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Impacts of Grand Ethiopian Renaissance Dam on Different Water Usages in Upper Egypt

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Authors' contributions

This work was carried out in collaboration between both authors. Both authors read and approved the final manuscript.

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ABSTRACT

A Large scale dam named as Grand Ethiopian Renaissance Dam (GERD) is currently under construction on the Blue Nile River in Ethiopia. The final report of the International Panel of Experts (IPoE) on the GERD project which was submitted to the governments of Ethiopia, Sudan and Egypt, reported that the Aswan High Dam (AHD) will reach the minimum operational level during 4 consecutive years. Consequently, this project could significantly affect the water supply to Egypt, in case if the first impounding of the GERD occurs during dry years. The present paper assesses the potential impact of the shortage of Egypt water resources that will reduce the releases from AHD due to the construction of the GERD on the Nile water in Egypt. Data was assembled and analyzed. SOBEK model was selected to be applied to the designed scenarios. The water levels so as discharges along the Nile River in Upper Egypt were produced under different water releases. Results were obtained and analyzed. The analyzed results indicated that the maximum allowable reduction in Egypt water share should not be more than 5 - 15%. So, the win–win strategy can defuse tensions between Egypt and Ethiopia over the GERD. Furthermore, Ethiopia has to agree with Egypt and Sudan on the capacity of the GERD reservoir, impounding rules of the GERD reservoir and operating rules. The results of this study most probably assist decision makers to identify possible measures to overcome water shortage problem.

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Keywords: Nile River; water scarcity; GERD; navigation; hydropower and numerical simulation.

ABBREVIATIONS

The following Abbreviations are used in this paper:

1D : One dimensional model;
AHD : Aswan High Dam;
AOD : Aswan Old Dam;
BCM : Billion Cubic Meters;
EEPC : Ethiopian Electric Power Corporation;
Fed : Feddans
GIS : Geographical Information System;
GERD : Grand Ethiopian Renaissance Dam;
HCEE : Holding Company for Electricity in Egypt;
HCWW : Holding Company for Water and Wastewater in Egypt;
HRI : Hydraulics Research Institute;
MCM : Million Cubic Meters;
MSL : Mean Sea Level;
MW : Megawatts;
MWRI : Ministry of Water Resources and Irrigation in Egypt; and
NRI : Nile Research Institute.

1. INTRODUCTION

Egypt has been listed among the ten countries that are threatened by need of water by the year 2025 due to the rapidly increasing population, [1]. The conventional water resources in Egypt are limited to the Nile River, ground water in the Delta, Western desert and Sinai, rainfall and flash floods. More than 96 percent of Egypt' all fresh water resources is supplied by the Nile River, which originates from outside of the country boundaries and supplies eleven countries. Fresh water sources from the Nile are limited for Egypt by the agreement between Sudan and Egypt since 1959. This agreement entitled Egypt to 55.5 Billion Cubic Meters (BCM) of Nile water per year and assigned 18.5 BCM for Sudan, [2]. Most of the main Nile water comes from the Ethiopian plateau through the Blue Nile and Atbara during the period of flood from August to December. Ethiopia's tributaries supply about 86 percent of the Nile water.

In 2011, the Ethiopian Government announced a plan to construct a hydroelectric dam on the Blue Nile River, 45 kilometers (km) east of its border with Sudan in Ethiopia, which has been named the Grand Ethiopian Renaissance Dam, (GERD). It will create a lake with a volume of 74 BCM, [3]. Tesfa [4] stated that "the power demand of Ethiopia has been growing at an average rate of 25 percent per year during the last five years and the demand forecast for the next five years is estimated to be 32 percent per year as Ethiopian Electric Power Corporation, (EEPC), to alleviate this challenge, GERD project will play a vital role in East Africa countries as well as Egypt for securing the electric supply. The GERD project will generate electric power with installed capacity of 6000 Megawatts, (MW). The GERD project will be the hub for clean and renewable energy supply for Ethiopia and other African countries at cheaper prices. For the above reasons, Ethiopia announced the construction of GERD in April 2011" [4,5].

Although, Ethiopia pronounces the dam will benefit downstream neighbors and will have no negative impacts on their water supply, there is no one can deny that the dam will give the upstream country greater control over an international river's flow. A major concern is how filling the huge reservoir which will affect water security in Egypt, which relies almost totally on the Nile for its water supply. Depending on how long it takes to fill the reservoir (it has been estimated to take from 3 to 7 years), the Nile flow into Egypt could be cut by 12-25% during the filling period. A major shortcoming is the lack of gauges on the Blue Nile in Ethiopia, which means that data on the flow of the Blue Nile is inadequate [4-6].

It is believed that the construction of GERD will affect the quota of Egypt. This effect on Egypt quota will decrease the AHD discharges, [3]. The international panel of experts that formed on April 11, 2012 and submitted its final report on May

31, 2013 stated that the main adverse impact in Egypt will be a reduction in power generated at Aswan High Dam due to a fall in the water levels of Nasser Lake, [3]. Furthermore, they reported that the AHD will reach the minimum operational level during 4 consecutive years which would significantly affect the water supply to Egypt, in case the first filling of the GERD occurs during dry years. The reduction of the AHD outflows has its adverse impacts on water supply, industrial and irrigation pump stations efficiency, navigation, and hydropower stations. It was further reported that Egypt is vulnerable to severe droughts even at present conditions (without the GERD construction) and therefore, the GERD will drastically alter the historical Nile flow regime on seasonal and inter-annual time scales, enabling high degree of flow regulation in the Blue and Main Nile reaches. As such, the GERD has the potential to exacerbate water stresses in Egypt if it is operated unwisely without Egypt and Sudan participation. This highlights the importance of this research paper which comes on line to assess the potential impacts of decreasing the outflows of the AHD due the construction of GERD on the different Nile water usages in Upper Egypt.

The water loss may be small and bearable if the reservoir of GERD is filled during years of high rainfall. However, if the reservoir is filled in dry years, the significantly impact on water supply of Egypt will be occurred and Egypt will face a horrible disaster in its water demands and hydropower generation, [5]. Barbary [7] studied the effect of low flow releases during low demand period on the operation of drinking and power stations along the Nile River. Ramadan et al. [8] investigated the effect of new upper Nile projects on the integrated management of the Nile basin. Their results may enable the water manger to evaluate and choose the most suitable operation guidelines for local conditions and objectives. Bastawesy et al. [9] presented hydrological scenarios of GERD to estimate the water storage for its lake in order to assess the impact of the dam on the net annual discharge downstream. They mentioned that the anticipated negative impacts for the GERD on downstream will be more pronounced for Egypt as it almost relies on the Nile water. They concluded that the completion of this project could occur over short duration and during a low-flood seasons. Consequently, the net annual discharge of the Blue Nile downstream could be minimal, and the Nasser Lake could also struggle to sustain the required water for all the Nile Valley and its Delta in Egypt.

Sadek [10] studied the effect of implementing upper Nile projects such as Ethiopia hydroelectric power dams and agriculture projects on water share of Egypt. She indicated that the discharge that reaches Nasser Lake may reduce by 5 BCM per year. In addition, the water level upstream of AHD will decrease. Sadek [11] studied water scarcity and its impacts on the social and economic national projects in Egypt. In her study, GSTAR3.0 numerical model was implemented to simulate the water flow and sediment transport in the fourth reach of the Nile River in Egypt. Locations of navigation bottlenecks were identified. In addition, affected drinking pump stations were evaluated.

Ismail [12] investigated numerically the impact of the reduction of AHD outflow on irrigation pump stations along the Nile River from Aswan to Delta Barrages. Different scenarios of flow reduction downstream of AHD ranged between 0 and 25%, were tested and water levels along the Nile River were computed to examine the impacts of flow reduction on the irrigation pump stations. Nada and Fathy [13] studied the effect of different scenarios of filling GERD on the reduction of water levels and discharges downstream of AHD. They found that the water levels decreased from 0.40 to 0.75 m when discharge decreased from 90 to 80% of the maximum outflow.

Ramadan et al. [14] studied the environmental impacts of GERD on the Egyptian water resources. They used a hydrological model (the river basin modeling and simulation package (MODSIM)). They concluded that impounding of GERD at normal flow from the Blue Nile through 6, 3, 2 years will decrease the active storage of Nasser Lake by 13.287, 25.413, 37.263 BCM through each year; impounding of GERD at min of average flow from the Blue Nile through 6, 3, 2 years will decrease the active storage of Nasser Lake by 25.963, 37.814, 45.105 BCM per year; and impounding of GERD at min flow case through 6, 3, 2 years will decrease the active storage of Nasser Lake by 44.398, 54.415, 55.138 BCM through each year.

Mulat and Moges [15] assessed the impacts of the GERD on the performance of AHD. They used the Mike Basin river basin simulation model. They concluded that if 6 years were used to fill the GERD, yearly outflows of the GERD during the impounding stage will never be lower than 28.9 BCM per year (about 58% of the mean flow).

Ramadan et al. [16] quantified using a hydrological model, the shortage of water in the active storage of Nasser Lake due to impounding of GERD reservoir. Different scenarios of impounding were considered as 6, 3 and 2 years under different inflow conditions. Their results indicated that the negative impacts on Egyptian water resources were severe especially if the filling period is shorter than 6 years and their results agreed well with the results obtained by Mulat and Moges [15].

Based on the results of the hydrological models given by Ramadan et al. [14], Ramadan et al. [16], Mulat and Moges [15], and due to the importance of the Nile in the Egyptians' life, this investigation was thus initiated in order to assess the potential impacts of decreasing the outflows of the AHD (Reductions percentage range between 0 and 40%) due the construction of GERD on the different Nile water usages in Upper Egypt (navigation, hydropower production, municipal water, industries, irrigation pump stations, and agriculture lands quantities).

2. METHODOLOGY AND MODEL SET-UP

Several site visits were carried out in order to perceive a complete data picture about the AHD area and its annual discharges. The Nile River in Upper Egypt, (first three reaches) was thus visited in order to accumulate data about the studied reaches and their characteristics, so as the Nile's neighboring communities, industries, and infrastructures.

2.1 Assembling Data

The Nile River in Egypt from Aswan to Mediterranean Sea is divided into six reaches by barrages, Fig. 1. This study relies on the historical measurements of water levels and flow discharges on a series of gauging stations located along the Nile River. The stations were selected based on their location, ensuring that there is a good coverage of information along the river course and the availability of flow and water level records. The recent bathymetric, topographic and hydrographic survey of 2003/2007 executed by the Hydraulics Research Institute, (HRI), [17] includes 2720 cross sections with spacing of 200 m, covering the studied reaches from AHD to Assiut barrage. Also, data about communities and industrial activities on the Nile, irrigation works downstream of AHD were assembled different sources. Moreover, data about river navigation, cultivated land, water supply and hydropower production on the studied reaches, were assembled. All these data was analyzed in order to fill in knowledge gaps on hydrodynamic characteristics (cross sections, water levels, discharges) of the study reaches network.

2.2 SOBEK Model Background

The effective use of computer models requires an adopted model to be commensurate with the nature of problems being studied; the available data; accuracy requirement; and computer environment, [18]. In the present study, SOBEK-1D Model was chosen to be implemented in order to simulate the Nile River in Upper Egypt. The selection of SOBEK package verified the prototype knowledge-based system on intelligent manipulation and calibration of parameters for models that has been developed by Chen and Chau [18]. Prinsen and Becker [19] mentioned that SOBEK-1D Model has been successfully applied on river systems all over the world. The computation of the water levels and discharges in the SOBEK-flow-network is performed with the Delft-scheme, [20]. This scheme solves the Saint-Venant equations (continuity and momentum equations) by means of a staggered grid in which the water levels are defined at the connection nodes and calculation points while the discharges are defined at the intermediate reaches or reach segments. This software allows for the inclusion of several types of hydraulic structures such as weirs, sluice gates, pumps and locks as well as their operation rules, [20].

2.2.1 SOBEK Setup

The domain of the developed model covers the first three reaches of the Nile River in Egypt from the outlet of Nasser Lake (upstream boundary) to Assiut barrage (downstream boundary). The length of the simulated reaches of the river is about 544.75 km. Fig. 1 presents the schematization of the Nile with its branches and its main structures. The daily outflow discharge from AHD defines the upstream boundary conditions of the hydrodynamic model, whereas the daily discharge time series of the drains described in Fig. 1 are used as lateral flows entering the system. Water extraction for different water usages is used as lateral flows leaving the system. The time series water levels upstream Assiut barrage, define the downstream boundary conditions. The model includes the Aswan Old Dam, New Esna, and New Naga Hammadi Barrages with their operation rules. Every reach was spilt into segments that bounded by two calculation nodes of 200 m apart. The value of the time-step was derived imposing the Courant condition. The calculations were executed to the segments, structures and the intermediate nodes to produce the water levels, depths, velocities, discharges and some hydraulic characteristics. The simulation period considered one year to simulate the different water usages all over a year whereas the screening of the available historical data revealed that the outflow of AHD per year had small difference in the last ten years [21].

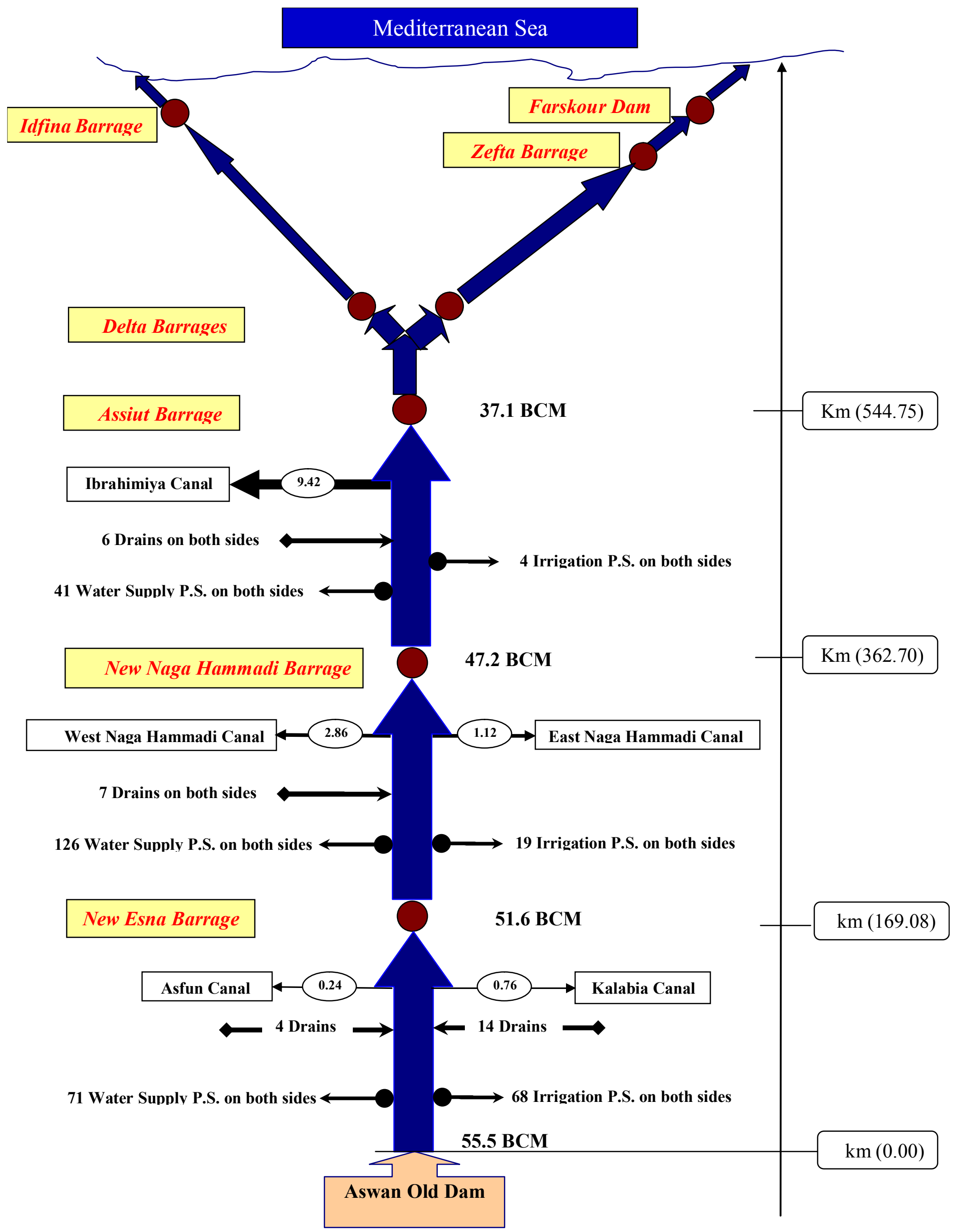


Fig. 1. Nile River reaches in Egypt

2.2.2 SOBEK Calibration and Validation

The idea underlying the calibration processes is to reduce the uncertainties of hydrodynamic variables by matching model results with the available measurements. The model should be able to capture the main discharge characteristics through the river network and to reproduce the relative water level fluctuations along the river network. Model calibration was carried out by comparing computed to collected maximum and minimum water levels at gauging stations downstream of the Aswan Old Dam (AOD) and along the simulated reaches; see Fig. 2. The primary parameter required for the calibration of SOBEK RURAL is the bed roughness. Manning's roughness coefficient (n) was chosen for the calibration. The model can freely calculate Manning's coefficient considering the local hydraulic radius taken from the last iteration loop. The calibration was performed by adjusting the values of n in order to get a good reproduction of the observed water level and discharges at a number of gauging stations. Several runs were carried out with different Manning's roughness coefficients, ranging between 0.014 and 0.033 ($S/m^{1/3}$) with the aim to optimize the reproduction of the observed water levels and discharges at a number of gauging stations. The adjusted values of Manning's coefficients were found and were tabulated, Table 1.

The results of model calibration in terms of discharges and water levels are shown in Fig. 2. The model calibration showed the relative difference between measured and computed water levels range between 0.02 to 0.04%. Because the calibration process involves some adjustments of parameter values that are optimized to fit a certain data set, good model calibration cannot automatically ensure that the model performs equally well also for other periods and circumstances. Therefore, model validations on independent data are required. Validation of the model was achieved based on real measurements of discharges and water levels. The measurements were carried out by the HRI, [17]. The comparisons between modeled and measured discharges and water levels show a good agreement between the model and the prototype.

2.2.3 SOBEK Application

Confidence with the calibration process, the model was applied to the designed scenarios. Nine (9) scenarios of Egypt quota reduction downstream of AHD were designed according to the results of the hydrological models given by Ramadan et al. [14], and Ramadan et al. [16] (they concluded that the active storage of Nasser Lake had a decrease between 13.28 and 55.138 BCM per year). Mulat and Moges [15] concluded that the yearly outflow of the GERD during the impounding stage will never be lower than 28.9 BCM. So, the annual outflow of the AHD will decrease with the same percentage. In order to conduct a comprehensive study, the designed scenarios consider yearly outflow downstream of the AHD ranges between 55.5 and 33.3 BCM. The considered scenarios are described in Table 2 and Fig. 3.

Table 1. Manning's values determined by model calibration

Reach no.	Reach (1D model)	Determined manning's factor (n) Roughness in SOBEK-River ($S/m^{1/3}$)
1	Aswan – Esna	0.025
2	Esna –Naga Hammadi	0.023
3	Naga Hammadi –Assiut	0.021

Table 2. Considered scenarios of Egypt quota reduction downstream of AHD

Scenario no.	Flow downstream of AHD (BCM/year)	Daily MIN. flow at Aswan (MCM/day)	% reduction
1	55.5	74.22	0
2	52.7	70.51	5
3	50	66.8	10
4	47.2	63.08	15
5	44.4	59.37	20
6	41.6	55.66	25
7	38.9	51.95	30
8	36.1	48.24	35
9	33.3	44.53	40

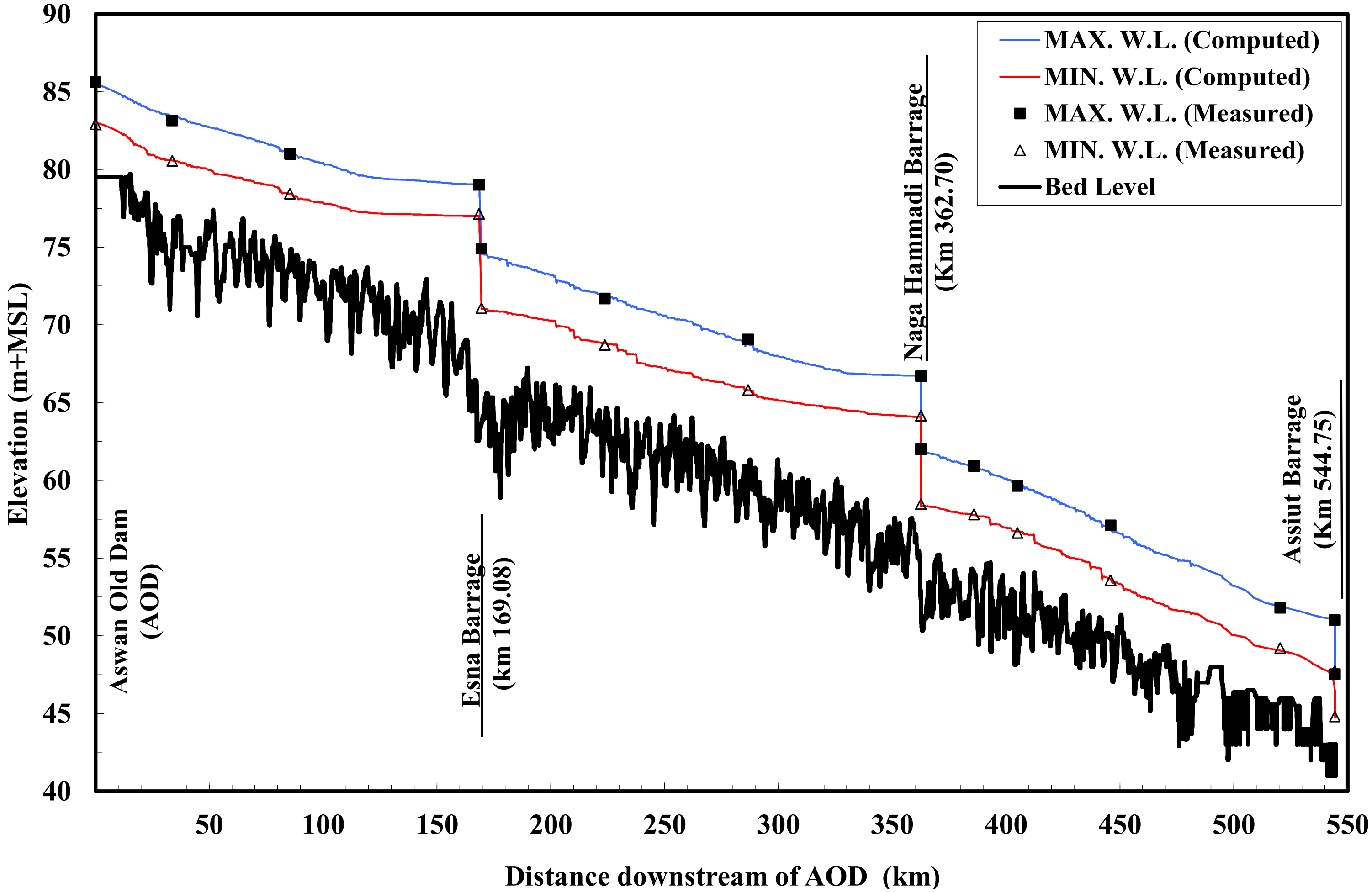


Fig. 2. Calibration process results

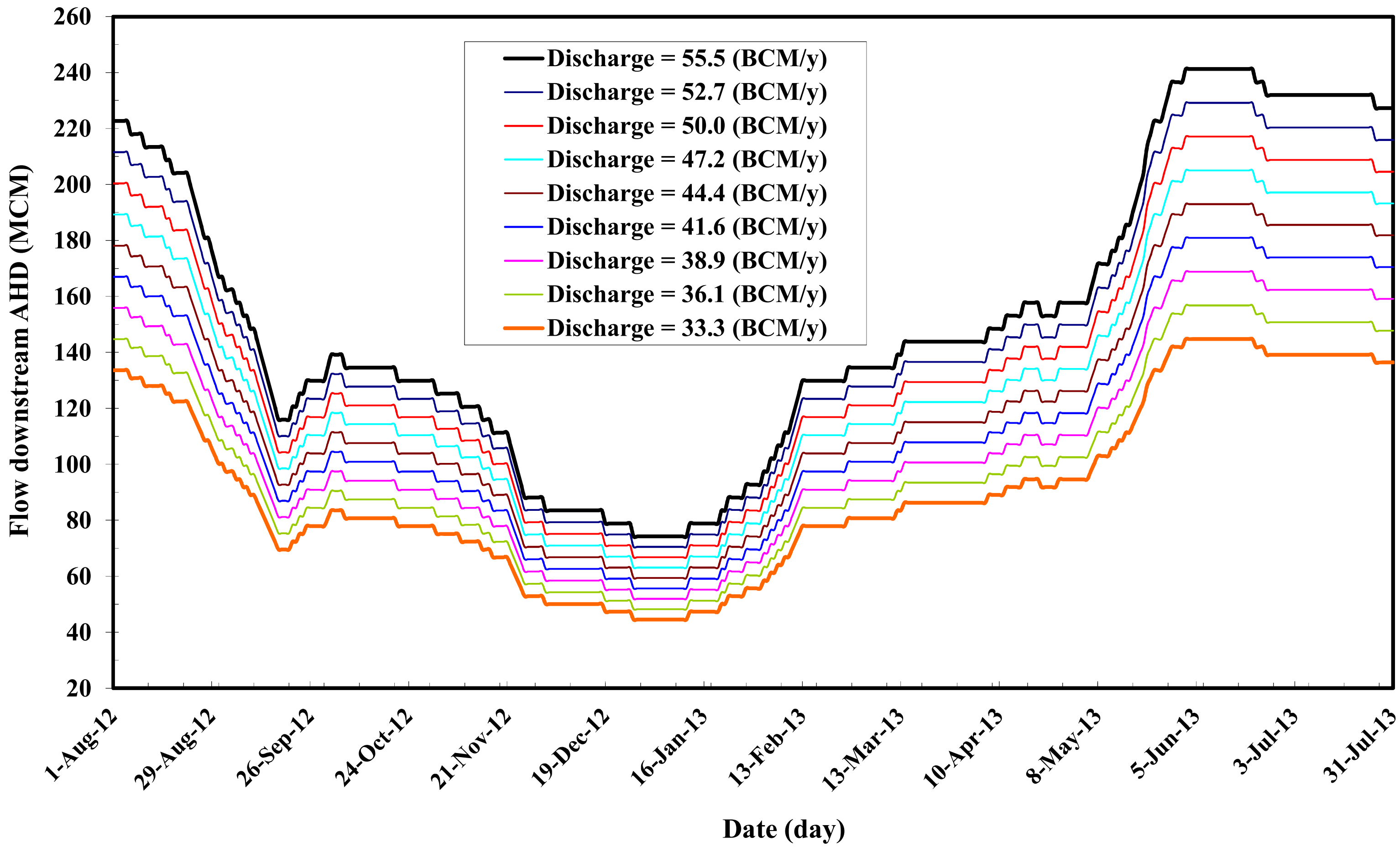


Fig. 3. Simulated scenarios

3. ANALYZING AND PRESENTING THE MODEL RESULTS

Negative impacts on Nile water discharge and levels along the considered Nile reaches in Egypt resulted from the reduction in water release downstream of AHD are evaluated and discussed as follow:

3.1 Impacts on Nile Water Levels

The impacts of GERD on the Nile water levels were investigated. Table 3 shows the impacts of the flow reduction downstream of AHD on Nile water levels. For each reach, some gauging stations were chosen which have average water level due to different scenarios. In addition, average reduction in water levels at different reaches was shown for each scenario. It is obvious that the average water level reduced at the first reach from 0.11 m for the second scenario to 1.02 m for the ninth scenario. Also, the average water level reduced at the second reach from 0.12 m for the second scenario to 1.09 m for the ninth scenario. The average water level reduced at the third reach from 0.10 m for the second scenario to 0.91 m for the ninth scenario. The results of the fourth and the eighth scenarios agreed well with the results obtained by Nada and Fathy [13].

3.2 Impacts on Nile Water Velocities

The impacts of GERD on the water velocity were studied. Fig. 4 shows the impacts of discharge reductions downstream of AHD on the Nile water velocities. It is clear that the Nile water velocities decreased through the studied reaches. These decreased velocities may increase the sedimentation process, which may affect the water surface profile. Moreover, it is believed that the increased sedimentation process will affect the quality of drinking water and the efficiency of pump stations.

3.3 Impacts on Municipal Pump Stations

The impacts of GERD on the municipal pump stations were obtained. The available data of drinking water plants were assembled from the Holding Company for Water and Wastewater, (HCWW), and were analyzed and the predicted minimum water levels were compared to the critical suction level of intakes in order to check their safety operation for each scenario. The collected data indicated that the first reach has 48 drinking water pump stations with vertical intakes and none with floating intakes. In the second reach, there are 47 stations with vertical intakes and none with floating intakes. In the third reach, there are 4 stations with vertical intakes and 11 with floating intakes. Fig. 5 and Table 4 indicate the impacts of different scenarios of flow reductions downstream of AHD on drinking water pump stations. From Fig. 5 and Table 4, it is obvious that scenarios 1, 2, 3, and 4 had no effect on the drinking water pump stations. This means that any reduction of Egypt water share up to 15% still results in water level higher than the minimum suction levels needed for all drinking water pump stations in reaches 1, 2, and 3. It is clear that for the fifth scenario, 3 stations in the first reach and 1 station in the second reach face a problem to operate under its designed suction water levels. Also, for the sixth scenario, 6 stations in the first reach and 5 stations in the second reach will not be able to operate. For the seventh scenario, up to 12 stations in the first reach and 15 stations in the second reach will not be able to operate due to the reductions in water level in front of their intakes. For the eighth scenario, 33 stations in the first reach, 37 stations in the second reach, and one station in the third reach will not be able to operate. For the ninth scenario, 37 stations in the first reach, 46 stations in the second reach, and 3 stations in the third reach will not be able to operate.

3.4 Impacts on Irrigation and Industrial Pump Stations

The impacts of GERD on the irrigation and industrial pump stations were studied. The available data for Irrigation and Industrial pump stations were obtained from database of the Nile Research Institute, (NRI), [22] and were analyzed, then the minimum water levels of each scenario were compared to the critical suction level of intakes at different irrigation and industrial pump stations to check their safety operation. These data indicated that in the first reach, 33 pump stations with vertical intakes and 35 with floating intakes. In the second reach, 15 stations with vertical intakes and 3 with floating intakes. And in the third reach, only 5 stations with vertical intakes and none with floating intakes. Fig. 6 and Table 5 indicate the effect of different scenarios of flow reduction downstream of the AHD on irrigation and industrial pump stations. From Fig. 6 and Table 5, it is obvious that scenarios 1, 2, and 3 had no effect on the irrigation and industrial pump stations. This means that, any reduction of Egypt water share up to 10% gives water level higher than the suction levels needed for all irrigation and industrial pump stations in the studied reaches. For the fourth and fifth scenarios, only El Radissia new pump station at the first reach faced a problem with the suction level. For the sixth and seventh scenarios, there were 4 stations in the first reach, one station in the second reach, and one station in the third reach will not be able to operate under its suction water levels. For the eighth scenario, 22 stations in the first reach, 9 stations in the second reach, and 4 stations in the third reach will face a problem to operate. For the ninth scenario, up to 28 stations in the first reach, 12 stations in the second reach, and 4 stations in the third reach will face a problem to operate under its designed suction water levels. The results of fourth, fifth and sixth scenarios agreed well with the results obtained by Ismail [12].

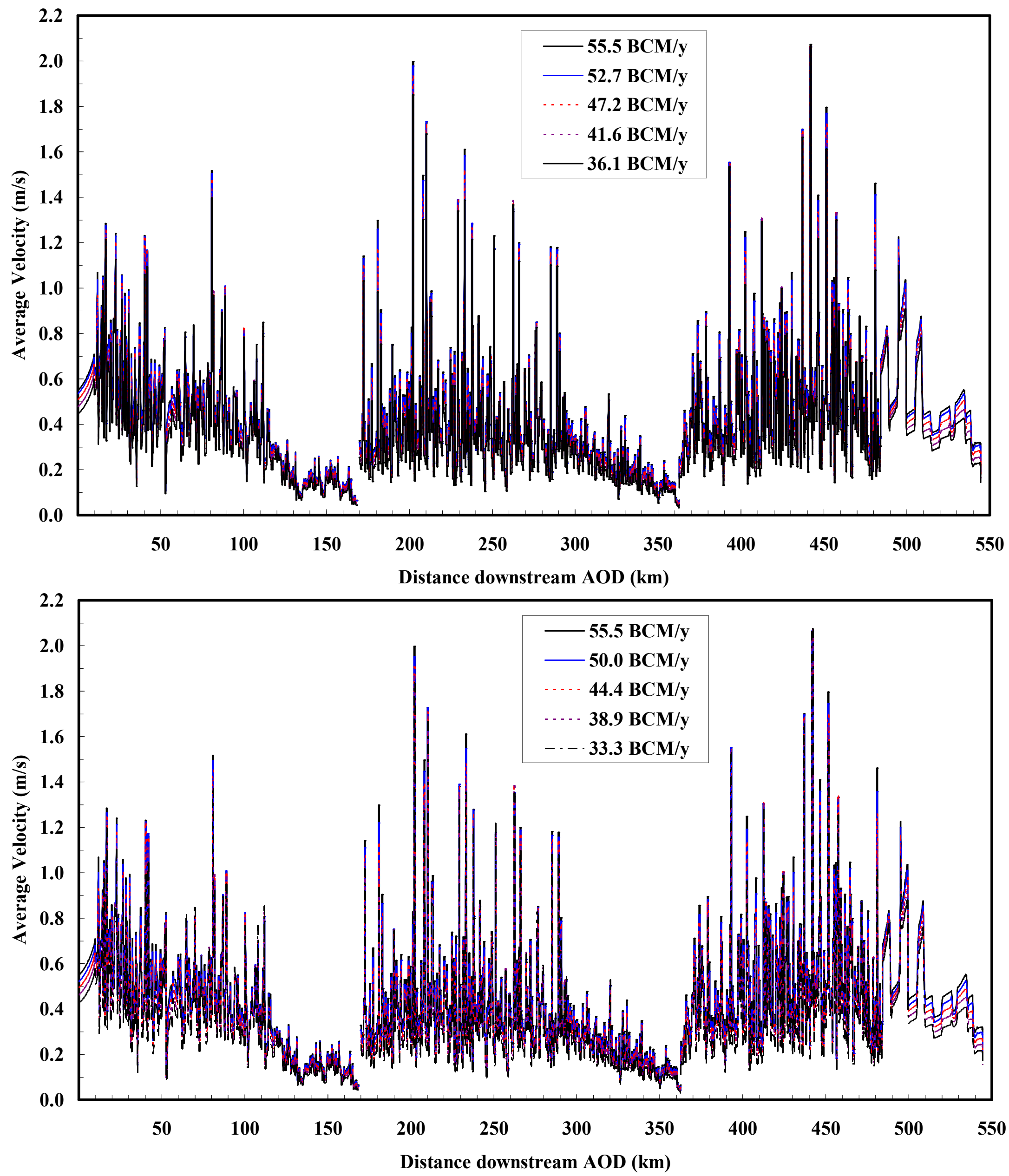
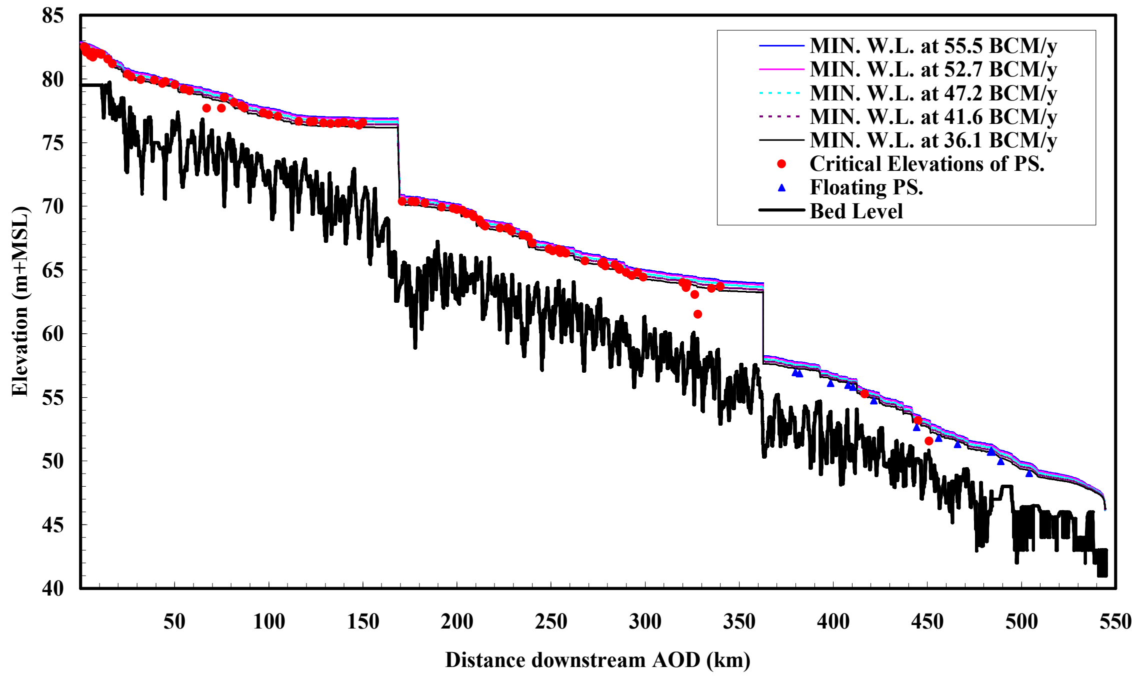


Fig. 4. Impacts of different scenarios on water velocity of the studied reaches

Table 3. Changes in average water levels due to flow reductions

Station name	Distance from AOD	AHD Discharge (BCM/year)	AHD Release (BCM/year)							
		55.5	***52.7***	***50.0***	***47.2***	***44.4***	***41.6***	***38.9***	***36.1***	***33.3***
		Average water levels	**Average water levels**							
	(km)	**(m+MSL)**	**(m)**							
Aswan	7.00	83.74	83.64	83.54	83.43	83.33	83.22	83.11	83.00	82.88
El Gaafra	33.75	81.90	81.78	81.66	81.54	81.41	81.28	81.15	81.01	80.86
Silwa Bahary	85.45	79.68	79.56	79.44	79.32	79.19	79.06	78.93	78.79	78.64
El Kalabia El Kadeema	155.70	77.94	77.81	77.68	77.55	77.41	77.27	77.12	76.97	76.81
Average reduction in water levels at Reach 1 (m)			*0.11*	*0.23*	*0.35*	*0.48*	*0.60*	*0.74*	*0.87*	*1.02*
DS. Esna Barrage	169.08	72.78	72.66	72.53	72.40	72.26	72.12	71.97	71.82	71.66
Luxor	223.80	70.33	70.23	70.12	70.01	69.90	69.78	69.67	69.54	69.42
Qena	286.75	67.20	67.06	66.93	66.78	66.64	66.49	66.33	66.17	66.01
Deshna	316.60	66.08	65.95	65.82	65.69	65.55	65.41	65.26	65.11	64.95
Average reduction in water levels at Reach 2 (m)			*0.12*	*0.25*	*0.38*	*0.51*	*0.65*	*0.79*	*0.94*	*1.09*
DS. Naga Hammadi Barrage	362.70	60.14	60.03	59.91	59.79	59.66	59.53	59.40	59.26	59.11
El Balyana	386.00	59.34	59.23	59.13	59.02	58.91	58.80	58.68	58.56	58.43
Sohage	445.95	55.36	55.25	55.14	55.03	54.92	54.80	54.67	54.54	54.41
Abo Teeg	520.50	50.46	50.38	50.29	50.20	50.11	50.02	49.92	49.82	49.72
Average reduction in water levels at Reach 3 (m)			*0.10*	*0.21*	*0.31*	*0.42*	*0.54*	*0.66*	*0.78*	*0.91*



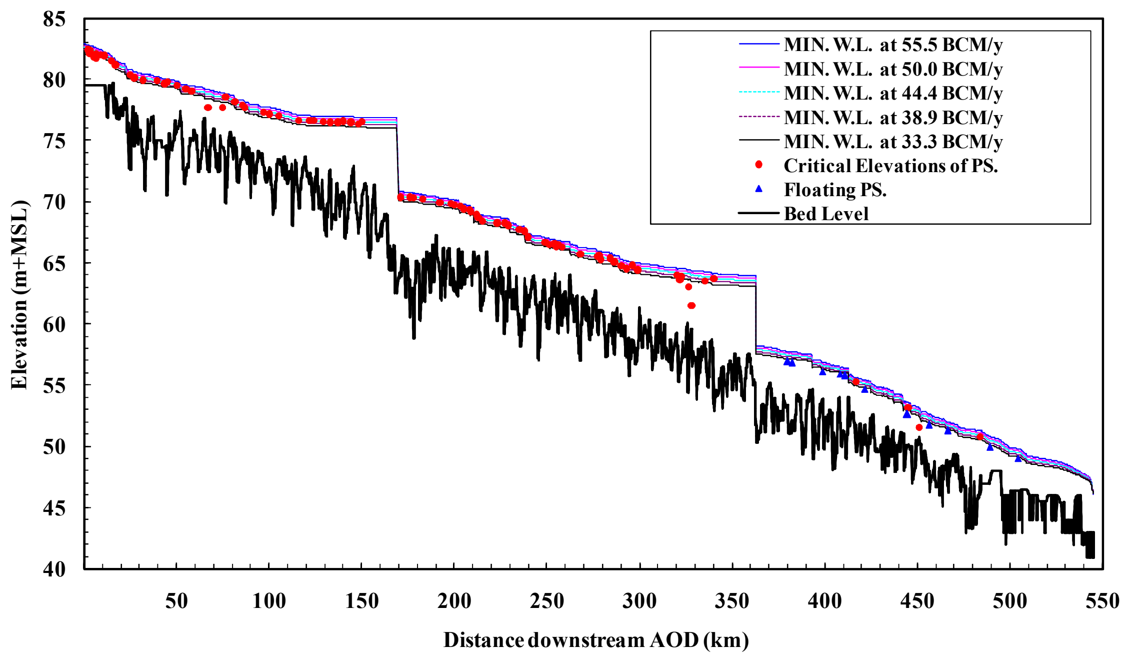


Fig. 5. Impacts of different scenarios on municipal pump stations

3.5 Impacts on River Navigation

The impacts of GERD on the navigation capability were examined. Nile River Navigation in Egypt consists mainly of the transportation of bulk materials from Aswan to Alexandria and tourist boats which offer hotel and travel between Luxor an Aswan. Touristic navigation considered one of Egypt's main income resource, especially in Upper Egypt in the first reach of the Nile. The touristic season in this area is in winter (closure period) so that more discharges are released downstream of AHD in the closure period. To ensure safety navigation on the Nile in Upper Egypt, the navigation pass was designed to have a navigation draft of 2.30 m at minimum flow conditions. Fig. 7 and Table 6 demonstrate the impacts of the flow reduction downstream of AHD on Nile water depths and navigation. It is clear that the first and the second scenarios had small effect on the navigation, where only one location of navigation bottleneck locates at the first reach at km 45.00 downstream of Aswan Old Dam, (AOD) with a shallow depth of 2.26 m in the first scenario and 2.13 m in the second scenario. The first scenario has no effect on the navigation in the second reach. For the second scenario, there is only one navigation bottleneck at the second reach at 189 km downstream of AOD with a water depth of 2.20 m. Meanwhile, there is one navigation bottleneck appeared as result of the first scenario at the third reach. There are two navigation bottlenecks at the third reach as result of second scenario. It is clear that the impacts of water release reduction downstream of AHD on the third reach are more significant than that of the first reach, which are more significant than that of the second reach. This means that the second reach has small negative impacts due to the flow reductions downstream of AHD on the Nile River navigation. Also, Table 6 clarifies the number and the location of bottleneck for different studied Nile reaches.

Table 4. Impacted drinking water pump stations

No.	Name	Distance from AOD	Flow at Aswan (MCM/day)				
		Km	59	56	52	48	45
1	Aoshkul	2.00				*	*
2	West Suhail Filtration	2.50				*	*
3	Nag station	3.00			*	*	*
4	Gabal Nicoq Water Plant	5.25				*	*
5	Sayeda Zeinab Filtration	5.95				*	*
6	Aswan West	9.00				*	*
7	Abu Rish Kibly	11.00				*	*
8	Nag strong Filtration	11.00			*	*	*
9	Bharrif Filtration	14.60					*
10	Abu Rish Bahri Filtration	17.00					*
11	Qurmalh Filtration	25.00				*	*
12	El Aakab Bahari Filtration	27.00					*
13	Bkulwas Filtration	32.00					*
14	Nag EL Hagar Filtration	39.20				*	*
15	Draw Water Plant	45.10				*	*
16	El Rakabaa Water Plant	43.50	*	*	*	*	*
17	Sheikh Abdullah Filtration	55.00			*	*	*
18	El Mansoureya Filtration	50.20	*	*	*	*	*
19	Meneha Water Plant	58.00				*	*
20	Fares Filtration	76.50				*	*
21	FiltrationAlcajoj	76.30	*	*	*	*	*
22	Shebikaa Filtration	81.50				*	*
23	Selwa Bahari Filtration	85.60			*	*	*
24	Alrikikin Water Plant	87.00			*	*	*
25	El Zenbka Filtration	97.00			*	*	*
26	El Serag Filtration	100.00				*	*
27	El Radissia Filtration	105.00				*	*
28	East Edfo Filtration	116.00				*	*
29	Azebat El Masary Filtrationr	122.00				*	*
30	El Domarya Filtration	124.00		*	*	*	*
31	Nasrab Filtration	129.00				*	*
32	El Saaida Filtration	133.00				*	*
33	Alzoaida	137.00				*	*
34	Aqaba Filtration	140.00		*	*	*	*
35	El Sebaeya Filtration	144.00				*	*
36	El Sebaeya Filtration	148.00				*	*
37	Nag El Sharawna Filtration	150.00		*	*	*	*

No.	Name	Distance from AOD	Flow at Aswan (MCM/day)				
		Km	59	56	52	48	45
38	El Deer Filtration	171.00					*
39	Abourit Taakh Filtration	176.00			*	*	*
40	Tafnas Filtration	178.00			*	*	*
41	El Kayman Filtration	183.00			*	*	*
42	El Ghoriera Water Plant	192.00				*	*
43	El Mahamid Filtration	198.00				*	*
44	El Rozaikat Filtration	200.00				*	*
45	El Ohdissat Filtrations	203.00			*	*	*
46	Armant El Waborat Filtration	205.00				*	*
47	Armant EL Waborat Island Filtration	208.00				*	*
48	El Tour Filtration	209.00				*	*
49	El Rozaikat Bahari Filtration	212.00		*	*	*	*
50	El Bayadya Filtration	213.00			*	*	*
51	El Dabayaa Filtration	215.00					*
52	El Baarat Filtration	223.00				*	*
53	El Kurna Filtration	227.00			*	*	*
54	El Rroajeh Filtration	229.00			*	*	*
55	El Zinnia Kibly Filtration	229.00				*	*
56	El Melahaa Filtration	235.00				*	*
57	EL Atti Filtration	238.00				*	*
58	El Mahrousa Filtration	240.00		*	*	*	*
59	El Gamaliaa Filtration	249.00				*	*
60	Dunfik Filter water	251.00					*
61	Water Filter Rouge and Aldjaafarh	254.00				*	*
62	Nakada Water Plant	254.00				*	*
63	Quos Water Plant	255.00				*	*
64	El Khattara Filter water	256.00			*	*	*
65	Tookh Water Plant	258.00			*	*	*
66	Faket Filtration	268.00				*	*
67	El Ashraaf Alasilah Filtration	277.00				*	*
68	El Ashraaf Kibalyiaa Filtration	278.00		*	*	*	*
69	El Deer Water Plant	278.00				*	*
70	El Ataiwarat Water Plant	279.00					*
71	El Salehia Water Plant	284.00		*	*	*	*
72	El Altramsh Water Plant	286.00				*	*
73	Safaga Water Plant	286.30				*	*
74	Qena Old Water Plant	286.30				*	*
75	DandaraWater Plant	290.00				*	*
76	El Sheikh Aissa Water Plant	293.00					*
77	El Qnawi Water Plant	296.00	*	*	*	*	*
78	Walaad Amr Filtration	299.00				*	*
79	Kulmina Water Plant	320.00				*	*
80	El Wakaf Water Plant	321.75				*	*
81	El Wakaf Bahari Water Plant	322.00					*
82	El Qasar Filtration	335.25					*
83	El Nagahah Water Plant	340.00			*	*	*
84	El Monshaa Water Plant	416.73				*	*
85	Sohag Water Plant	445.00					*
86	Tahta Water Plant	484.00					*

(*): Water levels lower than the critical suction elevation of pump stations (haven't adequate water depths at their intakes)

3.6 Impacts on Hydropower Production

The impacts of GERD on the hydropower production were induced. Hydropower significantly impacted by GERD due to flow reductions. The annual amount of energy produced form water passed through the barrages' turbines depends on the head and efficiency of turbines. Produced energy for hydropower plants in 2012/2013, was accumulated from the Holding Company for Electricity in Egypt, (HCEE), [23] as given in Table 7.

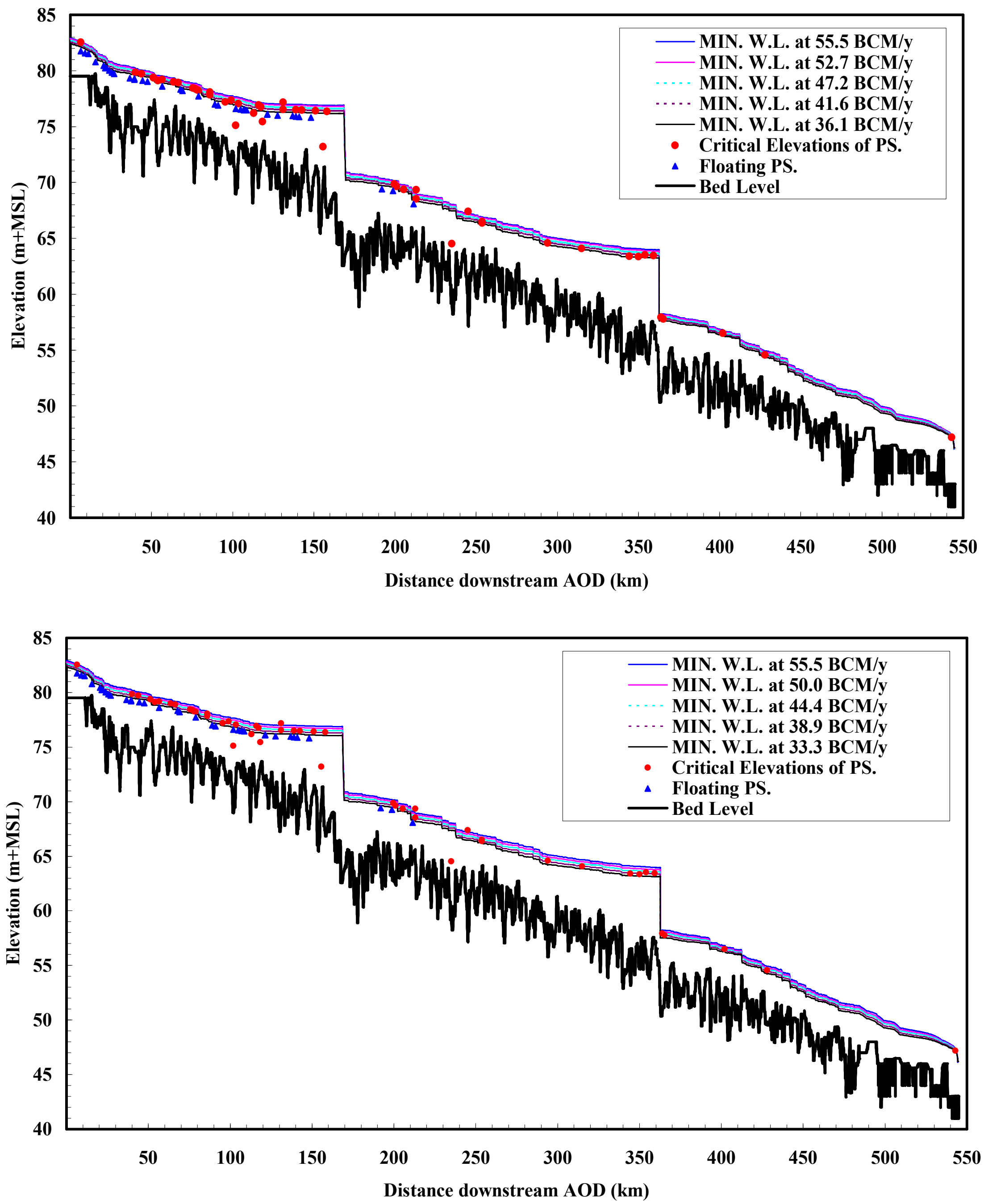
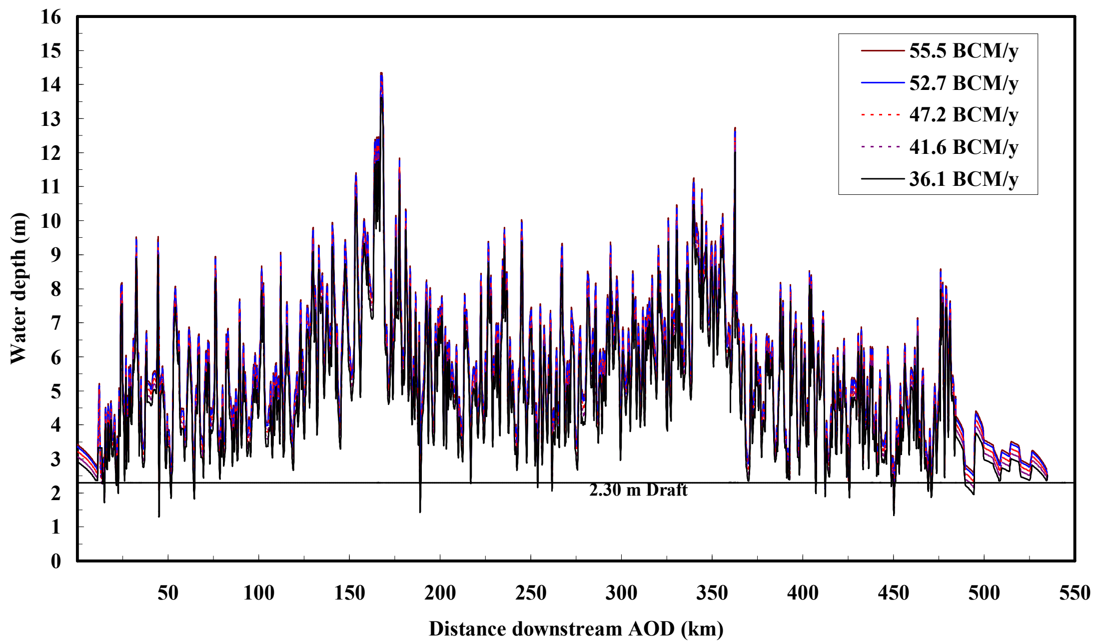


Fig. 6. Impacts of different scenarios on irrigation and industrial pump stations

Table 5. Impacted irrigation and industrial pump stations

No.	Name	Distance from AOD	Flow at Aswan (MCM/day)					
		Km	63	59	56	52	48	45
1	Draw	40.00					*	*
2	New Benban	44.00					*	*
3	Old Benban	44.00					*	*
4	El Bayyara (New)	51.15					*	*
5	El Bayyara (Old)	51.30					*	*
6	El Mansoureya	54.00					*	*
7	El Mansourya	54.00					*	*
8	Meneha Island	56.60					*	*
9	Old Ekleet	62.30					*	*
10	New Ekleet	63.60					*	*
11	El Boier	66.50			*	*	*	*
12	El Selsela	75.50					*	*
13	New Selwa Kibly	77.00					*	*
14	Selwa El Mostgada	78.00					*	*
15	Selwa Kibly (Old)	79.00					*	*
16	Selwa Bahri (Old)	86.00			*	*	*	*
17	New Selwa Bahari	86.00					*	*
18	El Radissia	95.40					*	*
19	El Serag	99.00			*	*	*	*
20	El Ramadi (New)	103.60					*	*
21	Blokhar	116.00					*	*
22	El Radissia (New)	117.50	*	*	*	*	*	*
23	El Bosilaia	131.02					*	*
24	El Hagz	138.88					*	*
25	El Sabaaya West (Old)	142.50					*	*
26	El Nesma	151.00					*	*
27	Naga Abo Arfa	155.70					*	*
28	El Kalabya	158.00					*	*
29	El Ghoriera	199.60					*	*
30	El Rozaikat	201.00			*	*	*	*
31	Sugar Factory	205.50					*	*
32	El Bayadya	213.00					*	*
33	Qaus Sugar Factory	253.70					*	*
34	Qaus Paper Factory	253.80					*	*
35	Dandara	294.00					*	*
36	El Marashda	315.00					*	*
37	El Derb	344.35					*	*
38	El Derb (Emergency)	350.00					*	*
39	El Khodirat	354.00					*	*
40	El Kheyam (Sohag)	359.20					*	*
41	Abu Homar	364.00					*	*
42	El Khiyan	365.33			*	*	*	*
43	Girga Island	402.00					*	*
44	El Ahawa Island	428.00					*	*

(*): Water levels lower than the critical suction elevation of pump stations (haven't adequate water depths at their intakes)



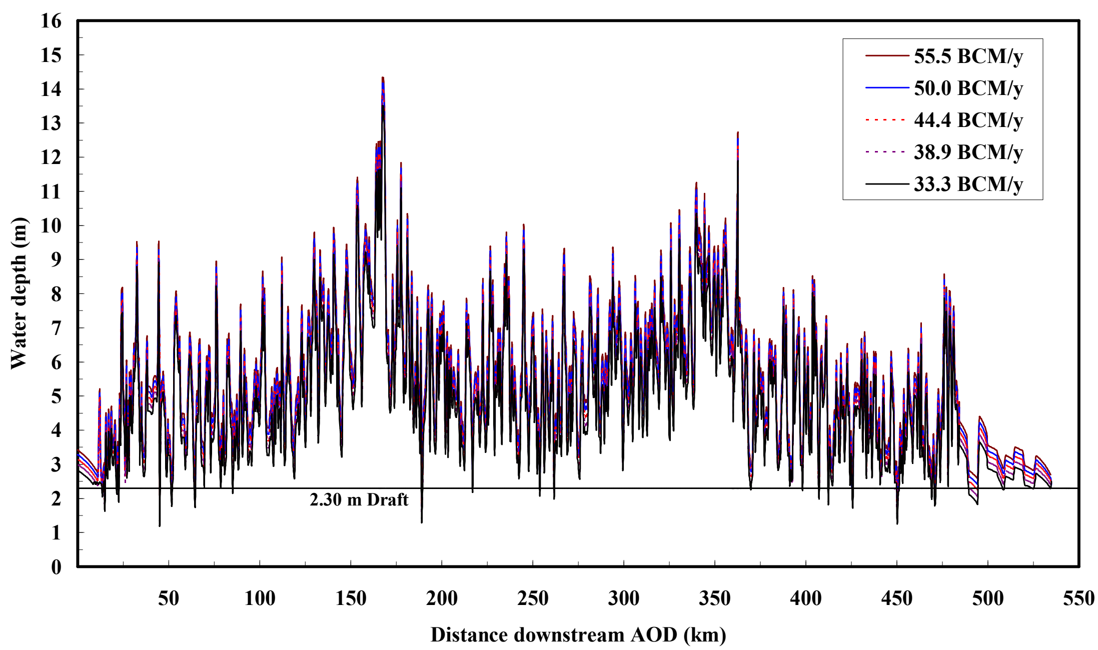


Fig. 7. Bottlenecks on the studied reaches of the Nile according to different scenarios

The produced energy from AHD, AOD station I and II, Esna, and Naga Hammadi hydropower plants are about 12% of the total produced electric energy of Egypt, [18]. Table 7 describes the impacts of flow reduction downstream of the AHD on produced hydropower in the study area. It is obvious that there were losses in annual produced energy from the AHD range from 11.5% for the second scenario to 44.3% for the ninth scenario while there are losses in annual produced energy from the AOD range from 6.3% for the second scenario to 25.1% for the ninth scenario. Moreover, the losses percentage in the annual produced energy of Esna and Naga Hammadi barrages are tabulated in Table 7.

Table 6. Locations of points of insufficient water depth

Locations of insufficient depth on the Nile at Reach1 (AOD –Esna barrage)

Flow at Aswan (MCM/day)	Bottleneck location Distance downstream AOD, (km)	Points depths	Total locations
74	45	a shallow with a depth of 2.26 m	1
71	45	a shallow with a depth of 2.13 m	1
67	45, 51.54, and 64.5	Shallow with depths range from 2.05 to 2.25 m	3
63	45, 51.54, and 64.5	Shallow with depths range from 1.91 to 2.17 m	3
59	45, 51.54, and 64.5	Shallow with depths range from 1.82 to 2.11 m	3
56	45, 51.54, and 64.5	Shallow with depths range from 1.69 to 2.03 m	3
52	22.52, 45, 51.54, and 64.5	Shallow with depths range from 1.57 to 2.17 m	4
48	14, 21.51, 22.52, 45, 51.54, and 64.5	Shallow with depths range from 1.46 to 2.29 m	6
45	13.51, 14, 21.51, 22.52, 45, 51.54, 64.5 and 85.20	Shallow with depths range from 1.35 to 2.20 m	8

Locations of insufficient depth on the Nile at Reach2 (Esna Barrage - Naga Hammadi Barrage)

Flow at Aswan (MCM/day)	Bottleneck location Distance downstream AOD, (km)	Points depths	Total locations
74	-	-	0
71	189	a shallow with a depth of 2.20 m	1
67	189	a shallow with a depth of 2.11 m	1
63	189	a shallow with a depth of 2.00 m	1
59	189	a shallow with a depth of 1.89 m	1
56	189, and 261.79	Shallow with depths range from 1.80 to 2.17 m	2
52	189, and 261.79	Shallow with depths range from 1.69 to 2.08 m	2
48	189, 217, 253.83, and 261.79	Shallow with depths range from 1.55 to 2.27 m	4
45	189, 217, 253.83, and 261.79	Shallow with depths range from 1.42 to 2.16 m	4

Locations of insufficient depth on the Nile at Reach3 (Naga Hammadi Barrage - Assiut Barrage)

Flow at Aswan (MCM/day)	Bottleneck location Distance downstream AOD, (km)	Points depths	Total locations
74	450.23	a shallow with a depth of 1.88	1
71	412.21, and 450.23	Shallow with depths range from 1.81 to 2.19 m	2
67	412.21, 450.23, and 470.75	Shallow with depths range from 1.72 to 2.25 m	3
63	412.21, 425.72, 450.23, 470.75, and 471.25	Shallow with depths range from 1.65 to 2.28 m	5
59	412.21, 425.72, 450.23,469.25, 470.75, 471.25, 493.79, and 494.29	Shallow with depths range from 1.58 to 2.19 m	8
56	412.21, 425.72, 450.23,469.25, 470.75, 471.25, 493.79, and 494.29	Shallow with depths range from 1.50 to 2.22 m	8
52	407.2, 412.21, 425.72, 450.23,469.25, 470.75, 471.25, 493.79, and 494.29	Shallow with depths range from 1.42 to 2.19 m	9
48	407.2, 412.21, 425.72, 450.23,469.25, 470.75, 471.25, 493.79, 489.78 and 494.29	Shallow with depths range from 1.34 to 2.20 m	10
45	369.67, 398, 407.2, 412.21, 425.72, 448.73, 450.23,469.25, 470.75, 471.25, 492, 493.79, 494.29, and 508.81	Shallow with depths range from 1.25 to 2.26 m	14

Table 7. Impacts on produced energy

Power plant	**Total installed capacity**	**% Efficiency (2012/2013)**	**Average head (2012/2013)**	**Produced energy (2012/2013)**	**AHD release (BCM/year)**							
					52.7	***50.0***	***47.2***	***44.4***	***41.6***	***38.9***	***36.1***	***33.3***
	(MW)		**(m)**	**(GWh)**	***% Losses in annual produced energy***							
Aswan High Dam	2100	*86.80*	65.57	8920	11.5	16.2	20.8	25.6	30.3	34.9	39.7	44.3
Aswan Old Dam I	280	*83.60*	23.99	1498	6.3	8.6	11.0	13.4	15.6	18.2	20.7	23.1
Aswan Old Dam II	270	*89.50*	23.99	1567	6.4	9.0	11.7	14.0	17.1	19.9	22.8	25.1
Esna Barrage	86	85.80	5.35	499	9.7	13.4	17.1	20.7	24.3	28.0	31.7	35.3
Naga Hammadi Barrage	64	82.70	5.19	450	8.7	11.9	15.2	18.4	14.6	25.0	28.3	31.5

3.7 Impacts on Agriculture Lands

The impacts of GERD on the agriculture lands were detected. Table 8 demonstrates the water resources and demands in Upper Egypt. It is obvious that, a current water demand of Upper Egypt is estimated at 12.69 BCM per year, from which the Nile River provides 12.17 BCM and therefore becomes an almost exclusive source of fresh water for Upper Egypt. The rest of the water requirements is met by a renewable groundwater with 0.46 BCM/year and a drainage water reuse which is estimated as 0.07 BCM. For water demand about 11.81 BCM for agriculture, 0.78 BCM for municipal water and 0.11 BCM for industries [22].

Table 9 presents the agriculture water demands in Upper Egypt. On the other hand, Table 10 shows the overall agriculture water demands in Egypt. Agriculture lands and water duties for each administration from Aswan to Assiut in the study area also are tabulated. There is about 1.459 million feddans agriculture land from Aswan to Assiut that required about 11.81 BCM/year of irrigation water. Table 10 clarifies the agriculture water demands and agriculture lands for Egypt. It is clear that, there is about 9.176 million feddans agriculture land from Aswan to Mediterranean Sea that require about 63.51 BCM/year of irrigation water.

Table 11 presents the impacts of flow reductions downstream of AHD on agriculture lands in Egypt. It is clear that there were losses in agriculture lands in Upper Egypt due to flow reductions range from 12.7% for the second scenario to 46.24% for the ninth scenario. In addition, there were losses in agriculture land in middle Egypt and Delta range from 7.09% for the second scenario to 38.97% for the ninth scenario.

Table 8. Water balance of Upper Egypt, (Studied reaches), (2012/2013)

Water resources		**Water demands**	
	BCM/year		
Nile River	12.17	Agriculture water	11.81
Ground water	0.46	Municipal water	0.78
Reused water	0.07	Industrial water	0.11
Total inputs and outputs	12.69		12.69

Table 9. Agriculture water demands in Upper Egypt (Studied Reaches)

Administration	**Areas (1000 Feddans)**	**Water Requirements (BCM/year)**	**Average Water duty m^3/Fed/year**
Aswan	326.31	3.17	9718.5
East Qena	174.95	1.28	7317.0
West Qena	227.22	1.51	6663.7
Sohag	406.63	2.86	7025.8
Assiut	324.84	2.98	9183.1
Total	**1459.94**	**11.81**	

Table 10. Agriculture water demands in Egypt

Locations	**Areas (1000 Fed.)**	**Water demands (BCM/year)**	**Average water duty m^3/Fed/year**
Upper Egypt	1459.94	11.81	8086.2
Middle Egypt	1470.18	11.50	7822.2
Delta	6246.57	40.21	6437.0
Total	9176.69	63.51	

Table 11. Impact of flow reductions on agriculture lands

Locations	**Current areas**	**AHD release (BCM/year)**							
		52.7	**50.0**	**47.2**	**44.4**	**41.6**	**38.9**	**36.1**	**33.3**
	(1000 Fed.)	**% Losses in Agriculture Lands**							
Upper Egypt	1459.94	12.70	17.48	22.26	27.04	31.84	36.63	41.43	46.24
Middle Egypt and Delta	7716.75	7.09	11.65	16.21	20.77	25.32	29.88	34.43	38.97

3.8 Other Impacts

Other impacts include water quality, environment, fisheries, and recreation aren't included in this research but due to flow reductions downstream of AHD, one has a strong believe that all these issues will be significantly negatively impacted due to decrease of the river flow.

4. CONCLUSIONS AND RECOMMENDATIONS

Based on the above investigation phases, conclusions were deduced. From the numerical simulation it was found that:

- Reducing Egypt water share more than 15% induces superficial effects on the drinking water stations.
- Reducing Egypt water share up to 10% induces no effect on the irrigation, and industrial pump stations.
- Reducing Egypt water share up to 5% produces small effect on the safe navigation.

The average water levels were reduced through all the studied reaches from the first to the ninth scenario as follow:

- From 0.11 m to 1.02 m at the first reach.
- From 0.12 m to 1.09 m at the second reach.
- From 0.10 m to 0.91 m at the third reach.
- The Nile water velocities were decreased.
- Hydropower losses from the AHD were between 11.5 and 44.3%.
- The losses in area of agriculture lands in Upper Egypt were between 12.7 and 46.24%.

The following recommendations are given for helping the decision makers:

- Pump stations with floating intake should be taken into considerations at designing of new pump stations.
- Constructing additional intakes to the existing pump stations to be suitable with minimum water levels.
- AHD operation rules should be readjusted to cope with the possible reduction in water release downstream in order to properly deal with stored water in Nasser Lake.
- More reliable water management policy for Egypt water resources should be developed to deal with possible future water shortage.
- Egypt, Sudan and Ethiopia have to develop their water resources for the benefit of their people based on the principle of equitable use.
- Serious negotiations between Egypt, Sudan, and Ethiopia should continue to solve the water conflict between them and a win–win strategy should be applied to defuse tensions between Egypt and Ethiopia over the GERD.
- Ethiopia needs to agree with Egypt and Sudan on the capacity of the GERD reservoir, rules for impounding the GERD reservoir and on operating rules, Whittington et al. [24].

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COMPETING INTERESTS

Authors have declared that no competing interests exist.

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