Effect of Grand Ethiopian Renaissance Dam on the Water Footprint of Aswan High Dam Hydropower

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Abstract

Construction of the Ethiopian Grand Renaissance dam (GRD) has many impacts and implication on the water share and future use in Egypt. Especially the period of the reservoir filling will have a great effect on the Nile River and its water in Egypt. Many of these effects of the GRD on Egypt has been studied before, but no study was done on the effect of its existence on the hydropower water footprint of the High Aswan dam. This research is concerned by simulating the effect of the different GRD reservoir filling scenarios on the water footprint of the hydropower generated from the High Aswan dam. Also, the effect on the hydropower of the Aswan dam itself is also simulated and assessed. Mathematical modeling is used to reach those goals. Three filling scenarios of the GRD were investigated: namely 3 years, 5 years, and 6 years. It was found that as the filling duration of the GRD decreases the negative effect on the hydropower water footprint increases.

Keywords

Nile River; Aswan High Dam; Water Footprint; Ethiopian Grand Renaissance; Hydropower

Introduction

“Egypt is the gift of the Nile”; that is how the Greek historian Herodotus described the relation between Egypt and the Nile River. Egypt is an arid dry area. In summer, the temperature usually exceeds 38°C in some parts of the country and the average annual rainfall amounts are very low all year long (1). With these nature and limited water resources, Egypt relies on the Nile River to fulfill 97% of the water needs of the Egyptian population that reached more than 100 million capita nowadays. However, the seasonal flow of the Nile River cannot fully satisfy these needs during the drought season; whereas, it overflows and causes disaster during excess flooding season. Due to these conditions, the Egyptian government had decided to build Aswan high dam which completed in 1968 and fully operated in 1972.

Aswan High Dam (AHD) is a rockfill hydraulic structure that is located 7 km south Aswan City (2). The dam is 3600 m in length, 111 m in height above the riverbed and 980 in top width (3). AHD is very important for the development of the country as it controls the flood of the Nile to protect the Nile valley and Delta areas from high floods and drought hazards. Its existence also led to agriculture developments and expansion and reclamation plans. It also improves the navigation in the Nile. In addition, the dam is supplied by a hydropower station with installed capacity of 2.1 million MW and it generates up to 10,000 Gwh. Upon building the dam, the hydropower generated from AHD was responsible for providing electricity for 4500 villages, many factories and pumping stations for irrigation and drainage which helped in raising the industrialization and standard of living in Egypt (1,3). On the other hand, the AHD reservoir is the

second greatest reservoir in the world as it occupies an area of 6000 km² (4). Lake Nasser is a vital water source as it fulfils the water needs of about 85% of Egypt's population in spite the fact that it has a high annual evaporation rate that ranges from 2.1 to 2.6 m/y due to the hot and arid weather of its location (Ebaid & Ismail, 2010; Muala et al., 2014). Although AHD and its reservoir play a vital role in the Egyptian water security, this role became threatened due to the construction of the Grand Ethiopian Renaissance Dam (GERD).

The Grand Ethiopian Renaissance Dam (GERD) is the dam that is announced to be constructed in April 2011. GERD is a rock-fill dam that is located 500 km North West of the capital Addis Ababa, in the region of Benishangul - Gumaz along the Blue Nile in Ethiopia. This dam is expected to be the largest in Africa with a length of 1800 m, a height of 155 m and total volume of 74 billion m³ (4). According to many studies, GERD has negative effects on the water security in Egypt. These studies showed that Egypt's share of the Nile river, which is 55.5 billion m³, will be deducted by an average of 20% in case of filling the GERD in 6 years, 27.3% in case of filling in 5 years and 45.5% in case of filling in 3 years (El Agroudy et al., 2014; Liersch et al., 2017; Zhang et al., 2016). These deductions will decrease Lake Nasser's storage which is a vital resource for irrigation and local water consumption. They will also reduce the area of the agriculture lands in Upper Egypt by 29.47% and in Delta by 23% ;as well as, stopping reclamation projects and agricultural expansion in many parts of Egypt which will increase the Egyptian food gap to 75% instead of 55% (4,9,10). Also, there will be negative effects on the quality of water in the Nile River and on the navigation in it and its branches. For the hydropower, GERD will reduce the water flow that reaches the AHD which will affect the hydropower generation. According to El Agroudy et al., 2014, in case of filling the GERD in 6 years, the hydropower generated from the AHD will be reduced by 16 – 20% in case of high flood, 25-40% in case of average flood and

60-80% in case of drought period. In addition, Abdel Ghani, 2013, the previous CEO of the Hydropower Plants Executive Authority (HPPEA) (11), declared that for each one billion m³ deduction from the Egypt's share of the Nile River water, the hydropower generated from AHD will be reduced by 2%. This reduction in the hydropower generation means that the water footprint of the generated hydropower will increase.

Water footprint is a comprehensive indicator of freshwater misuse in the production process of a certain product. It is defined as the total volume of freshwater consumed or polluted during the production process divided by the quantity of the product (Hoekstra & Chapagain, 2008; Hoekstra et al., 2009). Based on this definition, water footprint concept consists of three components: blue, green and grey water footprint. The blue water footprint is the total volume of surface water or groundwater consumed in the production process; while the green water footprint is the total volume of rainwater consumed. For grey water footprint, it is the quantity of polluted water resulted from the production process (14). The hydropower generation process takes into account the consumption of water through the evaporation of surface water from the dam's reservoir (15,16). So, the water footprint for hydropower plant is defined as the total volume of the evaporated water from the reservoir divided by the amount of electricity generated (Mekonnen & Hoekstra, 2012).

The concept of the water footprint of hydropower was studied in some research. Mekonnen and Hoekstra, 2011 studied the blue water footprint for 35 selected hydropower plants in different sites. The average blue water footprint for them was recorded to be 68 Gm³ yr⁻¹ which is equal to 10% of the blue footprint of global crop production 2000; as a result, the study recommended that water footprint should be added as part of the environmental assessment of hydropower plants and electric dams (16). In China, a study was conducted using different terms of water footprint to

evaluate the environmental effect of the hydropower stations on Yalong River Basin. In this study, the evaporated water footprint, the blue water footprint, and the blue water scarcity footprint were calculated as an environmental assessment for 19 hydropower stations; the results indicated that the stations will not affect the local environmental flow requirements (17). On the other hand, a global study was conducted on around 1500 hydropower stations, that generate around 43% of the global annual hydroelectricity generation, using a new approach in calculating the water scarcity footprint. This approach is taking into consideration the evapotranspiration before the dam construction, the seasonal dynamic storage of water, and the allocation of impacts among all purposes of multipurpose dams (18). All these studies spot the light on the importance of water footprint terms in evaluating the environmental effect of the hydropower stations and electric dams. However, this research paper is aiming to study the use of the water footprint concept in simulating and predicting the effect of the different scenarios of filling the GRED on the water security for the AHD electricity production.

The aim of this study is to calculate the water footprint of the hydropower generated from the AHD and then to use this estimated water footprint as an indicator of the negative effects of GERD on the hydropower generation from AHD. The water footprint will be calculated considering 3 scenarios of GERD filling period and the results will be analyzed to understand the effects of these scenarios on the hydropower generation from AHD.

Methodology and Data

The water footprint of electricity generated from the AHD hydropower plant was calculated first considering the case before filling the GRED. Then, three scenarios for the filling period of the GERD were assumed, and the water footprint of electricity generated from the AHD hydropower plant was recalculated for each scenario. The first scenario is assuming the filling

period to be 3 years, the second is assuming it to be 5 years and the third is assuming it to be 6 years. The calculations were conducted over two periods. The first period is at the highest discharge in Egypt and hence highest water level of the Nile River which takes place during months of June, July and August. The second period is the lowest discharge period of the river in Egypt, namely the drought period. At this time, the water level of the Nile River is at its minimum value. This happens during months of December, January and February.

To carry out the study a mathematical model was developed using Excel spreadsheets. The model uses the equations stated in the following paragraphs. Based on the previously discussed definition, the water footprint of electricity generated from the AHD hydropower plant was calculated according to the following equation (16):

$$WF = \frac{WE}{EG} \quad (\text{eq. 1})$$

Where WF is the water footprint of electricity generated (m^3GJ^{-1}), WE is the total volume of water evaporated (m^3yr^{-1}), EG is the amount of energy generated (GJ yr^{-1}).

a. The total volume of water evaporated Calculations

The total volume of water evaporated from Lake Nasser, which is the reservoir of AHD, was calculated according to the following equation:

$$WE = 10 \times \sum_{t=1}^{365} E \times A \quad (\text{eq. 2})$$

Where E is the daily evaporation rate ($\text{mm}\cdot\text{day}^{-1}$) according to Aswan weather. A is the area of the reservoir (ha) which is 600,000 ha for Lake Nasser. The daily evaporation rate, E, was calculated according to Penman–Monteith:

$$E = \frac{1}{\lambda} \times \left(\frac{\Delta_w \times (R_n - G) \times \gamma \times f(u) \times (e_w - e_a)}{\Delta_w + \gamma} \right) \quad (\text{eq. 3})$$

Where E is the daily evaporation rate (mm-day⁻¹), λ the latent heat of vaporization (MJ/kg), Δ_w the slope of the temperature saturation water vapor curve at water temperature (kPa/°C); R_n net radiation (MJ m²day⁻¹); G the change in heat storage in the water body (MJ/m²/day); f(u) the wind function (MJ/m²/day/kPa); e_w the saturated vapor pressure at water temperature (kPa); e_a the vapor pressure at air temperature (kPa); and γ the psychrometric constant (kPa/°C). According to McJannet et al., 2008, the latent heat of vaporization (λ) (MJ/kg) was calculated at air temperature (T_a) as:

$$\lambda = 2.501 - 2.361 \times 10^{-3} T_a \quad (\text{eq. 4})$$

Based on eq.4, the psychrometric constant (γ) (kPa/°C) at the atmospheric pressure (P) (kPa) was calculated as (Allen et al., 1998):

$$\gamma = \frac{1.63 \times 10^{-3} P}{\lambda} \quad (\text{eq. 5})$$

The wind function $f(u)$ (MJ/m²/day/kPa) was calculated as (El Baradei & Al Sadeq., 2019):

$$f(u) = \left[\frac{5 \times 10^6}{A} \right]^{0.05} \times (3.17 + 2.33 u_2) \quad (\text{eq. 6})$$

Where A is the surface area of Lake Nasser (m²) and u_2 is the wind speed at 2 m above the water surface (m/s).

150 On the other hand, net radiation (R_n) ($\text{MJ m}^2\text{day}^{-1}$) is the difference between the net
 151 incoming short-wave radiation (R_{ns}) ($\text{MJ m}^{-2} \text{ d}^{-1}$) and the net outgoing long-wave radiation (R_{nl})
 152 ($\text{MJ/m}^2/\text{day}$) (Allen et al., 1998):

$$153 \quad R_n = R_{ns} - R_{nl} \quad (\text{eq.7})$$

154 In which the net incoming short-wave radiation (R_{ns}) ($\text{MJ m}^{-2} \text{ d}^{-1}$), which is resulting from
 155 the balance between incoming and reflected solar radiation, is calculated as (Allen et al., 1998):

$$156 \quad R_{ns} = (1 - \alpha) \times R_s \quad (\text{eq.8})$$

157 Where α is the albedo coefficient for open water, which is equal to 0.07 according to (Lenters et
 158 al., 2005), and R_s is the incoming solar radiation ($\text{MJ/m}^2/\text{day}$) which is calculated according to
 159 Angstrom formula as follows:

$$160 \quad R_s = (a_s + b_s \times \frac{n}{N}) \times R_a \quad (\text{eq. 9})$$

161 Where $\frac{n}{N}$ is the relative sunshine duration (dimensionless), $(a_s + b_s)$ is the fraction of
 162 extraterrestrial radiation reaching the earth on clear days (when $n = N$), and R_a is the extraterrestrial
 163 radiation ($\text{MJ/m}^2 \text{ /day}$). The net outgoing long-wave radiation (R_{nl} , $\text{MJ/m}^2/\text{day}$) is calculated as
 164 the difference between the outgoing long-wave radiation ($R_{l\uparrow}$, $\text{MJ/m}^2/\text{day}$) and the incoming long-
 165 wave radiation ($R_{l\downarrow}$, $\text{MJ m}^{-2} \text{ d}^{-1}$) (Fischer et al., 1979; Henderson-Sellers, 1986):

$$166 \quad R_{nl} = R_{l\uparrow} - R_{l\downarrow} \quad (\text{eq. 10})$$

$$167 \quad R_{l\uparrow} = \varepsilon_a \times \sigma \times (T_a + 273.15)^4 \times (1 + 0.17C_f^2) \times (1 - r_{lw}) \quad (\text{eq. 11})$$

$$168 \quad R_{l\downarrow} = \varepsilon_w \times \sigma \times (T_a + 273.15)^4 \quad (\text{eq. 12})$$

169 Where ε_a is the emissivity of air (dimensionless); σ the Stefan-Boltzmann constant that equals
 170 4.903×10^{-9} MJ/K⁴/m²/day; C_f the fractional cloud cover (dimensionless); and r_{lw} the total
 171 reflectivity of the water surface for long wave radiation was taken as 0.03 , ε_w is the emissivity of
 172 water which is equal to 0.97, and T_w the water surface temperature (°C) which was calculated as
 173 (25):

$$174 \quad T_{w,i} = T_e + (T_{w,1-i} - T_e) \times \exp\left(\frac{-1}{\tau}\right) \quad (\text{eq. 13})$$

175 Where $T_{w,i-1}$ is the water temperature at day i-1 (°C), τ is the time constant (day) and T_e is the
 176 equilibrium temperature (°C) which was calculated as (25):

$$177 \quad T_e = T_n + \frac{R_n^*}{4\sigma \times (T_n + 273.15)^3 + f(u) \times (\Delta_n + \gamma)} \quad (\text{eq. 14})$$

178 T_n is the Wet-bulb temperature (°C) and it is calculated using vapor pressure e_a (kpa) and dew
 179 point temperature T_d (°C) according to (19):

$$180 \quad T_n = \frac{0.00066 \times 100 T_a + \left(\frac{4098 e_a}{(T_d + 237.3)^2}\right) \times T_d}{0.00066 \times 100 + \left(\frac{4098 e_a}{(T_d + 237.3)^2}\right)} \quad (\text{eq. 15})$$

181 Where vapor pressure e_a (kpa), which was used also in eq.3, was calculated as (16):

$$182 \quad e_a = 0.6108 \times \exp\left[\frac{17.27 T_a}{(T_a + 237.3)}\right] \quad (\text{eq. 16})$$

183 Using the resulted T_n value, the slope of the temperature saturation water vapor curve at wet bulb
 184 temperature Δ_n (kPa/K) is calculated as follows (16):

$$185 \quad \Delta_n = \frac{4098 \times \left[0.1608 \times \exp\left(\frac{17.27 T_n}{(T_n + 237.3)}\right)\right]}{(T_n + 237.3)^2} \quad (\text{eq. 17})$$

186 The net radiation at wet-bulb temperature R_n^* (MJ/m²/day) was calculated using the albedo
 187 coefficient α as follows (16):

$$188 \quad R_n^* = (1 - \alpha) \times R_s + (R_l \downarrow - R_l \uparrow_n) \quad (\text{eq. 18})$$

189 Where the outgoing long-wave radiation at wet-bulb temperature $R_l \uparrow_n$ (MJ/m²/day) was
 190 calculated as (26):

$$191 \quad R_l \uparrow_n = C_f \times (\sigma \times (T_a + 273.15)^4 + 4\sigma(T_a + 273.15)^3 \times (T_n - T_a)) \quad (\text{eq. 19})$$

192 The time constant τ (day), in eq. 13 was calculated as (25):

$$193 \quad \tau = \frac{\rho_w \times c_w \times h}{4\sigma \times (T_n + 273.15)^3 + f(u) \times (\Delta_n + \gamma)} \quad (\text{eq. 20})$$

194 Where ρ_w is the density of water which was taken as 1000 kg/m³; c_w is the specific heat of water
 195 which is equal to 0.0042 MJ/kg/K; and h is the depth of water (m) in Lake Nasser which is 21.4
 196 m.

197 The change in the heat storage in the water body G (MJ/m²/day), saturated vapor pressure
 198 at water temperature e_w (kPa) and the slope of the temperature saturation water vapor curve at water
 199 temperature Δ_w (kPa °C⁻¹) which were used in the Penman-Monteith equation (eq.3), are
 200 calculated as follows (16,27):

$$201 \quad G = \rho_w \times c_w \times h \times (T_{w,i} - T_{w,i-1}) \quad (\text{eq. 21})$$

$$202 \quad e_w = 0.6108 \times \exp \left[\frac{17.27T_w}{(T_w + 237.3)} \right] \quad (\text{eq. 22})$$

$$203 \quad \Delta_n = \frac{4098 \times e_w}{(T_n + 237.3)^2} \quad (\text{eq. 23})$$

204 All the calculations were conducted on a daily basis using Excel spreadsheet according to
 205 the meteorological data of Aswan City in 2016, which is the global hottest year since modern

recordkeeping began in 1880, collected from the Weather Underground which is a commercial weather services company (28,29). However the data of solar radiation was collected from the NASA website (30).

b. The amount of electricity generated data and calculations

AHD reservoir has a hydropower plant that consists of 12 generating units (turbines) of Frances Turbine type. The height of these turbines is 108 m. The highest water level in the reservoir reaches 175 m during the flood period of the Nile river and the lowest water level in the reservoir reaches 165 m (1). As a result, the range of head of turbines is 67 to 57 m. According to the annual report issued by Egyptian Electricity Holding Company, the maximum and minimum daily generated energy are 41.5 and 8.7 GWh, respectively (31). Based on these data, the maximum and minimum discharge (Q , m³/s) through each turbine can be calculated using the following equation (32):

$$Q = \frac{P(kW) \times 1000}{\eta \times \gamma \times H} \quad (\text{eq. 24})$$

$$P(kW) = \frac{E(GWh) \times 1000 \times 1000}{24} \quad (\text{eq. 25})$$

Where P (kW) is the generated electric power output of each turbine, η is station efficiency, γ is the specific weight of water (N/m³) and H is the head of turbine (m). The amount of energy generated annually EG (GJ/yr) was calculated as:

$$EG (GJ/yr) = P(kW) \times 0.0036 \times 24 \quad (\text{eq. 26})$$

For the 3 scenarios for the filling GRED, the reduction in AHD generated electricity was calculated based on the expectations that implied that for each billion m³ deducted from the

Egypt's share of Nile River water, the hydropower generated from AHD will be reduced by 2%. The maximum and minimum discharge flow through the turbines were assumed to be reduced by the same percentage of reduction of the Egypt's share of the Nile. So, the maximum and minimum head of turbines were calculated using eq. 24, the amount of energy generated annually EG was calculated using eq. 25.

Calibration

The mathematical model used for calculating the water footprint of the hydropower generation was calibrated using data for the Three Gorges hydropower plant in China (Zhao & Liu, 2015) and another 4 hydropower plants in Norway (Bakken et al., 2013). The error resulted from the calibration is approximately zero as shown in table 1. (Zhao & Liu, 2015)

Table 1: Calibration Results

Power Plant	Country	Referenced Dam Hydro power footprint	Modeled Dam Hydro power footprint	Error %
Three Gorges	China	17.1 (m ³ /GJ)	17.1 (m ³ /GJ)	0
Logna	Norway	34.8 (m ³ /MWh)	34.7 (m ³ /MWh)	0.3%
Skjerka	Norway	1.3 (m ³ /MWh)	1.3 (m ³ /MWh)	0
Haverstad	Norway	6.1 (m ³ /MWh)	6.1 (m ³ /MWh)	0
Laudal	Norway	6.2 (m ³ /MWh)	6.2 (m ³ /MWh)	0

It could be seen that the percentage errors are zero so it could be concluded that the model is a reliable mean to predict the hydro power water footprint of the High Aswan Dam.

Results

All calculations were conducted in an excel sheet and the results were summarized in the following sections.

a. The total volume of water evaporated

The daily evaporation rate of AHD reservoir (Lake Nasser) was calculated using Penman–Monteith equation for the period from December to February (drought period) and June to August (flooding period). Then the total volume of the evaporated water was calculated using eq.2 as shown in table 1.

Table 2: Total Volume of Evaporated Water

Period	Evaporation Rate (E) (mm/day)	Volume of evaporated water (WE) (m ³ /yr)
Dec- Feb	362.25	2,173,500,000.00
June- Aug	802.56	4,815,360,000.00

b. The amount of electricity generated

The generated electrical power output (P) and the energy generated annually (EG) from AHD, before filling the GRED, were calculated using the data collected from the annual report issued by Egyptian Electricity Holding Company, as explained before and the results are summarized in table 2. The number of turbines that operates in the summer is 12 turbines; however, in the drought period, which is during December to February, only 6 turbines are operated. The discharge values in table.2 were calculated using eq. 24.

Table 3: The Amount of Electricity Generated Before GRED

Season	No. of Turbines in Operation	Head (m)	Q (m ³ /s)	P (kW)	EG (GJ/yr)	WF (m ³ /GJ)
Flooding	2	67	254.92	288,188.18	24,899.46	169,218.14

	4			576,376.36	49,798.92	84,609.07
	6			864,564.54	74,698.38	56,406.05
	8			1,152,752.73	99,597.84	42,304.53
	10			1,440,940.91	124,497.29	33,843.63
	12			1,729,129.09	149,396.75	28,203.02
Drought	2	57	125.63	120,827.47	10,439.49	182,174.79
	3			181,241.20	15,659.24	121,449.86
	4			241,654.93	20,878.99	91,087.40
	5			302,068.67	26,098.73	72,869.92
	6			362,482.40	31,318.48	60,724.93

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260 For the filling scenarios, the generated electrical power output (P) and the energy generated
261 annually (EG) from AHD were calculated according to the expected reduction in the discharge
262 and the head of the turbines for each scenario; the results of these calculations were summarized
263 in tables 3, 4 and 5. The discharge values are reduced by the same percentage of deduction of
264 Egypt's share of the Nile for each filling scenario of the Ethiopian dam. However, the turbine head
265 values were calculated using eq. 24.

266 *Table 4: The Amount of Electricity Generated in Scenario 1*

GRED Filling Period = 3 years							
% Deducted from Egypt Share	Season	No. of Turbines in Operation	Head (m)	Q (m ³ /s)	P (kW)	EG (GJ/yr)	WF (m ³ /GJ)
45.50%	Flooding	2	61.41	138.93	143,956.93	12,437.88	387,152.82
		4			287,913.87	24,875.76	193,576.41
		6			431,870.80	37,313.64	129,050.94
		8			575,827.73	49,751.52	96,788.21
		10			719,784.67	62,189.40	77,430.56
		12			863,741.60	74,627.27	64,525.47
	Drought	2	52.24	68.47	60,353.29	5,214.52	416,816.55
		3			90,529.94	7,821.79	277,877.70
		4			120,706.58	10,429.05	208,408.27
		5			150,883.23	13,036.31	166,726.62

		6			181,059.87	15,643.57	138,938.85
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Table 5: The Amount of Electricity Generated in Scenario 2

GRED Filling Period = 5 years							
% Deducted from Egypt Share	Season	No. of Turbines in Operation	Head (m)	Q (m3/s)	P (kW)	EG (GJ/yr)	WF (m3/GJ)
27.30%	Flooding	2	64.49	185.93	202,320.23	17,480.47	275,470.89
		4			404,640.45	34,960.93	137,735.45
		6			606,960.68	52,441.40	91,823.63
		8			809,280.90	69,921.87	68,867.72
		10			1,011,601.13	87,402.34	55,094.18
		12			1,213,921.35	104,882.80	45,911.82
	Drought	2	54.86	91.33	84,540.87	7,304.33	297,563.18
		3			126,811.31	10,956.50	198,375.45
		4			169,081.74	14,608.66	148,781.59
		5			211,352.18	18,260.83	119,025.27
		6			253,622.61	21,912.99	99,187.73

Table 6: The Amount of Energy Generated in Scenario 3

GRED Filling Period = 6 years							
% Deducted from Egypt Share	Season	No. of Turbines in Operation	Head (m)	Q (m3/s)	P (kW)	EG (GJ/yr)	WF (m3/GJ)

20.00%	Floodin g	2	65.33	203.94	224,808.40	19,423.45	247,914.82
		4			449,616.79	38,846.89	123,957.41
		6			674,425.19	58,270.34	82,638.27
		8			899,233.59	77,693.78	61,978.71
		10			1,124,041.98	97,117.23	49,582.96
		12			1,348,850.38	116,540.67	41,319.14
	Drought	2	55.58	100.50	94,250.15	8,143.21	266,909.38
		3			141,375.23	12,214.82	177,939.59
		4			188,500.30	16,286.43	133,454.69
		5			235,625.38	20,358.03	106,763.75
		6			282,750.46	24,429.64	88,969.79

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c. Water Footprint (WF) of Electricity Generated

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Based on the results in the previous sections, the water footprint of electricity generated from the AHD was calculated before filling the GRED and in the case of the three filling scenarios as shown in figures 1 and 2. In addition, a comparison was conducted between the reduction in the generated electricity and the increase in the water footprint values during the three filling scenarios as shown in figure 3.

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Figure 1: Water Footprint for Electricity Generated in the Period from June to August

Figure 2: Water Footprint for Electricity Generated in the Period from December to February

Figure 3: Reduction in Electricity vs. Increase in Water Footprint

Discussion and Conclusion

The aim of this research is to study the effect of the filling of the Grand Ethiopian Dam reservoir on the hydropower footprint of the high Dam in Egypt. This is to assess and monitor the effect of the Ethiopian dam in Egypt.

The impact of three filling scenarios; namely 3 years, 5 years and 6 years, were modeled and the water footprint was calculated. The results of the simulation indicated that as the filling period of the Ethiopian Dam's reservoir decreases, the hydropower footprint of the Aswan High Dam increases. Also, as the filling period decreases the generated hydropower decreases.

From the previous paragraph, it could be concluded that the negative impact of the Grand Ethiopian Renaissance Dam on the hydropower and its water footprint in Egypt will be greater as the period of time of the filling is shorter. So, to reduce this negative impact, it is recommended to fill the Ethiopian Dam's reservoir on an extended period of time.

Declarations

Availability of data and materials

All data analyzed during this study are cited and the references are mentioned in the references section.

Authors' Contribution

Not Applicable

Competing interests

The authors declare that they have no competing interests.

Funding

This research was not funded by any sources of funding.

Acknowledgements

Not Applicable

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