysis in the simulation model of the AHDR.

The following sections are an executive summary of the assessment results. The presentation focuses on annual average quantities including water supply releases, reservoir level variations, hydropower production and evaporation losses in the four different scenarios:

Scenario 1 – climate change without the Millennium Dam effect with current operation rules;
Scenario 2 – climate change without the Millennium Dam effect with new operation rules;
Scenario 3 – climate change with the Millennium Dam effect with new operation rules;
Scenario 4 – climate change with the Millennium Dam effect with new operation rules.
Effect on level variations

Tables 4, 5, 6 and 7 represent a summary characterization of variation in the reservoir level, this analysis represents the water level limits and corresponding percentage of occurrence for all climate scenarios.

Without the Millennium Dam, the percentage of occurrence of water level greater than the highest level of the AHDR occurring only in period I (2010–2039) for the two global emission scenarios, A2 and B1, are 3.5 and 6.1%, respectively, compared with the baseline percentage 5.7%. In case of the new operation rules, the percentage of occurrence of water level greater than the highest level of the AHDR occurring only in period I (2010–2039) for the two global emission scenarios are 3.2 and 5.6%, respectively, compared with the baseline percentage 5.2%. This means the application of the new operation rules reduce the percentage of occurrence of highest level of the AHDR which is very beneficial in high flood periods.

Without the Millennium Dam, the percentage of occurrence of water level lower than the minimum level from the AHDR for period II (2040–2069), and period III (2070–2099) for the two global emission scenarios A2(B1) are 14.4% (16.7%) and 29.3% (24.2%), respectively. In the case of the new operation rules the percentage of occurrence of water level lower than the minimum level from the AHDR for period II (2040–2069) is 14% for global emission scenario A1, and for period III (2070–2099) with the two global emission scenarios, A2 and B1, are 27.9 and 21.7%, respectively. This means the application of new operation rules reduce the percentage of occurrence of lowest level of the AHDR which is very beneficial in low flood periods.

With the Millennium Dam, the percentages of occurrence of water level lower than the minimum level from the AHDR for the three periods (period I (2010–2039), period II (2040–2069), and period III (2070–2099)) and the two global emission scenarios A2(B1) are 9.9% (0), 13.9% (0) and 62.6% (44.7%), respectively, compared with the baseline percentage 4%. This means the building of the Millennium Dam increases the percentage of occurrence

Table 4 | Level variation characteristics in the AHDR in the case of current operation rules without the Millennium Dam

<table>
<thead>
<tr>
<th>Level</th>
<th>Baseline</th>
<th>2010-2039</th>
<th>2040-2069</th>
<th>2070-2099</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>%</td>
<td>%</td>
<td>%</td>
<td>%</td>
</tr>
<tr>
<td>&gt;181</td>
<td>5.7</td>
<td>3.5</td>
<td>6.1</td>
<td>0</td>
</tr>
<tr>
<td>&gt;178</td>
<td>13.5</td>
<td>19.9</td>
<td>30.6</td>
<td>2.5</td>
</tr>
<tr>
<td>&gt;175</td>
<td>26.2</td>
<td>44.4</td>
<td>52.2</td>
<td>4.7</td>
</tr>
<tr>
<td>&gt;160</td>
<td>95.6</td>
<td>99.5</td>
<td>100</td>
<td>53.3</td>
</tr>
<tr>
<td>&lt;150</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>14.4</td>
</tr>
</tbody>
</table>

Table 5 | Level variation characteristics in the AHDR in the case of new operation rules without the Millennium Dam

<table>
<thead>
<tr>
<th>Level</th>
<th>Baseline</th>
<th>2010-2039</th>
<th>2040-2069</th>
<th>2070-2099</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>%</td>
<td>%</td>
<td>%</td>
<td>%</td>
</tr>
<tr>
<td>&gt;181</td>
<td>5.2</td>
<td>3.2</td>
<td>5.6</td>
<td>0</td>
</tr>
<tr>
<td>&gt;178</td>
<td>15.9</td>
<td>19.9</td>
<td>30.3</td>
<td>2.5</td>
</tr>
<tr>
<td>&gt;175</td>
<td>25.9</td>
<td>44.6</td>
<td>55.8</td>
<td>5.3</td>
</tr>
<tr>
<td>&gt;160</td>
<td>99.2</td>
<td>99.5</td>
<td>100</td>
<td>54.9</td>
</tr>
<tr>
<td>&lt;150</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>14</td>
</tr>
</tbody>
</table>

Table 6 | Level variation characteristics in the AHDR in the case of current operation rules with the Millennium Dam

<table>
<thead>
<tr>
<th>Level</th>
<th>Baseline</th>
<th>2010-2039</th>
<th>2040-2069</th>
<th>2070-2099</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>%</td>
<td>%</td>
<td>%</td>
<td>%</td>
</tr>
<tr>
<td>&gt;181</td>
<td>0</td>
<td>12.5</td>
<td>3.1</td>
<td>12.5</td>
</tr>
<tr>
<td>&gt;178</td>
<td>0</td>
<td>6.5</td>
<td>33.1</td>
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<td>&gt;175</td>
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<td>4</td>
<td>9.9</td>
<td>0</td>
<td>13.9</td>
</tr>
</tbody>
</table>

Table 7 | Level variation characteristics in the AHDR in the case of new operation rules with the Millennium Dam

<table>
<thead>
<tr>
<th>Level</th>
<th>Baseline</th>
<th>2010-2039</th>
<th>2040-2069</th>
<th>2070-2099</th>
</tr>
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<tbody>
<tr>
<td></td>
<td>%</td>
<td>%</td>
<td>%</td>
<td>%</td>
</tr>
<tr>
<td>&gt;181</td>
<td>0</td>
<td>0</td>
<td>12.5</td>
<td>3.1</td>
</tr>
<tr>
<td>&gt;178</td>
<td>0</td>
<td>8.1</td>
<td>33.6</td>
<td>14.5</td>
</tr>
<tr>
<td>&gt;175</td>
<td>0.8</td>
<td>20.2</td>
<td>54.2</td>
<td>23.4</td>
</tr>
<tr>
<td>&gt;160</td>
<td>83.6</td>
<td>62.4</td>
<td>100</td>
<td>61.8</td>
</tr>
<tr>
<td>&lt;150</td>
<td>1.9</td>
<td>9.7</td>
<td>0</td>
<td>10</td>
</tr>
</tbody>
</table>
of lowest level of the AHDR which is very critical in dam operation. In the case of the new operation rules, the percentage of occurrence of water level lower than the minimum level from the AHDR for the three periods (period I (2010–2039), period II (2040–2069), and period III (2070–2099)) and the two global emission scenarios A2(B1) are 9.7% (0), 10% (0) and 49.4% (31.67%), respectively, compared with the baseline percentage 1.9% which is better than with current operation rules.

**Effect on release variations**

Figure 10 shows the Predicted Mean Annual Release from AHDR in the four cases. In general without the Millennium Dam, the mean annual withdrawals from the AHDR for the three periods (period I (2010–2039), period II (2040–2069), and period III (2070–2099)) and two global emission scenarios A2(B1) are 54.8 (55), 47.4 (48) and 43.4 (44.7) BCM, respectively, compared with the baseline release of 53.5 BCM. Egypt’s average annual withdrawal from the AHDR is expected to increase due to climate change by 1.30 BCM early in the 21st century (2010–2039). However, Egypt might suffer significant shortfalls relative to historical average releases from the AHDR reaches of 7 and 10 BCM by mid (2040–2069) and late (2070–2099) century, respectively.

In the case of the new operation rules, the mean annual withdrawals from the AHDR for the three periods (period I (2010–2039), period II (2040–2069), and period III (2070–2099)) and two global emission scenarios A2(B1) are 53.9 (54.8), 46 (46.7) and 42.7 (44.1) BCM, respectively, compared with the baseline release of 52.5 BCM. Egypt’s average annual withdrawal from the AHDR is expected to increase due to climate change by 1.30 BCM early in the 21st century (2010–2039). Therefore, the application of new operation rules causes a slight improvement in water release.

With the Millennium Dam, the mean annual withdrawals from the AHDR for the three periods (period I (2010–2039), period II (2040–2069), and period III (2070–2099)) and two global emission scenarios A2(B1) are 49.8 (47.9), 46 (49.6) and 42 (44.9) BCM, respectively, compared with the baseline release of 50.4 BCM. Egypt might suffer shortfalls relative to historical average releases from the AHDR reaches of 4 and 8 BCM by mid (2040–2069) and late (2070–2099) century, respectively.

In the case of the new operation rules, in general with the Millennium Dam, the mean annual withdrawals from the AHDR for the three periods (period I (2010–2039), period II (2040–2069), and period III (2070–2099)) and two global emission scenarios A2(B1) are 47.9 (55.3), 44.96 (48) and 41 (43.7) BCM, respectively, compared with the baseline release of 48.9 BCM. Therefore, the application of the new operation rules causes improvement in water release from the AHDR.

![Figure 10](https://iwaponline.com/jh/article-pdf/15/4/1491/387205/1491.pdf) | Predicted mean annual release from AHDR.
Effect on evaporation variations

Without the Millennium Dam, the mean annual evaporation losses from the AHDR for the three periods (period I (2010–2039), period II (2040–2069), and period III (2070–2099)) and two global emission scenarios A2(B1) are 12.2 (13), 7.2 (7.5) and 5.1 (5.7) BCM, respectively, compared with the baseline release of 9.8 BCM. In the case of the new operation rules, the mean annual withdrawal from the AHDR for the three periods (period I (2010–2039), period II (2040–2069), and period III (2070–2099)) and two global emission scenarios A2(B1) are 12.3 (13), 7.3 (7.9) and 5.2 (6.3) BCM, respectively, compared with the baseline release of 9.8 BCM (Figure 11).

With the Millennium Dam, the mean annual evaporation losses from the AHDR for the three periods (period I (2010–2039), period II (2040–2069), and period III (2070–2099)) and two global emission scenarios A2(B1) are 14 (16.5), 11.5 (15.5) and 7.3 (10.7) BCM, respectively, compared with the baseline release of 8.4 BCM. In the case of the new operation rules, the mean annual withdrawal from the AHDR for the three periods (period I (2010–2039), period II (2040–2069), and period III (2070–2099)) and two global emission scenarios A2(B1) are 8.4 (13.2), 6.7 (8.8) and 3.6 (4.9) BCM, respectively, compared with the baseline release of 8.9 BCM (Figure 11).

Effect on hydropower variations

Without the Millennium Dam, the mean annual hydropower generated from the AHDR for the three periods (period I (2010–2039), period II (2040–2069), and period III (2070–2099)) and two global emission scenarios A2(B1) are 9,614 (9,875.8), 6,501 (6,773.6) and 5,094.5 (5,553.8) GWh, respectively, compared with the baseline release of 8,842 GWh. It means Egypt will suffer from a 26.5% (23.4%) decrease in power generated during period II (2040–2069), and a 42.3% (37.2%) decrease in period III (2070–2099) and a 8.74% (11.7%) increase in period I.

In the case of the new operation rules, the mean annual hydropower generated from the AHDR for the three periods (period I (2010–2039), period II (2040–2069), and period III (2070–2099)) and the two global emission scenarios A2(B1) are 7,380.5 (10,003.2), 6,257.7 (7,416.4) and 4,135.3 (5,192.4) GWh, respectively, compared with the baseline release of 8,914 GWh. It means Egypt will suffer from a 27.9% (24.5%) decrease in power generated during period II (2040–2069), and from a 44.2% (36.3%) decrease in power generated period III (2070–2099) and from a 6.6% (11%) increase in power generated in period I.

With the Millennium Dam, the mean annual hydropower generated from the AHDR for the three periods (period I (2010–2039), period II (2040–2069), and period III (2070–2099)) and the two global emission scenarios A2(B1) are 7,380.5 (10,003.2), 6,257.7 (7,416.4) and 4,135.3 (5,192.8) GWh, respectively, compared to the baseline release of 7,521.7 GWh. It means Egypt will suffer from a 16.8% (32.9%) decrease in power generated during period II (2040–2069), and a 45.2% (30.9%) decrease in period III (2070–2099) and a 1.9% (32.9%) increase in period I.
In the case of the new operation rules, the mean annual withdrawal from the AHDR for the three periods (period I (2010–2039), period II (2040–2069), and period III (2070–2099)) and the two global emission scenarios A2(B1) are 7,175.8 (10,110.1), 6,095.1 (7,362) and 4,199.5 (5,624.5) GWh, respectively, compared with the baseline release of 7,517.9 GWh (Figure 12). It means that Egypt will suffer from a 18.9% (2%) decrease in power generated during period II (2040–2069), and 44% (25%) decrease in power generated during period III (2070–2099) and 4.6% (34.5%) increase in power generated during period I.

**CONCLUSION**

This paper introduces a user-friendly DSS for reservoir management, which was shown to yield accurate operating rules for the AHDR, integrates the various model components effectively, and provides a reliable and user-friendly decision aid. The major contribution of our flexible AHDRMS is that it enables a scenario analysis that captures the decision maker’s judgments, facilitating a flexible decision process. Depending on the decision situation and expertise available, it is possible to use simple simulation methods, as we did in our application, or sophisticated optimization methods. The participation in the decision process is not limited to reservoir operators, and many parties – such as administrators and politicians – can be involved in the decision making process as well. The future hydrologic scenarios developed have been used to assess the expected impacts to potential climate change and Millennium Dam development scenarios. The operation policies which were determined by the MWRI were used for the scenarios analysis in the simulation model of the developed AHDR Management Model.

In the simulation experiment, it can be concluded that overall applying the new operation rules will decrease the percentage of occurrence of minimum water levels. Also, the Millennium Dam will increase the percentage of occurrence of minimum water levels. In addition, the period III (2070–2099) with the two global emission scenarios A2 (B1) is very critical for the dam operation as there is the highest percentage of decrease of water level below the minimum level, as well as the highest decrease in water release, evaporation losses and hydropower generated. Also, in the case of global emission (B1 for periods I and II), there is an increase in water release, evaporation losses and hydropower generated compared with the baseline. Hence, our basic AHDR Management Model can be generalized to a wider class of reservoir management problems.
As climate change in coordination with water conservation projects can impact on Nile water availability, the assessments carried out demonstrate that management models are necessary to assess the potential benefits of future development and management strategies that might mitigate adverse effects. The developed AHDRMS has produced meaningful results that can now be incorporated in water management and policy-making considerations. It is hoped that the results of these assessments will lead to be more informed AHDR strategies for future development, adaptive management, and risk assessment. The results from this study would provide an objective basis for decision makers to weight scenario outcomes.

REFERENCES

Dow, K. 2005 Vulnerability Profile of West Africa. Poverty and Vulnerability Programme, Stockholm Environment Institute (SEI), UK.
El-Sammany, M. S. 2002 Design of Lake Nasser Environmental Monitoring System. Faculty of Engineering, Cairo University, Egypt.


NRI 2010 Nile Research Institute Database. Nile Research Institute, NWRC, Cairo, Egypt.


Sadek, N. S. 2002 Lake Nasser Flood Analysis. Ph.D. Thesis, Irrigation and Hydraulics Department, Faculty of Engineering, Ain Shams University, Cairo, Egypt.


World Bank 2006b Implementation Completion Report (# 35573) for Energy II project. World Bank, Washington, DC.


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