



Defining the Hydraulic Dimensions and Operation Conditions for a Multi-Purpose Dam Using a 1-D Model (Case Study: Sue Dam, South Sudan)

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ABSTRACT

In this paper, a 1-D model; SOBEK was used for modeling the Sue River, the suggested dam, reservoir and spillway. The reservoir operations of filling and emptying would be simulated. The average discharge hydrograph was used for the dam design. The model was used for defining the required discharges for the operation of the hydropower generators, domestic use and agricultural use. The exclusive Geographical Information System (GIS) of the model was used to manage the input and output results. The affected huts due to the rising water level in the reservoir upstream of the dam were defined. The hydropower discharges, dead zone & storage volumes and hydraulic dimensions for the dam and spillway were computed. The study proved that if the Sue Dam was constructed; 40000 feddans would be cultivated, drinking water would be supplied to 500,000 inhabitants all year round, and 9 MW of electricity will be generated for the South Sudan development

1. Introduction

The Republic of South Sudan became the world's newest nation in July 2011, after a peaceful referendum held in January 2011. The Republic of South Sudan is blessed with abundant water resources. However, most of these resources are unevenly distributed across the country, and are affected by wide seasonal variations. As a result of the difficult political and economic situation experienced in the country, about 75 percent of the rural population and 70 percent of the urban population of then South Sudan lacked access to safe water. Most of the existing water supply facilities

were in very poor condition, and water consumption was as low as 6 liters per capita per day, representing only about 30 percent of the recommended 20 liters per capita per day. About 50 percent of existing primary schools and health centers lacked access to safe water supply and sanitation (WSS) services [1]. Moreover, South Sudan is suffering from a complete shortage of infrastructures especially electricity, roads network and telecommunications facilities. Therefore, the overall goal of the economic development strategy has been defined in Article 40 (1) of the Interim Constitution of South Sudan to be:

(a) Reduction of poverty;

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- (b) Attainment of the Millennium Development Goals;
- (c) Guaranteeing the equitable distribution of wealth;
- (d) Redressing imbalances of income; and
- (e) Achieving a decent standard of life for the whole people

In the water sector, the main focus of the government nowadays is to start studying and developing a long term plan to establish a strategy for the best utilization of the available land and water resources. Managing water projects was determined to be one of the top priorities of this plan. Construction of Dams has been identified as a key factor for those projects. Among others, the main objectives for dam construction are:

1. Control of water resources, in addition to the development of river basins, watersheds and water catchments; so as to meet social and developmental needs of the people. For instance, seasonal flows and springs would be harnesses to overcome water shortage during the dry season or drought time.
2. Avail water for the enhancement of the productivity of the agricultural, livestock and fisheries sectors.
3. Enhance the hydropower generation potential

"EFTCA" is the Egyptian governmental instrument that coordinates official development assistance and development cooperation programs with African countries. The EFTCA is considered a part of the Egyptian Ministry of Foreign Affairs with an independent budget and has its development cooperation programs that cover most of the African continent. Since its establishment in 1980, "EFTCA" contributed effectively in building capacities and developing human resources in African countries aiming at attaining sustainable development across the continent through dispatching more than 8,500 Egyptian experts in all disciplines, like medicine, engineering, agriculture, irrigation, water resources and education, as well as affording training courses to nearly 10,000 African trainees in all fields in Egypt.

Within the Egyptian Fund for Technical Cooperation with Africa "EFTCA and financial support from the government of Egypt to the government of south Sudan, a set of development projects have been identified in consultation with the south Sudan government. One of these projects was to construct a multi-purpose dam at Sue River which has the objective to contribute to the livelihood conditions of the people of Wau city, south Sudan. A decision has

been made to initiate the feasibility study of a dam construction at the Sue River beside Wau city, (Figure 1).

The suggested dam will make water available around the year especially during the dry seasons. Consequently, locals shall not need to move long distances with their livestock to search for forage and water as the dam will provide them with adequate water (both in terms of quantity and quality) for domestic use as well as for their livestock. Currently, potable water supply coverage is extremely limited and is obtained from the limited unprotected traditional sources.

After constructing the dam, a water treatment plant shall be constructed in Wau city, South Sudan, to serve about 500,000 inhabitants. The raw water shall be drawn from the Sue River after being released from the hydro power station downstream of the proposed Sue Dam. An irrigation intake shall also be implemented downstream of the dam to divert water to irrigate 40000 feddans.

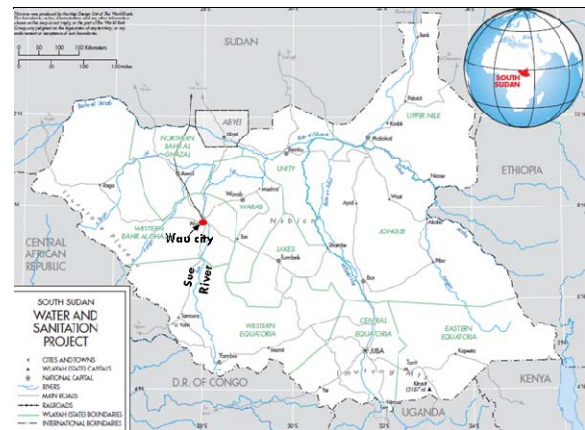


Fig. 1. Site Location of the Multi- Purpose Dam at Sue River [1]

This study was carried out using a one dimensional mathematical model named SOBEK (1D), which was used for simulating the river as 1-D, Delft Hydraulics (2009). The model simulated water flows upstream and downstream of the dam. The main goal of the simulation is defining the Hydraulic dimensions and Operation Conditions for the Multi-Purpose Dam. The detailed study objectives are:

- To determine the suitable dam crest level and the dimensions of the reservoir
- To define the capacity of the reservoir at different water levels
- To determine the daily discharges downstream of the dam and the operation rules of the reservoir (daily water levels upstream and downstream of

- the dam)
- To define the dimensions of the emergency spillway
- To define the expected urban areas that will be affected upstream of the dam.

The pre-mentioned parameters are key factors in the design of the hydropower plant, in defining the area of the irrigation scheme and designing the water treatment plant.

2. The Study area

The suggested dam is located at km 7 from the confluence of the Sue and Bossery Rivers near Wau City as shown in Figure (2). This location for the dam construction was selected for structural design purposes and based on the coordination and discussion with officials of the water authorities in South Sudan. The cross section of the river at this location is smaller than other locations along the river.



Fig. 2. Dam location

The Sue River is one of the main tributaries of the Jur River at Bahr El Ghazal Basin, South Sudan. The Jur is the most important tributary of Bahr El Ghazal. It lies in the Upper part of Bahr El Ghazal watershed between Latitudes of 8° 30' and 9° 02' N, and longitudes of 26° 10' and 29° 08' E. The watershed of the Jur River has an estimated area of 49000 Km². The altitude upstream of the dam ranges from (320) to (480) m above sea level. The total lengths of the Sue and the Jur Rivers is about 485 km. The Jur is a seasonal stream. Its discharge can reach 400 m³/s in September [2].

2.1. River discharges

The Sue River Watershed Authority provide values for the river discharges. Monthly maximum,

minimum and average discharges for the Sue River are shown in Figure (3). The flow in the Sue River begins in July, the peak discharge occurs in September and decreases until December based on the available data from 1953 to 1961. The average discharge in July is about 92.6 m³/s and the maximum is about 304.78 m³/s in September. The average discharge for the Sue River will be used for the design of the dam. The Hydropower plant, the irrigation project and the water treatment plant designs will be based on the average discharge, while the emergency spillway dimensions will be designed based on the maximum discharge.

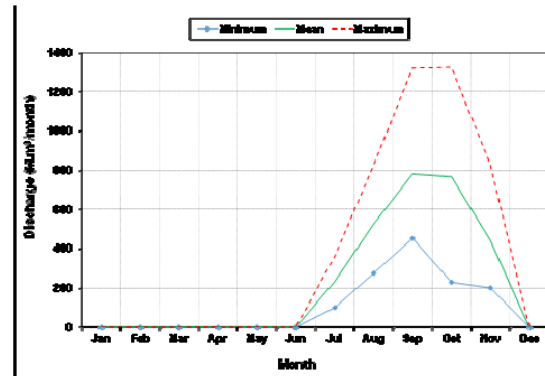


Fig. 3. Sue River, Max., Min. and Mean Discharges

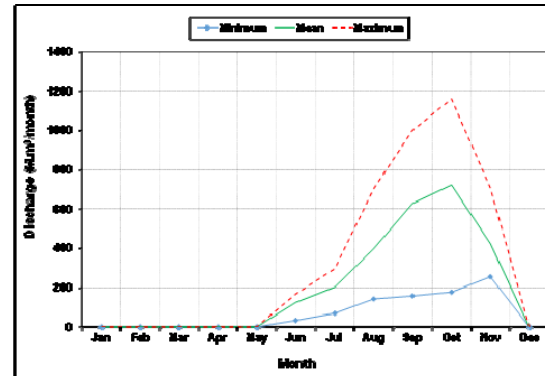


Fig. 4. Bossery River, Max., Min. and Mean Discharges.

The Bossery River shown in Figure (2) is a seasonal stream. Figure (4) shows its monthly maximum, minimum and average discharges. The flow in the River begins in June, the peak discharge occurs in October and decreases until December. The average discharge in June is about 47.67 m³/s and the maximum is about 278.46 m³/s in October. Bossery River outlet meet with Sue River outlet at km 0.0 at Wau city as shown in Figure (2).

3. Methodology

This study was carried out using a one

dimensional mathematical model named SOBEK-Rural. SOBEK-Rural is a powerful modelling suite for flood forecasting, optimization of drainage systems, control of irrigation systems, river morphology, salt intrusion and surface water quality. The programmes within the SOBEK modelling suite simulate the complex flows and the water related processes in almost any system. The programmes represent phenomena and physical processes in an accurate way in one-dimensional (1D) network systems and on two-dimensional (2D) horizontal grids. It is the ideal tool for guiding the designer in making optimum use of resources. Many large projects were modeled using SOBEK, [3], [4], [5], [6], [7], [8] and [9].

This model could quickly, easily and accurately simulate the flow in simple or complex channel networks consisting of thousands of reaches, cross sections and hydraulic structures. The modeler is responsible for defining all types of boundary conditions, and lateral inflows and outflows using time series or standard formulae.

For the Sue River simulations, the Flow Module has been used which is capable of simulating fully unsteady flow.

The flow module in SOBEK that is used for Regular River applications could be described by the full Saint-Venant equations for unsteady open channel flow, shown in equations (1) to (4), [10].

The continuity equation (representing the conservation of mass):

$$\frac{\partial A_t}{\partial t} + \frac{\partial Q}{\partial x} = q_{lat} \quad (1)$$

The momentum equation (representing the conservation of momentum):

$$\frac{\partial Q}{\partial t} + \frac{\partial}{\partial x} \left(\alpha_B \frac{Q^2}{A_f} \right) + gA_f \frac{\partial h}{\partial x} + \frac{gQ|Q|}{C^2RA_f} = 0 \quad (2)$$

With:

- A_f = conveying cross-section [m²]
- A_t = total cross-sectional area [m²]
- C = Chézy coefficient [m^{1/2}/s]
- g = gravitation constant [m/s²]
- h = water level relative to reference level [m]
- q_{lat} = lateral inflow per unit length [m³/m/s]
- Q = discharge [m³/s]
- R = hydraulic radius (roughly equal to the water depth) [m]
- t = time [s]
- W_f = width of conveying cross-section at water surface [m]
- x = distance along the channel [m]

α_B = Boussinesq coefficient [-]

The Boussinesq coefficient is a correction factor in the convective acceleration term in equation (2), to account for the non-uniform velocity distribution in the cross-section. It is computed from:

$$\alpha_B = \frac{\sum_{i=1}^n C_i^2 R_i A_{fi}}{C^2 R A_f} \quad \text{and} : \quad C^2 R = \left(\frac{\sum_{i=1}^n C_i A_{fi} \sqrt{R_i}}{A_f} \right)^2 \quad (3)$$

where:

i = index indicating type of sub-section in conveying cross-section ($i \leq 3$)

The last expression C^2R in equation (3) is also used in the bed-friction term in equation (2). The Chézy coefficient C is computed as a function of Manning's roughness coefficient n_m :

$$C = \frac{R^{1/6}}{n_m} \quad (4)$$

For the Sue River model, the Manning's roughness coefficient provides a good representation of the hydraulic roughness for a wide range of discharges

3.1. The Modeled Area

The study area covers 112.00 km of the Sue River and 6.00 km of the Jur River. The dam was suggested to be at km 7.00 from the Sue estuary near Wau City, the modeled area is presented in Figure (5). The area is relatively flat with floodplain levels ranging between (415) m and (500) m above the mean sea level and the bed levels of the Sue River range from (418) m to (470) m.

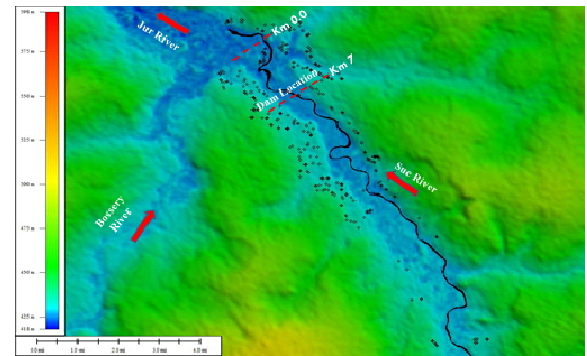


Fig. 5. The study area

3.2. Model Construction

During constructing the model, several elements were considered including cross sections, lateral intakes, suggested dam, hydropower plant and

spillway, evaporation, flood discharge and the boundary conditions. These elements are discussed below:

The Cross Sections were simulated using the bathymetric survey carried out on 2008, [11]. The survey covered a 32 km of the Sue River and 5.5 of the Jur River. Missing cross sections were estimated using GIS and topographic maps [12].

As for the cross sections, the following was considered:

- The Sue River and the flood plain were simulated using the bathymetric survey. The cross-section data of the 10/2008 survey was used [11].
- The survey covered a length of 32 km of the Sue River and 5.5 km of the Jur River.
- Missing other cross sections along the Sue River were estimated using GIS and topographic Maps [12].

Dam and Spillway

- The dam and spillway are simulated as weirs.

Hydropower

- The hydropower is simulated as an intake, it takes its discharge from the upstream and its outlet is located at the downstream of the dam

Lateral intakes

The inflow of the Bossery River and other sources were specified as a function of time. These values must be positive in the case of intakes. The lateral discharges were specified as point discharges (m³/s). The Bossery discharges are shown in Figure (4), the main nodes are shown in Figure (6)

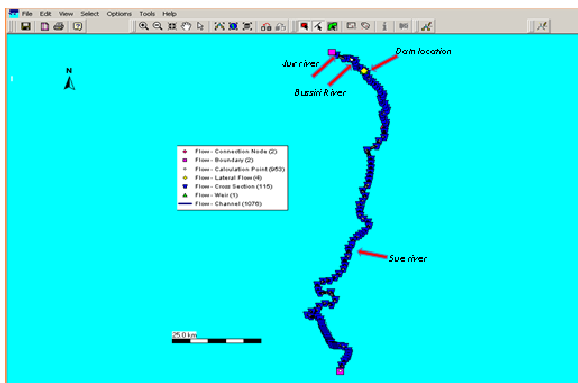


Fig. 6. Layout of the SOBEK 1-D Model

Evaporation

Evaporation was specified as an outflow and was expressed as an off-take, depending on the area of the reservoir that stores the water. This area is a function

of water level in this lake. Figure (7) shows the relationship between the areas of the formed reservoir with its water level.

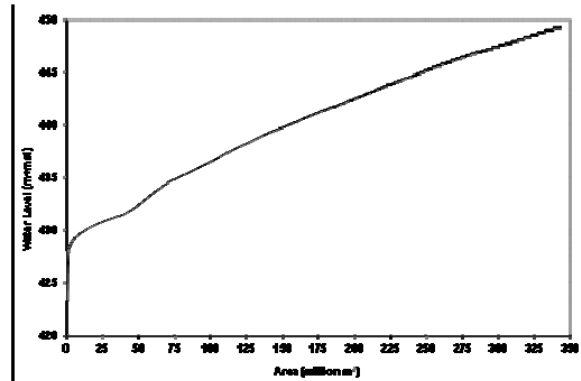


Fig. 7. Reservoir Surface Area versus Water Level

3.3. Boundary conditions

Boundary conditions are needed to solve the basic equations for unsteady flow. In this study, there are two boundary conditions; upstream and downstream boundaries as specified below:

Upstream Boundary Condition

The average discharge of the Sue River is considered as the upstream boundary. The discharges of the Sue River were imported from the hydrological data of the Sue River. The net discharges for the Sue River was defined using the data in Figure (3).

Downstream Boundary Condition

For the downstream boundary, water levels in the Jur River are defined based on the Jur River- Wau station and the used data is shown in Table (1). Levels in Table (1) are calculated based on the discharges of the hydropower plant and The Bossery River.

Table 1. Estimated Water level (Downstream boundary)

Date	Water Levels (m)	Date	Water Levels (m)
Jun.	423.69	Dec.	423.18
Jul.	423.93	Jan.	423.18
Aug.	424.50	Feb.	423.18
Sep.	425.04	Mar.	423.18
Oct.	425.25	Apr.	423.18
Nov.	424.55	May.	423.18

4. Results and Discussion

4.1. Model Calibration

The calibration of the model of the Sue River was performed based on actual measurements of inflow discharges, and water levels. The measurements were executed during the high discharge period [10], the measured discharge for Sue River is 233 m³/s. The Manning's roughness values, obtained during the calibration, were applied in the SOBEK model. The calibration results of the Sue River are shown in Figure (8). From this Figure, it could be concluded that the model could provide accurate results. The differences between the measured and computed water levels were ≤ 0.08 m.

4.2. Model Runs

The model was run using the dry condition for 5 years. The reservoir was empty at the beginning of the first flood. The bed level upstream of the dam is about (425.0) m. The following parameters were assumed during the dam operation:

- The Crest level of the spillway was assumed to be 446.5 m,
- The water discharge data summarized in Figures (3) and (4) were used,

The model was run many times by changing the discharge of the hydropower until it reached constant maximum and minimum water levels upstream of the reservoir

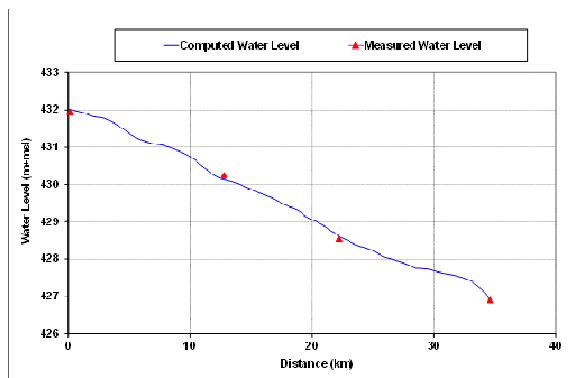


Fig. 8. Comparison between Measured and Computed Water Levels

4.3. Model Results

The most daily important results from the model which are very useful for the hydropower design are

the discharges from the reservoir, the water levels upstream and downstream of the reservoir and the volume of the reservoir. These results are illustrated below

Discharge of the Hydropower

The model results showed that the daily average discharge from the reservoir through the hydropower is 62 m³/s. Discharges that are higher or lower than this discharge makes the maximum and minimum water levels change every year, while the discharge of 62 m³/s makes the maximum and minimum values for water levels constant for consecutive floods as shown in Figure (9). The discharge of the hydropower which was taken to be 62 m³/s is higher than the drinking and irrigation water requirements, and at the same time keeps enough upstream water level to operate the hydropower plant all over the year. The required discharge to cultivate 40000 faddens is about 30 m³/s, [13]. The required discharge for the water drinking treatment plant is 8.75 m³/s, [14].

Water Levels Upstream and Downstream of the Dam

The results of the model showed that the maximum water level in the reservoir reached to level 445.10 m at the first year and 445.50 m for the other years. The minimum upstream water level is (435.97) m in the first years and 436.05 m in the next years. Figure (9) shows the upstream water level during the simulated period. Figure (10) shows the relationship between the water level and time, downstream of the dam. From the Figure, it can be seen that the downstream water level changes with time due to the change in the Bossery River discharges. Water levels range from (425.61) m to (426.67) m.

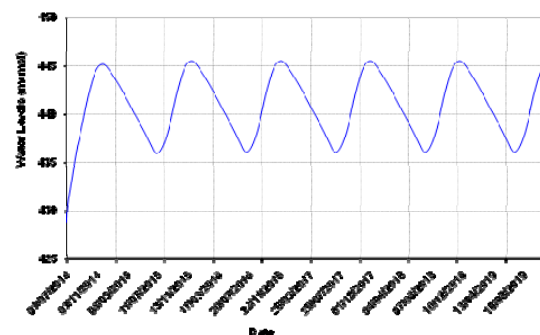


Fig. 9. Water Levels upstream The Dam for The Simulated Period 5 Years

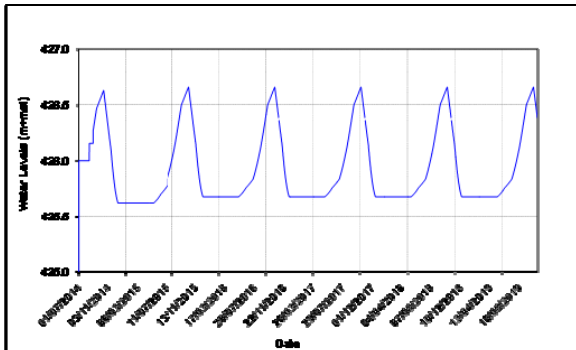


Fig. 10: Water levels downstream of the dam for the simulated period of 5 years

The relationship between time and the head difference upstream and downstream of the dam during the simulated period is shown in Figure (11). The maximum head difference is about 19.62 m while the minimum head difference is about 10.00 m as seen in Figure (11). These differences are enough to operate the electric power plant.

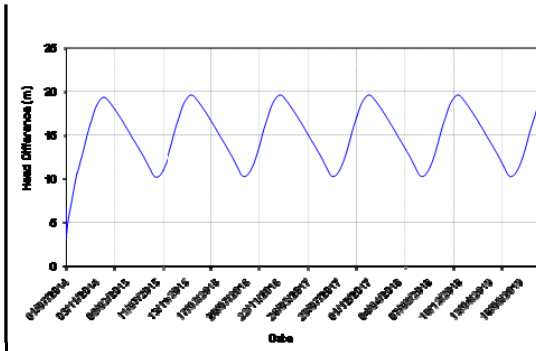


Fig. 11. Head Difference U/S and D/S of the dam for the simulated period of 5 years

Emergency Spillway

The model was also used to design the suitable length of the emergency spillway. Different lengths for the spillway that vary from 100.0 m to 250.0 m at a crest level of (446.50) m were tested by the model during maximum flood for a return period of 200 years. Table (2) shows the discharges of the maximum flood for a return period of 200 years. The results of the model showed that the maximum water level upstream of the spillway reached (448.5) m for the spillway with length of 100.0 m which is very close to the crest level of the dam (which is 449 m) while the maximum water level upstream of the spillway reached (447.59) m for the spillway with a length of 250 m. Table (3) presents maximum water levels upstream of the dam for different lengths for spillway, the selected length of the spillway will be 200 m, maximum emergency water level upstream of the dam will be (447.78) m.

Table 2. Discharge of Maximum Flood for a Return Period of 200 Years

Date	Discharge (m ³ /s)	Date	Discharge (m ³ /s)
Jun.	0	Dec.	0
Jul.	192.90	Jan.	0
Aug.	345.29	Feb.	0
Sep.	632.72	Mar.	0
Oct.	671.30	Apr.	0
Nov.	380.02	May.	0

Table 3. Maximum Water Levels for Different Lengths of the Spillway

Spillway Length (m)	Max. Water Level (m+msl)
100	448.50
150	448.04
200	447.78
250	447.60

Volume of the Reservoir

The relationship between the volumes of the reservoir and the water levels upstream of the dam was computed and presented in Figure (12). It could be noticed that the maximum capacity of the reservoir reaches 2.00 Billion cubic meters at water level of (445.50) m.

Figure (13), shows the operational levels of the Sue reservoir. The volume of the reservoir is about 375 million m³ at the minimum operational level (436.05) m, while reaches to 2000 million m³ at maximum operational level (445.50) m. The dead zone volume will be 375 million m³ while the operating volume will be 1625 million m³ as shown in Figure (13). The crest level of the emergency spillway is (446.50) m and the maximum emergency water level is (447.78) m.

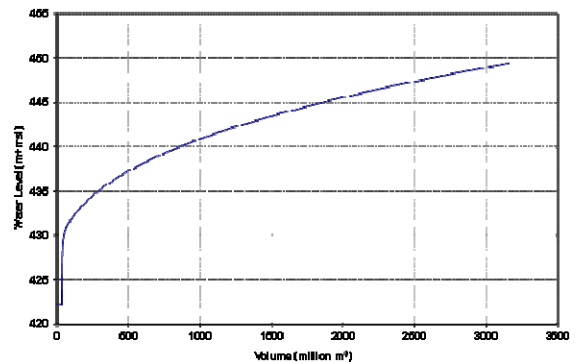


Fig. 12. Relationship between Reservoir Volumes and Water Levels Upstream of the Suggested Dam

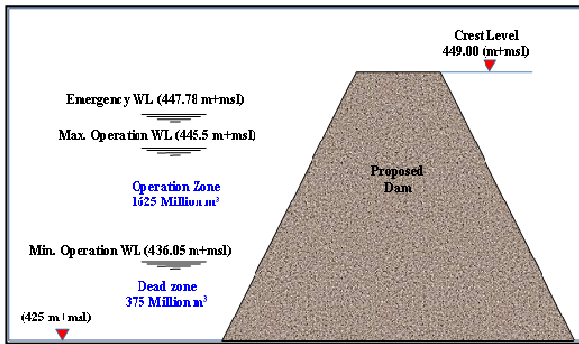


Fig. 13. Levels Upstream of the Suggested Dam, and the Storage Volume

Location of Inundated Land

The water levels that were extracted from the model output were used in GIS to identify the location of the houses and structures within the study area that were inundated due to the increasing of the water levels upstream of the suggested dam. A digital elevation model (DEM) with 90 m resolution was calibrated using the available surveyed elevation data which was collected during the survey mission conducted by the HRI surveying team. The calibrated DEM was then used to extract profiles along the river path. The inundated areas at different water levels; (445.5), (446.5) and (447.5) m were defined, consequently. The location of the expected threatened huts due to the dam construction at water levels of (445.5) m, (446.) and (447.5) m were defined using UTM coordinates. An example of the inundated huts is shown in Table (4).

Table 4. An example of The Inundation Huts due to Location of dam Construction

Hut No.	X-Coordinate	Y-Coordinate
457	619149.07	842319.22
458	622029.74	843223.84
459	619114.68	843202.14
460	619147.23	843094.83
461	618830.12	843727.84
462	618284.33	844515.59
463	618308.04	844520.41
464	618067.97	849139.16
465	619825.09	841711.31

5. Conclusions

Based on the Sue River investigations, in South Sudan, and the results of the hydrographic survey, a 1-D mathematical model for the river and dam was

developed by using SOBEK 1-D model. The model provided a hydraulic design of the dam and defined the rules of the reservoir operation.

The study proved that the Sue Dam would be able to provide enough water on yearly basis to provide an area of 40,000 acres with irrigation system and drinking water for about 500,000 inhabitants. The dam will also have electricity generation of 9 MW.

These results, obtained from the model simulation are very important for carrying out the feasibility study including the social, economic and environmental aspects.

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Notation and Abbreviation

Symbols

A_f	: Conveying cross-section	[m ²]
A_t	: Total cross-sectional area	[m ²]
C	: Chézy coefficient	[m ^{1/2} /s]
g	: gravitational acceleration	[m/s ²]
h	: Water level relative to reference level	[m]
q_{Lat}	: Lateral inflow per unit length	[m ³ /m/s]
Q	: Discharge	[m ³ /s ⁻¹]
R	: Hydraulic radius (roughly equal to the water depth)	[m]
t	: Time	[s]
W_f	: Width of conveying cross- section at water surface	[m]
X	: Distance along the channel	[m]
α_B	: Boussinesq coefficient	[-]
n_m	: Manning's Roughness	[-]
i	: Index	[-]

Abbreviations

EFTCA	: Egyptian Fund for Technical Cooperation with Africa
GIS	: Geographical Information System
MW	: Megawatt
msl	: Mean Sea Level
m	: Meter
S	: Second
M	: Million
HRI	: Hydraulics Research Institute
DEM	: Digital Elevation Model
1-D	: One – Dimensional
m ³ /s	: Meter Cube per Second
Max.	: Maximum
Min.	: Minimum
WB	: World Bank