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*Research Article*

# A Water Management Model for Toshka Depression

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Toshka Depression (TD), located about 250 km south west of the High Aswan Dam (HAD), consists of four deep-cut basins connected by natural sills. It is required to assess the contribution of TD as a spillway, in enhancing the effectiveness of Lake Nasser in flood control and water availability. However, most related previous works are descriptive and use qualitative methods. In order to provide the required assessment quantitatively, we developed a numerical model which computes TD mass balance and interbasin water movements. The model computes the variation of water volume, surface area, and water level in each one of the four basins (subdepressions), thus depicting their filling sequence, for the past 130 years. This TD response to realistic time series of water inflow gains and evaporation losses is analyzed to compute the TD overflow time series. This response helps assess water availability for agricultural use and effectiveness in alleviating flood risks. Furthermore, the developed model compares between three TD configurations to help the decision maker and recommends (i) building a dam—height 10 m—at the end of the fourth subdepression near Kharga Oasis and/or (ii) incorporating the third subdepression into TD by digging a canal through the hill that blocks it from the first subdepression.

## 1. Introduction

Lake Nasser is the huge lake formed after the construction of HAD for the purposes of flood control and water storage. To avoid flood damages, control imposed two requirements on Lake Nasser operation rules [1]: (a) the maximum allowed water discharge should not exceed 0.25–0.30 billion cubic meter (BCM) per day and (b) water levels upstream HAD should be kept at 175 m on August 1st, the beginning of the flood season.

However, during the years 1996–2000, water levels in Lake Nasser reservoir reached high values: 178.54 m (in November 1996) and 181.19 m (in November 1998). Furthermore, studies predicted that a flow rate of more than 0.26 BCM/day may create serious degradation of the Nile bed [2]. It also may endanger the stability of the river banks and the safety of structures like bridge piers, weirs, barrages, and other structures. Most of these structures were built in the low-discharge flood plain to avoid possible structural damage in cases of high water discharge.

Water was spilled to the TD to avoid releasing high discharges of water to the River Nile.

TD is located about 250 km south of HAD and consists of four deep-cut basins or subdepressions, interconnected by natural sills. The High Dam Authority has labeled these basins 1, 2, 3, and 4. Satellite images of TD after floods showed the filling sequence between August 1998 and March 1999: basin 1 is filled first and then basin 2. However, the flood of years 1999–2002 filled basin (reservoir) 4 in addition to reservoirs 1 and 2 (see Figure 1). Amount of water spilled to TD can be seen in Table 1 as seen in [2].

Therefore, TD proved to be a significant factor in alleviating these high floods since a total of 41.0 BCM were diverted into it.

However, satellite images showed these stored water in TD lakes was subject to considerable losses due to evaporation [3, 4]. In order to estimate these water losses, El Bastawesy et al. [3] integrated remote sensing and GIS techniques to process collected images and estimated the aerial extended shrinkage of TD lakes between years 2002 and 2006. El Bastawesy et al. [3] made a spatial analysis of TD bathymetry and showed a water loss rate of 2.50 m per year, and the lakes stored around 25.26 BCM of water in 2002. But in 2006 the stored water was greatly reduced to 12.57 BCM.

Table 1: TD conditions during the flood period 1996–2002.

| Flood year | Amount spilled to TD | Reservoir filled |
|---|---|---|
| 1996-1997 | 0.10 BCM | Reservoir 1 |
| 1998-1999 | 12.6 BCM | Reservoir 1 and 2 |
| 1999-2000 | 14.15 BCM | Reservoir 1, 2, and 4 |
| 2000-2001 | 8.6 BCM | Reservoir 1, 2, and 4 |
| 2001-2002 | 5.7 BCM | Reservoir 1, 2, and 4 |

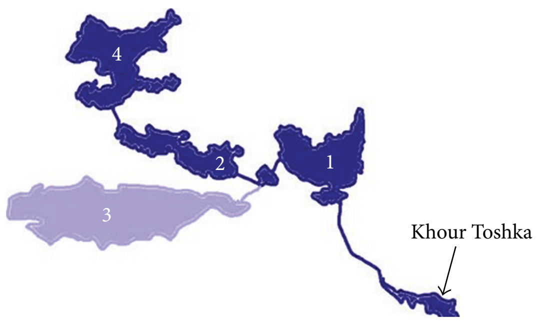


Figure 1: Toshka depression four subdepressions.

The sills between the subdepressions have changed in form and elevation due to water flushing from the Toshka canal to the first subdepression (Basin 1) and subsequently from it to the second and fourth subdepressions. These changeable sills' elevations affected the filling sequence of the TD basins.

Therefore, these interbasin sill levels should be considered as design parameters to be selected by decision makers to achieve required performance criteria. Each subdepression lake has only one inflow source determined by the filling sequence shown in Figure 2.

B1, B2, B3, and B4 refer to the subdepressions of TD labeled according to the HAD authority. However, B5 and B6 refer to regions outside the current Toshka depression with B5 referring to the undesirable Oasis Kharga and B6 referring to the desirable extension of the third TD subdepression.

It is required to develop a numerical simulation model for TD to quantify TD contribution to two management goals: flood control measures and water availability for agricultural use. Previous works that deal with real-time flood control systems, other than the HAD system, include Unver and Mays [5], Eichert and Pabst [6], and Can and Houck [7]. However, these works lack the essential quantitative assessment because they are descriptive and use qualitative estimates of TD contribution to management goals. Even the works that employ analyses of satellite images, such as El Bastawesy et al. [3] and Sparavigna [4], also lack the quantitative detailed simulation of the time-dependent variations of water levels, surface areas, and water volumes for the TD lakes and water movements between TD basins. These simulations are essential for the quantitative assessment of TD contribution.

Accordingly, the current Toshka depression simulation model (TDSM) is developed to provide detailed output numerical results that are essential for strategic decisions: (i) time series of overflow (excess water volumes that cannot be accommodated by TD) and (ii) time series of water levels and volumes in each one of the TD four subdepressions for quantitative assessment of water availability for agricultural use.

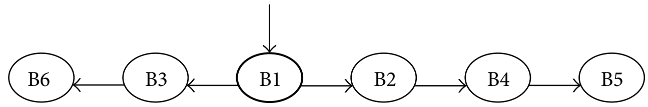


Figure 2: Schematic diagram for the filling sequence of TD.

In Section 2 we present TDSM assumptions and the definitions for the key associated terms, parameters, and variables. In Section 3 we present TDSM computational scheme and its structural submodels. In Section 4 the validation of TDSM is tested using a virtual time series for inflow gains. In Section 5, a realistic time series for both inflow gains and evaporation is presented. Also in Section 5, the TD response to these realistic time series' for the past 130 years for both inflow gains and evaporative losses is presented as a comparative study of three TD configurations. The predictive capabilities of TDSM are demonstrated in Section 6 (the filling sequence of TD basins during major flood periods) and Section 7 (the monthly water level variations during critical, drought and flood, periods). In Section 8, a conclusive summary of TDSM output results and recommendations for decision makers is presented.

## 2. TDSM Assumptions and Definitions

*2.1. Assumptions.* Because the geographic location of TD is in a hyperarid desert region, inflow gains due to rainfall may be neglected. Also, losses due to seepage or percolation may be neglected because the region bed is geologically composed of an impermeable 200 m thick layer of clayey rock.

*2.2. Definitions of Associated Terms.* In this section associated terms and notations are defined in order to distinguish between them.

(1) Basin-reservoir-lake:

Basin refers to an empty subdepression.

Reservoir refers to a filled subdepression.

Lake refers to a partially filled subdepression.

(2) Elevation-level-depth:

Elevation is the height above mean-sea-level of a basin location or a contour $Z = Z(x, y)$ of a basin, where $x$-$y$ plane refers to the TD horizontal plane.

Level is the height of water surface above mean-sea-level of the water surface in a lake $h = h(x, y, t)$.

Depth is the height of water surface above the basin local bottom $D = h - Z$.

(3) Sills-hills:

Sills are connections that allow overflow between the subdepressions. They are in the form of canals of small width (300–400 m). Their elevations are parameters. $S_{mn}$ is the elevation of the sill between $m$, $n$ basins.

Hills are connections that block overflow between the subdepressions, $H_{mn}$.

## 3. The Structure of TDSM and Its Computational Submodels

The model is built to simulate water availability, surface area, and surface level in the four basins comprising TD as time series. The inputs of the model are monthly averaged time series of inflow from HAD to basin 1 of TD and time series of evaporation rates. Elevations of the sills between basins are given parameters while the height of the dam to be built at the end of basin 4 and initial volumes, surface areas, and water levels in the four subdepressions are initial conditions for the models. It consists of two linked models:

(i) a level-area-volume model (LAVM),

(ii) a model of interreservoir water movements (MIWM),

where MIWM consists of three submodels. The interactive structure of SMTD and inputs are shown in Figure 3.

*3.1. The LAVM for the TD Four Basins.* The objective of this model is to transform the topographic data into digitized relationships for water surface level $h$, water surface area $A$, and water volume $V$ for the TD four basins:

$$A = A(h), \qquad V = V(h),$$
$$h = h(A), \qquad h = h(V). \tag{1}$$

The horizontal extents of each basin of the four subdepressions of TD are divided into a 20 m × 20 m grid cells, $\Delta x = \Delta y = 20$ m, where the elevation of each grid cell is available with 0.1 m accuracy; that is, $\Delta Z = 0.1$ m. The elevation contour 160 m is considered the outer boundary of the four basins comprising TD. The lower and upper limits of water surface level $h$ for each basin $Z_{\min}$ and $Z_{\max}$ are defined, and then the LAVM model is developed in two steps.

*First*, water surface area $A_i$ and water volume $V_i$ of a basin filled to level $h_i$ are calculated as follows:

$$A_i = \sum_{j=1}^{i} N_j P, \tag{2}$$

$$V_i = \Delta h A_i, \tag{3}$$

where

$$h_i = Z_{\min} + (i-1)\Delta h, \quad i = 1, 2, 3, \ldots, I, \tag{4}$$

$$I = 1 + \frac{(Z_{\max} - Z_{\min})}{\Delta h}, \tag{5}$$

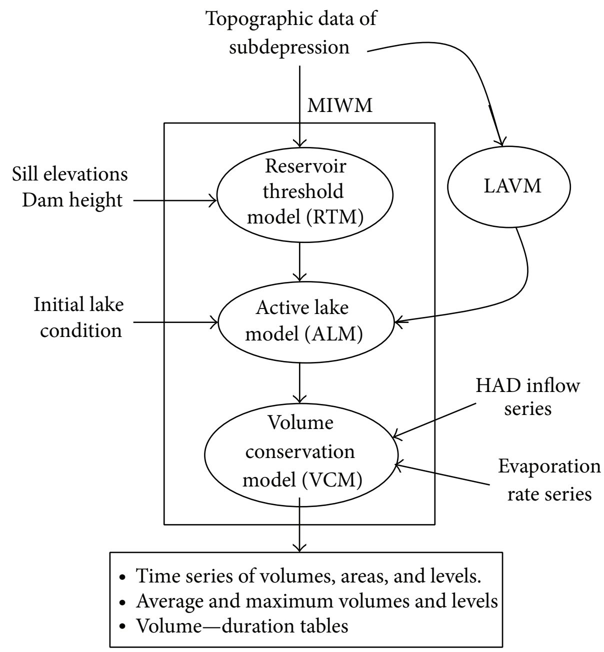


Figure 3: Interactive structure of the simulation model.

where $N_i$ is the number of wet cells, that is, cells that have elevations $Z_i$ such that $Z_i \le h_i$, $P$ = area of one cell = 20 m × 20 m = 0.0004 Km$^2$, and $\Delta h = 0.1$ m is the water level increment.

Then a database is created for TD which contains water level, surface area, and water volume for each subdepression with water level increment of 10 cm.

*Second*, seven mathematical functions are developed. Four of these functions are direct functions that use interpolation to get surface area and water volume of any basin for a given water level. These functions deal also with multibasin lakes where more than one basin works as one lake. The rule of combining volumes, areas, and levels of multibasin lakes is as follows.

For example when basins 1 and 2 work as one lake,

$$A_j^{12} = A_j^1 + A_j^2,$$
$$V_j^{12} = V_j^1 + V_j^2, \tag{6}$$
$$h_j^{12} = h_j^1 = h_j^2.$$

The remaining three functions are inverse ones where the water level corresponding to a given water volume is calculated. The multibasin lakes are also considered in these functions.

Figure 4 shows how water surface area (km$^2$) is related to water level for each basin while Figure 5 shows how water volume (BCM) is related to water level. The basins capacities of the four TD basins are shown in Table 2.

*3.2. The Model of Interreservoir Water Movements (MIWM).* The model is built to simulate water movement between the four basins comprising TD and the filling sequences.

Table 2: LAV output of basin capacities.

| Basin | Area ($km^2$) | Volume (BCM) | $Z_{max}$ (m) | $Z_{min}$ (m) |
|---|---|---|---|---|
| B1 | 609 | 11.69 | 160 | 122 |
| B2 | 747 | 11.5 | 160 | 109.5 |
| B3 | 384.7 | 4.93 | 160 | 125.1 |
| B4 | 1259.8 | 38.01 | 160 | 100 |

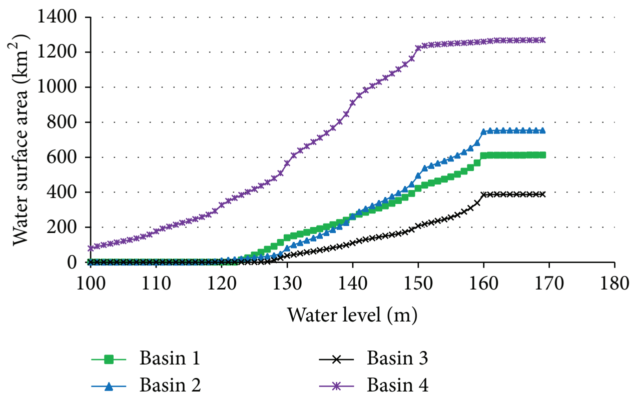


Figure 4: Topographic relation of water surface area versus water level.

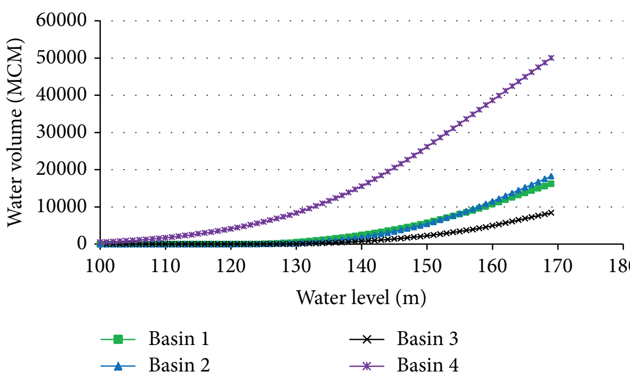


Figure 5: Topographic relation of water volume versus water level.

It consists of three submodels: volume conservation model (VCM), active lake model (ALM), and reservoir threshold model (RTM). The outputs of the model are time series of volumes and levels, maximum and average volumes and levels, and volume-duration tables.

*3.2.1. VCM and Mass Balance Equation.* The mass conservation equation for any of the TD subdepression lakes may be written in the following form, Zaki and Fassieh [8]:

$$\frac{dV}{dt} = I - E - Q, \tag{7}$$

where $dV/dt$ = time rate of change of lake volume, $I$ = volume inflow rate into the lake, $Q$ = volume outflow rate from the lake, and $E$ = volume evaporation rate from the lake.

The volume inflow $I$ has two possible sources:

(i) inflow from lake Nasser to basin 1,

(ii) overflow from an adjacent reservoir basin.

The volume outflow $Q$ can be an interreservoir as described in (ii), the outflow from basin 1 = inflow to basin 2, and so forth.

Volume evaporation rate can be written as

$$E = \alpha A, \tag{8}$$

where $\alpha$ is a time-dependent evaporation rate $\alpha = \alpha(t)$ (the decrease in the water level in TD lakes due to evaporation), given in units of m/10 day.

The available data on $\alpha$ is monthly averaged as obtained from HAD authority.

Since the time series of lake Nasser inflow and evaporation losses is given in 10 daily intervals, that is, $\Delta t = 10$ days, it is better to integrate the above equation over one time step assuming the quantities: $\alpha$, $I$, and $Q$ are quasi-steady during these 10 days.

Equation (7) will be

$$\begin{gathered} V(t) - V(0) = -\int \alpha A dt + \int I dt - \int Q dt, \\ V(\Delta t) - V(0) = -\alpha A(0)\Delta t + I(0)\Delta t - Q(0)\Delta t. \end{gathered} \tag{9}$$

In general the time domain of 130 years is divided into time steps whose number is

$$J = 4750 \text{ time steps}. \tag{10}$$

Equation (9) will read for the $m$th Lake

$$V_{j+1}^{m} = V_{j}^{m} + I_{j}^{m}\Delta t - \alpha_j A_j^m \Delta t - Q_j^m \Delta t, \tag{11}$$

where $m = 1, 2, 3,$ and $4$ is an index for the reservoir (lake) and $j = 0, 1, 2, \ldots, J$ is an index for the time series interval.

Considering all quantities in (11) as volumes, $\Delta t$ may be absorbed:

$$V_{j+1}^{m} = V_{j}^{m} + I_{j}^{m} - Q_{j}^{m} - \left(\Delta V_{\text{evap}}\right)_{j}^{m}, \tag{12}$$

where $(\Delta V_{\text{evap}})_j^m$ equals water volume lost by evaporation from the $m$th lake.

*3.2.2. Inflow Gains to Lakes.* Assuming quasi-steady flow, the overflow from a filled lake to an empty adjacent basin may be considered as an allocation of the inflow. Hence

$$I_j^m = T_j \delta_{ml}, \tag{13}$$

where $T_j$ is the HAD 10 daily series of fresh inflow of the water volume in BCM/10 days and $l$ is an index of the lake that is active in receiving this inflow. This active lake may receive the water volume gain either directly through the Toshka canal, like lake 1, or through an adjacent filled-up lake like lake 2:

$$\begin{gathered} \delta_{ml} = 1 \quad \text{if } m = l, \\ \delta_{ml} = 0 \quad \text{if } m \neq l. \end{gathered} \tag{14}$$

The Kronecker-delta $\delta_{ml}$ insures that one, and only one, lake gains water during the $j$th time step. The active lake submodel (ALM) is designed to determine the index $l$ for each time step $j$.

Now it is not correct to define lake as a partially filled subdepression because when two adjacent basins are filled, they act as one lake and are filled together under certain conditions. These possible lakes are ten as follows:

(i) single subdepression lake:

$$m = 1, 2, 3, 4,$$

(ii) two-subdepression lake:

$$m = 7 \text{ for 2 and 4,}$$
$$m = 8 \text{ for 1 and 2,}$$
$$m = 9 \text{ for 1 and 3,}$$

(iii) three-subdepression lake:

$$m = 10 \text{ for 1, 2 and 4,}$$
$$m = 11 \text{ for 3, 1 and 2,}$$

(iv) four-subdepression lake:

$$m = 12 \text{ for 1, 2, 3 and 4,}$$

(v) $m = 5$ is the outside basin of Oasis Kharga. $m = 6$ is the outside basin of subdepressions in the third subdepression beyond the closest portion to basin 1:

index for the considered lake $m = 1, 2, 3, \ldots, 12$,
index for the active lake $l = 1, 2, 3, \ldots, 12$,
index for the evaporating lake $k = 1, 2, 3$, and 4.

*3.2.3. Evaporation Losses from Lakes.* Water surface loses water to the atmosphere all the time. This loss occurs in all basins of TD all the days of the 130-year period of investigation. The average decrease of a lake volume per time step of 10 days is obtained by

$$\Delta V^{m}_{\text{evap}} = \alpha_j A^{m}_{j}, \tag{15}$$

where $\alpha_j$ is the average lowering of a lake surface level per 10 days.

To avoid counting evaporation losses twice for a particular lake, we restrict calculations on the single subdepression lakes: that is, $m = 1, 2, 3$, and 4.

This is accomplished by multiplying the evaporation loss term by kronecker-delta:

$$\left(\Delta V_{\text{evap}}\right)^{m}_{j} = \alpha_j A^{m}_{j} \delta_{mq}, \tag{16}$$

where $q$ is an index for the single-basin lakes $q = 1, 2, 3, 4$.

When two lakes combine and start filling together, the evaporation losses from their combined surface are simply the superposition of their individual losses. Now the full operating equation for mass conservation is obtained by substituting (13) and (15) into (12):

$$V^{m}_{j+1} = V^{m}_{j} + T_j \delta_{ml} - \alpha_j A^{m}_{j} \delta_{mq}. \tag{17}$$

*3.2.4. The Reservoir Threshold Model (RTM).* The objective of this model is to determine the threshold elevation of each lake, $L^m$. When water surface level reaches this threshold value, the lake is full and becomes a reservoir. Each lake has a threshold elevation, $L^m$ an outer boundary elevation that is equal to the minimum of the sill elevations that bound it.

These are given below:

$$L^1 = \min\left(S_{12}, S_{13}\right), \qquad L^2 = \min\left(S_{21}, S_{24}\right),$$
$$L^3 = \min\left(S_{31}, S_{36}\right), \qquad L^4 = \min\left(S_{42}, S_{45}\right), \tag{18}$$

where $S_{mn} = S_{nm}$ is the elevation of the sill between the $n$th basin and the $m$th basin.

When two lakes reach the same water level and start to be filled together as one lake, we give it the double index name; that is, $L^{mn} \equiv$ threshold of the combined lake composed of the $n$th and $m$th lakes filling together:

$$L^{24} = \min\left(S_{21}, S_{45}\right), \qquad L^{13} = \min\left(S_{12}, S_{36}\right),$$
$$L^{12} = \min\left(S_{13}, S_{24}\right) \tag{19}$$

For more than two lakes filling together

$$L^{124} = \min\left(S_{13}, S_{45}\right), \qquad L^{312} = \min\left(S_{36}, S_{24}\right),$$
$$L^{3124} = \min\left(S_{36}, S_{45}\right), \tag{20}$$

where $S_{45}$ = the elevation of the sill between the fourth subdepression and the Kharga Oasis with $D_h$, the added height of the proposed dam:

$$S_{45} = 150 + D_h, \tag{21}$$

where $0 \le D_h \le 20$ m.

*3.2.5. The Active-Lake Submodel (ALM).* The objective of this model is to determine the index $l$ of the lake that is ready to receive the inflow gain of the next time step, $j$.

Each subdepression lake has only one inflow source determined by the sequence.

(1) A one-basin lake is active in the beginning of the $j$th time step, that is, $m = l$ when two conditions are satisfied.

(a) Its current water level is smaller than its threshold elevation $h^{l}_{j} < L^{l}$.

(b) Its input lake source is filled; that is, it becomes a reservoir $h^{k}_{j} = L^{k}$.

For example, B2 is active when $h^{2}_{j} < L^{2}$ and $h^{l}_{j} = L^{l}$.

(2) A Combined two-basin lake is active (lake $l$ is composed of the combination of the $m$th and $n$th lakes) when three conditions are satisfied.

(a) They reach a common level, $h^{m}_{j} = h^{n}_{j} = h^{mn}_{j}$.

(b) The common level exceeds their intersill elevation but is still smaller than the two-basin lake threshold, $L^{mn} > h^{mn}_{j} \ge S_{mn}$.

(c) Their inflow source becomes a reservoir $h^{k}_{j} = L^{k}$.

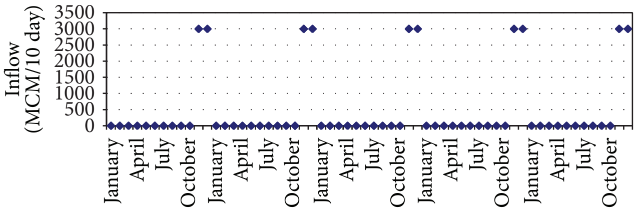


Figure 6: Virtual inflow time series.

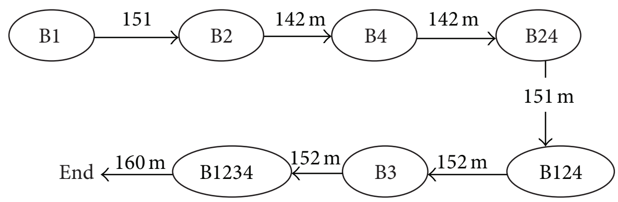


Figure 7: The filling sequence for the test case.

For example, B24 is active when $h_j^2 = h_j^4 = h_j^{24}$, $L^{24} > h_j^{24} \geq S_{24}$, and $h_j^1 = L^1$.

(3) A combined three-basin lake is active (lake $l$ is composed of the $m$th, $n$th, and $p$th lakes) when three conditions are satisfied.

(a) They reach a common water level, $h_j^m = h_j^n = h_j^{lmn}$.

(b) The common water level exceeds their intersill elevation and is still smaller than the three-basin lake threshold elevation, $L^{lmn} > h_j^{lmn} \geq \max(S_{mn}, S_{nl})$.

(c) Their inflow source becomes a reservoir $h_j^k = L^k$.

For example, B124 is active when $h_j^1 = h_j^{24} = h_j^{124}$, $L^{124} > h_j^{124} \geq \max(S_{12}, S_{24})$, and $h_j^1 = L^1$.

(4) A combined four-basin lake of the entire Toshka depression is filled together when three conditions are satisfied. $h_j^3 = h_j^{124} = h_j^{3124}$, $L^{3124} > h_j^{3124} \geq \max(S_{31}, S_{12}, S_{24})$.

## 4. Testing the Validity of SMTD

A virtual inflow time series is chosen to test the validity of SMTD predictive capability in simulating TD performance in both flood and drought situations. The model simulates the gradual water filling of each basin and the possible joining of two or more adjacent subdepressions as a function of time. The present state of sills after the three consecutive floods of 1996–2000 is considered:

$$S_{12} = 151\text{ m}, \qquad S_{24} = 142\text{ m},$$
$$S_{13} = 152\text{ m}, \qquad S_{45} = S_{36} = 160\text{ m}. \tag{22}$$

The virtual inflow time series has a two-month per year flood as shown in Figure 6.

The filling sequence followed the expected pattern shown in Figure 7.

Evaporative emptying is demonstrated and the validity of the developed model is asserted as shown in Figure 8.

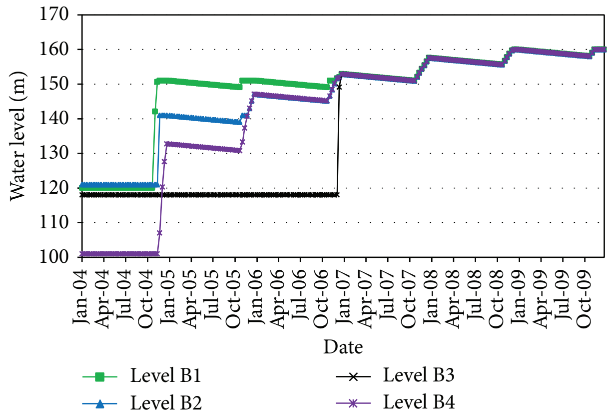


Figure 8: Water level time series for the validity test.

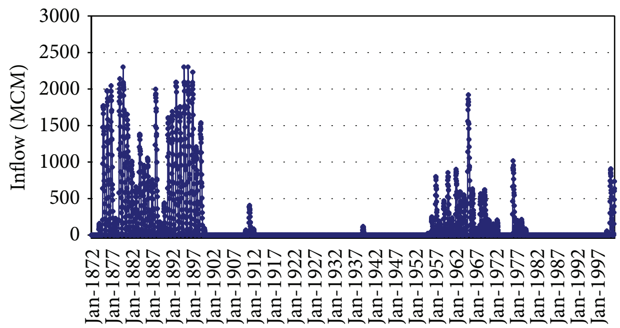


Figure 9: Realistic inflow time series.

## 5. Realistic Inflow Gains and Evaporative Losses

*5.1. Time Series of Inflow Gains.* Data about the water arriving at Aswan is available from 1869, Suteliffe and Parks [9] and also from Zaki and Fassieh [10]. Figure 9 shows a realistic inflow time series for the 130-year period from 1872 to 2000 as 10 daily values of Nile water discharged to the TD spillway in million cubic meter (MCM).

This realistic inflow time series has three features:

(a) two long flood periods 1873–1899 and 1955–1971,

(b) two long drought periods 1890–1954 and 1977 to 1998,

(c) three short flood periods 1910-1911, 1976-1977, and 1999-2000.

*5.2. Evaporation Losses.* Different methods were used to estimate evaporation rates of Aswan High Dam lake and Toshka lakes, for example, Aly et al. [11] and El Bastawesy et al. [3]. The Egyptian Ministry of Water Resources and Irrigation adopted the figure of 7.54 mm per day as the annual mean evaporation rate according to Elsawwaf et al. [12].

Table 3: Evaporation rates.

| Month | Evaporation rate (m/10 days) |
|---|---|
| January | 0.055 |
| February | 0.05 |
| March | 0.06 |
| April | 0.065 |
| May | 0.073 |
| June | 0.076 |
| July | 0.093 |
| August | 0.1 |
| September | 0.1 |
| October | 0.09 |
| November | 0.075 |
| December | 0.065 |

More detailed data are depicted in Table 3 obtained from the planning sector of the ministry.

From Table 3 it can be shown that the annual lowering of a lake surface level is about 2.7 m. El Bastawesy et al. [8] studied the water loss of Toshka lakes from the year 2002 up to 2006 using multitemporal satellite images coupled with digital elevation model (DEM) analysis. They estimated the loss rate to be around 2.5 m/year. Hence, the maximum annual volumetric loss due to evaporation (in a Toshka depression with a 160 m contour as an outer boundary, that is, with approximate surface area of 3000 km$^2$) may be roughly estimated as

$$\Delta V_{\text{evap}} = 2.7 \times 3000 \times 10^6 = 8.1 \text{ BCM/year}. \quad (23)$$

This means that evaporation losses should be considered and computed because it takes only about a decade to completely empty a filled-up Toshka Depression.

*5.3. Comparative Study of Three Alternative TD Configurations.* The appropriate flood management strategy depends on the local conditions and consists of a combination of measures. One of these measures is TD configuration, defined by interbasin sill elevations and a dam.

Specifically, TD configuration is defined by two parameters.

(a) The elevations of interbasins connecting sills: $S_{12}$, $S_{13}$, and $S_{24}$.

(b) The Kharga Oasis dam whose height is $D_h$, thus $S_{45} = 150 + D_h$, $D_h = 0$, and $S_{45} = 150$ m, TD without dam (the current status), $D_h = 10$ m, and $S_{45} = 160$ m, TD with dam.

We study the effect of changing the TD configuration by considering three different cases. These configurations are summarized in Table 4.

The response of TD to each configuration is shown in two separate figures. The first figure depicts the time series of water levels in the four TD lakes while the second one depicts the time series of water overflow (the excess water volume that cannot be accommodated by TD).

Table 4: TD configurations A, B, and C.

| Configuration | Dam | $S_{45}$ | $S_{13}$ | $S_{12}$ | $S_{24}$ |
|---|---|---|---|---|---|
| A | Dam | 160 m | 152 m | 151 m | 142 m |
| B | No Dam | 150 m | 152 m | 151 m | 142 m |
| C | Dam | 160 m | 149 m | 151 m | 142 m |

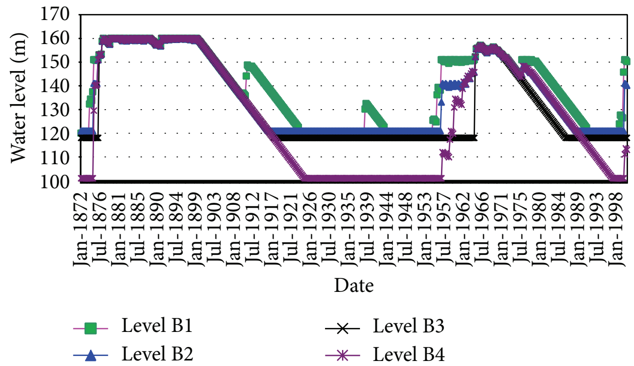


Figure 10: Water level time series for TD configuration A.

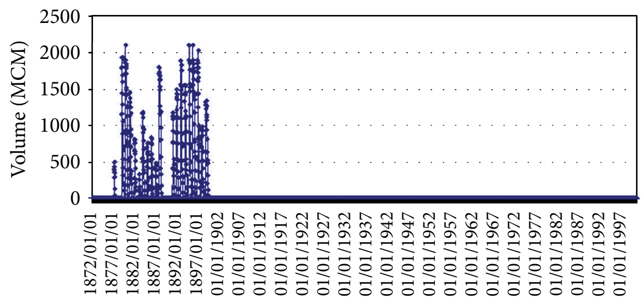


Figure 11: Overflow time series for TD configuration A.

This response is for the TD configuration A as shown in Figures 10 and 11. Figure 10 shows the time series of the water levels of each one of the four subdepressions during the 130-year period. First we see how TD responded to the first major flood period by being completely filled in 3 years and it continued being filled for the next 23 years. There was two short evaporative emptying periods during this period. When the drought began, TD continued losing water by evaporation steadily for ten years. When the sudden flood of 1910 came, the water level in the first subdepression started rising again for a short period. The same phenomenon was repeated as a response to the sudden flood of 1939. But we can say that during the drought period there was almost 30 years (1924–1954) of complete dryness of TD. During the second flood major period, TD started filling again in a slower rate; it took almost 10 years to reach maximum water level of 157 m. During the second drought period, evaporative emptying occurred again until the recent floods at the end of the twentieth century.

In Figure 11 the overflow time series of the 10 daily incremental volumes are shown. We can see that, during the first major flood period, the amount of inflow to TD

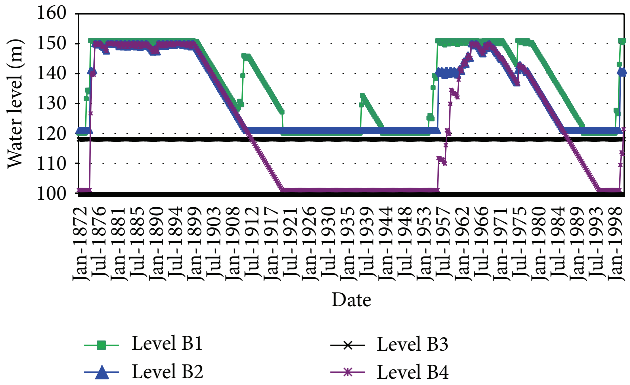


Figure 12: Water level time series for TD configuration B.

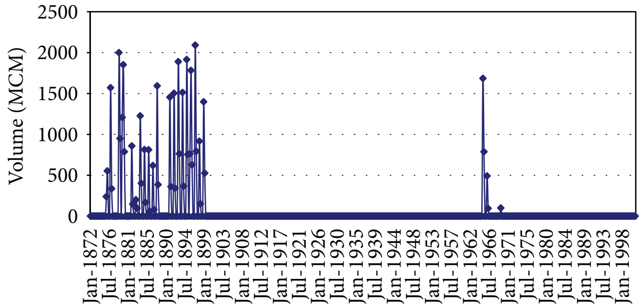


Figure 13: Overflow time series for TD configuration B.

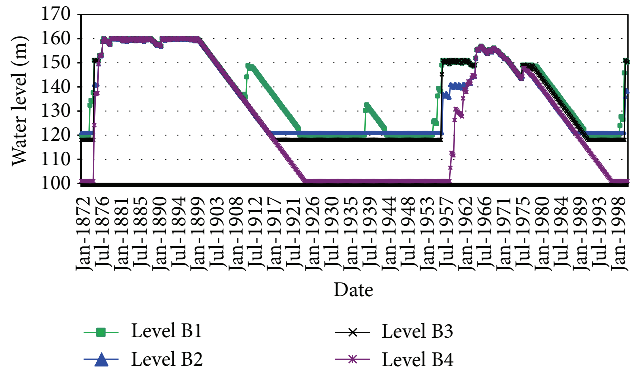


Figure 14: Water level time series for TD configuration C.

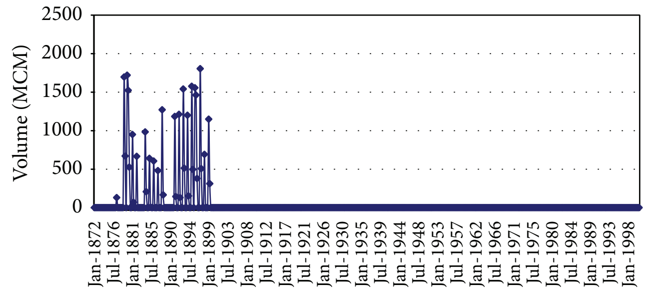


Figure 15: Overflow time series for TD configuration C.

that could not be accommodated is substantial and justifies building a higher dam.

For both configurations B and C the water level time series in all basins are shown in charts (Figures 12 and 14) and the overflow volumes time series are shown in charts (Figures 13 and 15).

Results show that configuration C produces less overflow amounts and more water storage in TD when struck by floods. Hence, we can conclude that building a dam at the end of subdepression 4 near Kharga Oasis and lowering the hill that separates of subdepression 3 from subdepression 1 may be the best TD configuration.

## 6. Filling Sequence of TD Basins during Major Flood Periods

One of the major outputs of this model is the simulation of the manner by which the flood water is accommodated by gradual (or sudden) filling of the separate subdepression. The filling sequence of TD depends not only on the inflow time series but also on the configuration of the TD.

Of particular interest is the TD filling sequence during the two major flood periods of the time series. These are the 6 crucial years of the first flood period (1872–1878) and the 12 crucial years of the second flood period (1955–1967). These are shown in Figures 16 and 17 where the short-term gradual increases of the water levels in the separate subdepressions are plotted. Because the second flood is weaker, the TD filling

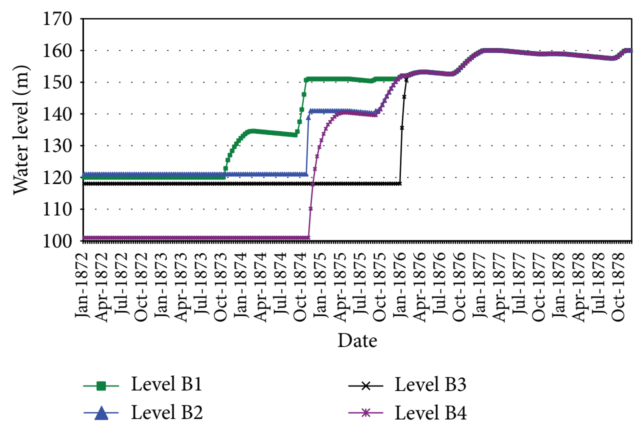


Figure 16: Water levels during the first flood period.

process was slower (Figure 17) and interrupted by several evaporative emptying episodes. This explains the absence of the volume overflow as the highest elevation contour of 160 m has not been reached during that flood.

## 7. Monthly Water Level Variations during Critical Periods

In order to demonstrate the high time resolution of the simulation model of Toshka depression (SMTD), we zoom in to critical periods where changes in levels, volumes, and areas are drastic. These critical periods are the drought years

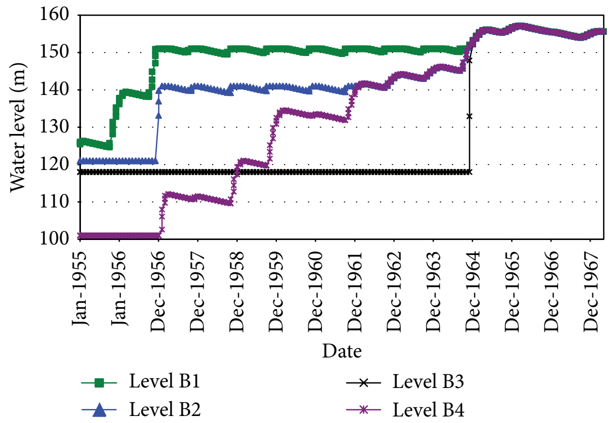


FIGURE 17: Water levels during the second flood period.

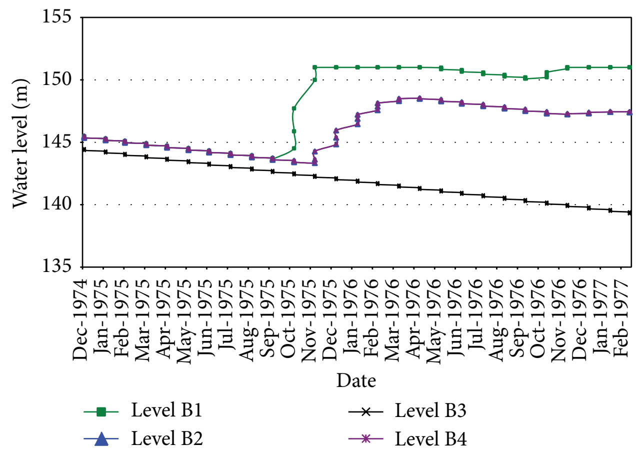


FIGURE 18: Water level variations during the draught period.

1975-1976 and the flood years 1999-2000. In Figures 18 and 19 these monthly variations of water levels in each one of the four separate subdepressions of configuration A are plotted.

Similar variations in lake volumes and surface areas may be shown for these or other critical periods. The user of SMTD can change the sill elevations and/or the dam height to investigate the response of a particular TD configuration. The flexibility of SMTD allows the user to investigate different scenarios for design and planning purposes.

## 8. Summary of Simulation Model Capabilities and Recommendations

(1) The developed model computes the time variations of water levels, water surface areas, and water volumes in each one of the four basins of the TD. This time variation constitutes the detailed response of TD to realistic time series of both inflow gains and evaporation losses during the past 130-year period.

(2) The model provides detailed time-dependent TD response which includes the monthly patterns of inter-basin water movements and their filling sequence.

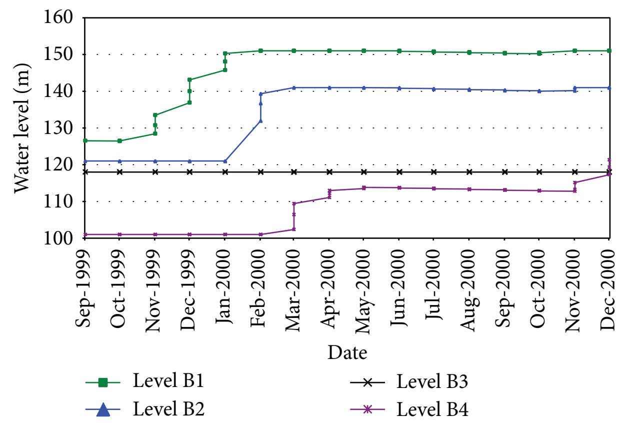


FIGURE 19: Water level variations during the flood period.

This is essential for the decision maker to assess quantitatively water availability for the feasibility of agricultural use; water volumes with appropriate levels that may be stored for extended periods of time, in each one of the four TD subdepressions.

(3) The model provides a tool to assess quantitatively the flood control effectiveness and limitations of TD. The output results show its strong time dependence on three alternative TD configurations (elevations of inner sills and outer boundary).

(4) The model gives the time series of the overflow. These are the volumes that cannot be accommodated by the TD of a certain storage capacity. This capacity in turn is defined by the TD configuration. In addition to assessing TD limitations, this is important for developers and inhabitants of the regions close to TD, Oasis Kharga, for example.

(5) The model quantifies the gains to flood control of two management decisions and hence recommends TD configuration C:

   (a) building a 10 m height dam at the 4th basin boundary ($S_{45} = 160$ m),

   (b) digging a canal through the hill between 1st and 3rd basins ($S_{13} = 149$ m).

## Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

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