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Assessment of water resources system in Qena governorate, Upper Egypt under different hydrological and agronomic conditions

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ABSTRACT

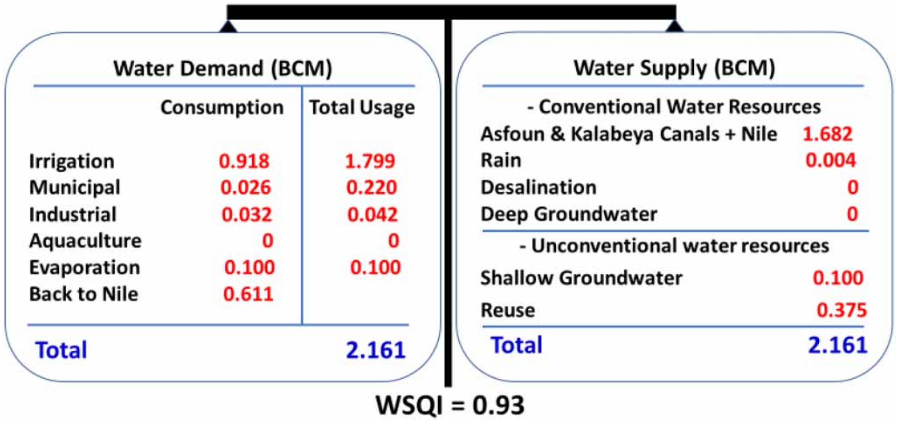
This paper assessed the current water resources system and two future scenarios in the Qena Governorate by developing a Water Balance Model (WB Model) and Water Security Quality-based Index (WSQI). The first scenario presented 25% reduction in Nile flow, while the second scenario suggested adaptation measures to comply with flow reduction. The measures included leveling 100,000 feddans, serving 70,000 feddans with sprinkler irrigation, and lining 2,977 km of canals. The WB Model estimated WB components. The WSQI was a new index suitable for Egypt's conditions considering water quality. The water supply from High Aswan Dam (HAD) was predicted by the BlueM model for hydrological simulations of Nasser Lake. The study found that the current water shortage was fulfilled by drainage reuse and shallow groundwater, and the WQSI indicated a low water insecurity. The flow reduction increased the water shortage and reuse quantity. As a result, the WSQI indicated high water insecurity. The suggested measures improved agricultural water use efficiency from 51% to 63%, reduced water shortage, and improved the water insecurity level from high to medium. This study concluded that adaptation measures can improve the future water system and water security in the Qena Governorate. The study recommended upscaling WSQI use for the entire country.

Key words: climate change, Water Balance Model, Water Security Quality-based Index

HIGHLIGHTS

- It provided the first water security index considering the water quality aspect.
- No previous publications have provided clear assessment values as this research did.
- First water security index suitable for Egyptian conditions.
- Impacts of adaptation measures to Nile flow reduction have been quantified.

GRAPHICAL ABSTRACT



Water Demand (BCM)

	Consumption	Total Usage
Irrigation	0.918	1.799
Municipal	0.026	0.220
Industrial	0.032	0.042
Aquaculture	0	0
Evaporation	0.100	0.100
Back to Nile	0.611	
Total		2.161

Water Supply (BCM)

- Conventional Water Resources	
Asfoun & Kalabeya Canals + Nile	1.682
Rain	0.004
Desalination	0
Deep Groundwater	0
- Unconventional water resources	
Shallow Groundwater	0.100
Reuse	0.375
Total	2.161

WSQI = 0.93

1. INTRODUCTION

Egypt is as an arid country suffering from chronic water stress due to its limited water resources, the growing population and escalating water demands. Egypt depends on the Nile River, which provides 95% of its renewable water resources. Nile water reduction has adverse impacts on the total cropped area and 13 crops areas, self-sufficiencies of wheat, rice, cereal and maize, and socio-economic indicators (Omar *et al.* 2021). For adaptation to Nile water reduction, many studies have investigated the effectiveness of different agronomic interventions on Egypt water balance (WB) (Scheierling *et al.* 2014; Omar & Moussa 2016; Amer *et al.* 2017). All previous studies have focused on achieving water security by eliminating the water shortage quantity, but they ignored the water quality acceptability.

On the global scale, a diverse set of water availability and security indices has been developed to assess water systems and quantify the extent of water shortage. Vörösmarty *et al.* (2005) and Pfister *et al.* (2009) developed similar water stress indices based on the ratio of water withdrawals to water resources. Sun *et al.* (2008) and McNulty *et al.* (2010) also developed water supply stress indices which included more water supply components. However, all indices ignored the water reused or recycled water which is an essential water resource in Egypt. Other indices were developed focusing on consumptive water rather than gross withdrawals (Tidwell *et al.* 2012; Moore *et al.* 2015; Brauman *et al.* 2016), which are also not suitable for Egypt, as the irrigation systems are of high losses, and hence, gross withdrawals should be considered. Therefore, absolute indices are needed for assessing the status of water resources' system in Egypt.

Water security is defined by UN-Water as the capacity of a population to safeguard sustainable access to adequate quantities of acceptable quality water for sustaining livelihoods, human well-being, and socio-economic development, for ensuring protection against water-borne pollution and water-related disasters, and for preserving ecosystems in a climate of peace and political stability. Therefore, water security is a matter of both water quantity and quality. In Egypt, the reuse of drainage is the first and immediate alternative to cover the gap between water supply and demand. This might be a proper solution only if it is of good quality ensuring satisfactory agricultural productivity, soil health conditions and public health conditions. The reuse quantity is expected to increase in the future due to population increase and its accompanied activities. Therefore, there should be a water security index expressing Egypt's characteristics, presenting the status of water resources' system, and considering water quality of different water supply components. The Qena Governorate shares Nile surface water with Luxor Governorate via Kalabia and Asfoun main canals. The characteristics of water resources system in Qena Governorate is presented in Table 1. The most challenges facing water resources in the governorate can be summarized as the limited quantity and quality of water resources, low water use efficiency, the continuous population growth, the agricultural and urban expansion in desert lands, and climate change projections.

The main objective of this work was to assess the water resources' system of Qena Governorate by developing a Water Balance Model (WB Model) and a Water Security Quality-based Index (WSQI). Three scenarios were assessed: (i) Base Case Scenario in 2020, (ii) Scenario 1 representing 25% reduction of Nile flow at Nasser Lake entrance in 2050, and (iii) Scenario 2 investigating the effectiveness of several adaptation measures enacting in case of Nile flow reduction. It was assumed in this paper that the water decrease was proportionally allocated over the governorates.

2. METHODOLOGY

2.1. Study area description

Qena is the third governorate from the Egyptian southern border after Aswan and Luxor. It is bounded from the south by Luxor Governorate, which separated from Qena in 2010, and from the north by Sohag Governorate, the New Valley Governorate from the west, and the Red Sea Governorate from the east as shown in Figure 1.

The total area of Qena Governorate is about 2.3 million feddans, from which 13.50% is in the Nile Valley. The Nile River is the main geographical phenomenon in Qena Governorate and runs from south to north through the valley, separating the governorate's land to the east and west. Administratively, Qena Governorate is divided into one new urban community, 112 continued villages, 41 main village units, and nine local units. The population of the Qena Governorate reached 3,224,573 capita, 19.7% of the people living in urban areas and 80.3% lived in rural areas. Qena Governorate is one of the most densely populated governorates.

Qena Governorate is considered one of the governorates with the predominant agricultural sector. The cultivated area is estimated at about 247 thousand feddans. The province is characterized by cultivating sugar cane and bananas alongside wheat, corn, vegetables (tomatoes), alfalfa, sesame, and palm trees, in addition to some aromatic and medicinal plants. Sugar cane is the main crop and wheat comes as the second major winter crop, and corn is the second major summer crop.

Table 1 | Characteristics of water resources system in Qena Governorate

Surface water		
Annual quantity	1.682 BCM	
Main canals from Nile River	Kalabia and Asfoun main canals	
Total length of main canals	Kalabia	162 km
	Asfoun	125 km
Reach length within the governorate	Kalabia	86.4 km from km 75.6 until its end
	Asfoun	60.25 km from 64.75 km until its end
Number and length of sub-canals	Kalabia	166 sub-canals with total length of 673 km
	Asfoun	173 sub-canals with total length of 671 km
Served command area	Kalabia	126,000 feddan
	Asfoun	121,000 feddan
Groundwater		
Annual quantity of deep groundwater for new lands	0.381 BCM	
Annual quantity of shallow groundwater for old lands	0.1 BCM	
Rainfall		
Annual height	3.83 mm less than annual evaporation rate (11.3 mm)	
Annual quantity	0.004 BCM	
Drainage reuse		
Number/length of drains collecting agricultural drainage water	39 open drains with a total length of 214 km	
Annual reuse quantity	0.4 BCM	

Figure 1 | Study area of Qena Governorate.

2.2. Blue M

The BlueM model was used in this study to simulate the operational process of Nasser Lake considering the decrease of flow entering the lake. The BlueM model was developed by Darmstadt University of Technology, in Germany, for river basin management (Bach *et al.* 2009). The operation of Nasser Lake was described by the WB equation under various constraints concerning storage volume, outflow from the lake, and water losses, and WB calculation was performed monthly, as follows:

$$\Delta V_t = I_t – Q_t – M_t – D_t – T_t – S_t – E_t \tag{1}$$

where I_t is the mean inflow in month t (m^3); Q_t is the outflow from the dam (m^3); M_t is the flow released from the emergency spillway (m^3); D_t is the water demand of the Toshka Project for reclamation of 226 800 ha from Nasser Lake (m^3); T_t is the volume of water released from the Toshka Spillway to empty the reservoir down to the level of 175 m before floods (m^3); S_t is the seepage losses from the lake (m^3), which was assumed to be 7% of the average annual losses (Moussa 2017). ; and E_t is the mean open water evaporation from the lake (m^3), which is expressed as follows:

$$E_t = \frac{A_t + A_{t+1}}{2} \times C_t \tag{2}$$

where A_t and A_{t+1} are the lake areas at the beginning and end of month t, respectively. The lake surface area changes according to water level (WL) based on the latest survey of Lake Nasser survey in 2013 using the technology of the Multi Beam Echo sounder which resulted in the following equation governing the relation between the WL and the surface area (Shafik 2016):

$$\text{Surface area} = 55979.564 – 1763.753\ (WL) + 20.777\ (WL)^2 – 0.109\ (WL)^3 + 0.000221\ (WL)^4$$

C_t is the evaporation coefficient in month t, which was determined using the method of Ebaid & Ismail (2010) as follows:

$$C_t = \frac{0.622 \times \rho_a \times (0.4)^2}{P\rho_w \left[\ln\left(\frac{z_m - z_d}{z_0}\right)\right]^2} \tag{3}$$

ρ_a is the density of air [1.220 kg m^{-3}]
ρ_w is the density of water [1,000 kg m^{-3}]
P is the atmospheric pressure [kPa]
Z_m is the height at which wind speed and air vapor pressure are measured [m]
Z_d is zero-place displacement [m]; $Z_d = 0$ over typical water surfaces
Z_o is roughness height of the surface [m]; $Z_o = 2.30 \times 10^{-4}$ m over typical water surfaces.

Model calibration was conducted by comparing the simulated daily WL upstream of HAD with observations with the absolute error as the error index.

2.3. Assessment tools for Qena water resources' system

The current study aimed at developing the WB Model and the WSQI to assess the current and future water resources system in Qena Governorate.

2.3.1. Water Balance Model

The WB Model was a simple Microsoft Excel model developed by authors to estimate the different components of the future WB for Qena Governorate. The developed WB Model was a mass balance model to calculate different WB components estimated by formulas, rates, and factors that changed the different components of the Base Case and future scenarios (Table 2). The calculation procedures of WB different scenarios can be summarized in two parts. The first part was by estimating the volumes of water supply divided into conventional and non-conventional water resources. The conventional resources were the Nile water, deep groundwater, and rainfall. The values of these conventional sources are known from records. The non-conventional resources included reused shallow groundwater and drainage water used only in case of water shortage. Hence, they had the same value as the difference between total water usage and the conventional water resources.

Table 2 | Set of formulas representing different water balance components

Formula	Components	Definitions
$Q_{in} = Q_{\text{bas}} \times f_1$	Q_{in}	Surface water discharge entering the governorate in billion cubic meter (BCM)
	Q_{bas}	Basic surface water discharge entering the governorate (BCM) = 100% of the current discharge
	f_1	Factor of surface water according to climate change
$A_{cult} = A_{\text{bas}} + (R_{\text{expansion}} - R_{urban}) \times N$	A_{cult}	Cultivated agricultural area (m^2)
	A_{bas}	Cultivated agricultural area in the base year (m^2)
	$R_{expansion}$	Horizontal expansion rate per year (m^2)
	R_{urban}	Lost agricultural area per year by urbanization (m^2)
	N	Number of years from base year to the target year
$Irr_{total} = A_{\text{cult}} \times Irr_{fedan}$	Irr_{total}	Total irrigation withdrawals (BCM)
	Irr_{feddan}	Feddan consumption rate (m^3/feddan), (1 feddan = 4,200 m^2)
$Irr_{crop} = Irr_{total} \times e$	Irr_{crop}	Actual irrigation withdrawal by crops (BCM)
	E	Use efficiency of agricultural sector (%)
$Dom_{total} = PN \times C_{person}$	Dom_{total}	Total domestic demand (BCM)
	PN	Population number
	C_{person}	consumption rate per person (l/c/d)
$Dom_{loss} = Dom_{total} \times f_2$	Dom_{loss}	Domestic loss (BCM)
	f_2	Domestic losses factor
$WW_{treated} = PN \times CWW_{person} \times f_3$	$WW_{treated}$	Treated wastewater discharge (BCM)
	CWW_{person}	Per capita wastewater discharge (l/c/d)
	f_3	Actual ratio of treated wastewater discharge to total discharge of wastewater (%)
$WW_{untreated} = (PN \times CWW_{person}) - WW_{treated}$	$WW_{untreated}$	Untreated wastewater discharge (BCM)
$Reuse = Irr_{total} + Dom_{total} + E + Aquaculture - Q_{in} - Desalination - R{-}GW$	$Reuse$	Reuse to cover the water shortage (BCM) including drainage and shallow groundwater
	E	Evaporation (BCM)
	R	Rainfall (BCM)
	GW	Deep groundwater (BCM)

The second part was estimating the volumes of water demand which were divided into water consumption and usage. The total usage is the actual consumption by different sectors in addition to losses, sea water disposal, and the minimum environmental flows to clean up some water ways. Water usage describes the total amount of water withdrawn from its source to be used. The amount of water usage is required, even if a part of it returns to the system. Water consumption is the portion of water usage that is not returned to the water system after being withdrawn. The efficiency of the water system was calculated as the ratio between both water consumption and water usage. The difference between them is the water quantity lost. In agriculture, water consumption is the quantity of water consumed by crops for vegetated growth to evapotranspiration and building of plant tissues plus evaporation from soils and intercepted precipitation. Water usage includes water consumption and both the field application and conveyance water losses. Model calibration was conducted by comparing the simulated yearly drainage water reuse with collected data from the Ministry of Water Resources and Irrigation using the absolute error as the error index.

2.3.2. Water Security Quality-based Index

The current paper developed a new water shortage index, as all previous indexes either ignored the drainage reuse or focused on consumptive water rather than gross withdrawals. Therefore, it was necessary to develop a new index suitable for Egypt's conditions. In case water shortage increases, drainage water reuse will be the immediate alternative to cover this gap. However, reuse of drainage water below the water quality standards reduces the agricultural productivity, deteriorates the soil, and harms the public health and environment. Therefore, water quality was considered in the current index. The current water security index (WSQI) was calculated as following:

$$WSQI = \frac{\sum [WS \times Fq] \times 100}{WD} \tag{4}$$

where,

WD – Sum of water demand.
WS – Water supply components including surface river flow, groundwater, rainfall, and reuse.
Fq – Variance factor considering water quality.

The Fq value was obtained based on different water quality parameter values, each of which was transformed to a subindex of either 1 if it was complied with the standards or 0 if it was not complied. Fq represented the average value of all parameters' subindices for total dissolved solids (TDS), nitrate (NO_3), total phosphorus (TP), biological oxygen demand (BOD), chemical oxygen demand (COD), and dissolved oxygen (DO). The Fq value was only estimated for water supplies in agriculture including drainage water reuse, shallow groundwater, and Nile water, as irrigation water is being used without treatment. The drainage water in Qena Governorate is available in three main drains; Sheikhia, El Ballas, and Hamed disposing into the Nile River at 265, 270.7, and 331.2 km from HAD, respectively. The drainage water in the three drains was collected and analyzed in a mobile laboratory established by the Nile Research Institute in Isna governorate located 120 km from Qena Governorate. The values of water quality parameters used in WSQI were the average values from the three drains, which were very similar. Law 48 issued in 1982 and its amendment in 2013 were used in this paper for comparison and to find the new subindices.

WSQI ranges from 0 to 1 (Table 3), where 1 means the water resources fulfill the water demand in terms of water quantity and quality. Values lower than 1 indicate that the water resources fall short of sufficiency or quality.

2.4. Tested scenarios

The current scenario and two future scenarios were established. Scenario 1 investigated the impacts of Nile flow reduction from the HAD. Scenario 2 evaluated the effectiveness of the adaptation measures for the Nile flow reduction conditions using the same reduction rate as in scenario 1. Comparing the three scenarios provides a clear comparison between the negative effect of Nile flow reduction and the effectiveness of selected adaptation measures on water resources system status in Qena Governorate.

2.4.1. Base Case Scenario in 2020

This scenario represented the actual current conditions of the water resources system. In this scenario, the surface water of Qena Governorate was based on preserving Egypt's traditional share of the Nile water. Hence, Q_{in} and Q_{base} were the same, with a value of 1.682 BCM/year, and the reduction factor (f_1) was assumed 1 (Table 2). Rainfall harvesting and torrential also supplied another 0.004 BCM/year to the system. The difference between total water usages, agricultural (Irr_{total}), and domestic and industrial demands (Dom_{total}) in one side and the total supply in the other side, was covered by reuse. The known inputs to this case were the water usage of municipal and industrial sectors and their use efficiencies, by which the water consumptions were calculated.

Table 3 | WSQI values and categories

Index	Category
1	Complete water security
0.90–0.99	Low water insecurity
0.85–0.89	Medium water insecurity
Less than 0.85	High water insecurity

For the agricultural sector, the water usage (Irr_{total}) was 7,000 m^3/feddan according to data collected from Qena Irrigation Directorate. The difference between Irr_{total} and Irr_{crop} is water loss, which is divided into conveyance loss and field application loss. The conveyance loss is caused by evaporation and seepage via irrigation channels, but the field application loss is caused by percolation underneath the root zone in agricultural fields. The field application efficiency for the Qena based on FAO (1989) indicative values was 60% considering surface irrigation as the dominant irrigation system. The conveyance efficiency was 85% based on FAO (1989) indicative values considering the length and the soil type of canals. Hence, the water use efficiency of the agricultural sector (e) was 51% in this scenario. Accordingly, the calculated water consumption (Irr_{crop}) was 3,570 m^3/feddan, which should be guaranteed to fulfill the cropping pattern requirements of Qena Governorate. If e changes in any future scenario, Irr_{crop} should remain at 3,570 m^3/feddan.

Similarly, the water consumptions for municipal and industrial sectors were calculated. The ratios of shallow groundwater and drainage reuse to the total reuse were 0.85 and 0.15, respectively, which were assumed in this scenario. This scenario was used for calibration.

As the reuse of drainage and shallow ground water is only applied to cover the water shortage, the model calibration was conducted by comparing the predicted drainage reuse with the actual reuse in Qena Governorate in the Base Case Scenario. For the base year, all data of WB components were collected from the Ministry of Irrigation and Water Resources, Water Distribution Unit, the Irrigation District, the Agricultural District, and the Affiliated Company for Water and Wastewater. After estimating the water consumption efficiencies of different sectors, the model estimated the water shortages, which were compensated for by drainage water reuse. The percentage error (PE) was used to evaluate the trueness and exactness of the estimated drainage reuse value. The PE for the volume of drainage water reuse in the year 2020 was calculated as following:

$$PE = \frac{(Estimated\ result - Actual\ result)}{Actual\ result} \times 100 \tag{5}$$

2.4.2. Scenario 1 with Nile reduction in 2050

The available Nile water in this scenario was based on a significant reduction in Egypt's traditional share of the Nile water. In this scenario, the surface water factor (f_2) was 0.75 of the current amounts, with a value of 1.261 BCM/year. On the demand side, all agricultural needs, domestic and industrial needs were equal to those in scenario 1, since Irr_{feddan}, e, PN, C_{person} and water losses were equal in both scenarios.

2.4.3. Scenario 2 with adaptation measures in 2050

This scenario considered the adaptation measures to substitute the water shortage due to climate change effects. The current paper also evaluated the selected measures according to the so-called SMART criteria, which guide setting reasons for failure or success of measures and activities. SMART criteria stand for: S: specific, the indicator clearly and directly relates to the outcome, and is described without ambiguities and parties have a common understanding of the indicator, M: measurable, the indicator is preferably quantifiable and objectively verifiable, and parties have a common understanding of the ways of measuring the indicator, A: achievable, the required data and information can actually be collected, R: relevant, the indicator must provide information which is relevant to the process and its stakeholders, and T: time-bound, the indicator is time-referenced, and is thus able to reflect changes and it can be reported at the requested time.

The suggested adaptation measures were:

(1) Increasing the efforts towards serving 100,000 feddans with laser-leveling increasing the field application efficiency by 5% in the served area (Omar & Moussa 2016).
(2) The use of sprinkler irrigation in about 70,000 feddans increasing the field application efficiency by 15% in the served area (FAO 1989).
(3) Implementing projects for lining the total length of 2,977 km of canals increasing the conveyance efficiency by 10% in the entire governorate (FAO 1989).

Measures 1 and 2 targeted the field application efficiency, which increased from 60% in the Base Case Scenario to 66% in this scenario. Measure 3 increased the conveyance efficiency from 85% to 95%. The package of measures increased e from 51% to 63%. To insure fulfilling the actual Irr_{crop} with 3,570 m^3/feddan with the improved e, the Irr_{feddan} decreased to 5,667 m^3/feddan in this scenario.

The adaptation measures in the domestic and industrial sectors assumed that the rate of population increase in the optimistic scenario was 2.16%, so *PN* reached 6.3894 million capita, and assuming also a decrease in the C_{person} from 180 to 160 liters/capita/day because of improving the citizens' standards of living and the high level of awareness and culture among the citizens. It has also been assumed that water loss decreased from 21% to 15% in this scenario, because of conducting further activities in dilapidated pipes, valves, connections, and treatment plants, in addition to removing illegal connections or installing meters for them. The needs of industry outside drinking water networks jumped from 0.038 to 0.047 BCM because of the increased demand for some products associated with the increase in population, especially food industries. Table 4 shows different values of rates in the four tested scenarios which differentiate the model outputs.

3. RESULTS AND DISCUSSION

3.1. BlueM model calibration

Regarding the BlueM model, the average monthly WL data upstream of the HAD in the period from 2013 to 2017 were used for model calibration. Figure 2 shows that the BlueM model provided a satisfactory WL simulation with an absolute error index ranging from −0.23 m to 0.17. The WB Model also shows excellent water shortage and drainage reuse simulations with an absolute error index ranging from −0.01 to 0.002 (Figure 3).

3.2. Comparison between scenarios

The outputs of the WB Model for the current and two future tested scenarios were presented including the water usages and consumptions of all sectors and the quantities returning to the system. The performance of scenarios was evaluated by the outputs of the WB Model and the WSQI.

Table 4 | Values of WB Model parameters in the three scenarios

Parameters	Base Case	Scenario 1	Scenario 2	Units
f_1	1	0.75	0.75	Number
$R_{expansion}$	0	0	0	m^2/year
R_{urban}	0	0	0	m^2/year
E	51	51	63	%
CWW_{person}	0.56	0.56	0.65	Liter/capita/day
f_3	0.25	0.39	0.59	Number
PN	3,224,573	6,389,400	6,389,400	Capita
C_{person}	180	180	160	Liter/day

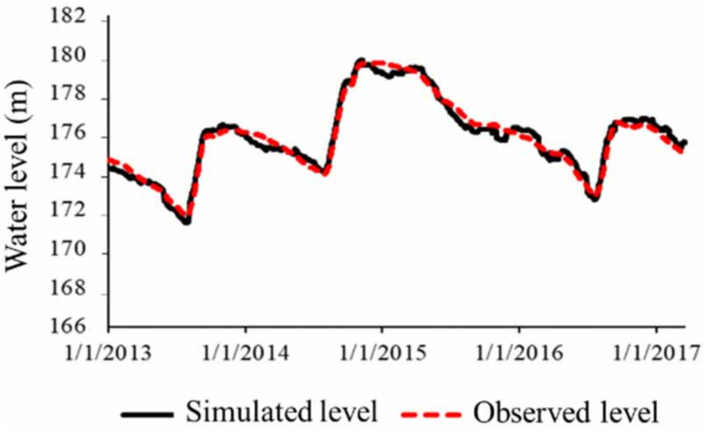


Figure 2 | Simulated mean monthly water level upstream of HAD in the period from 2013 to 2017 using the BlueM model.

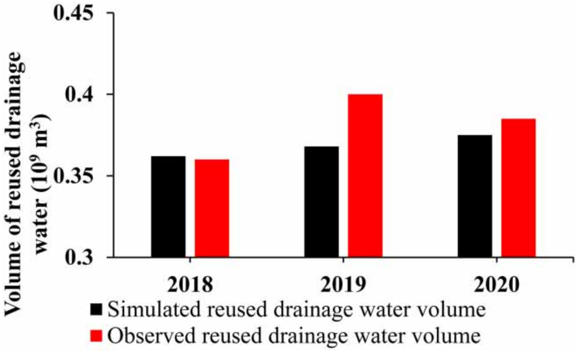


Figure 3 | Simulated and observed yearly drainage reuse using the WB model.

3.2.1. Base Case Scenario 2020

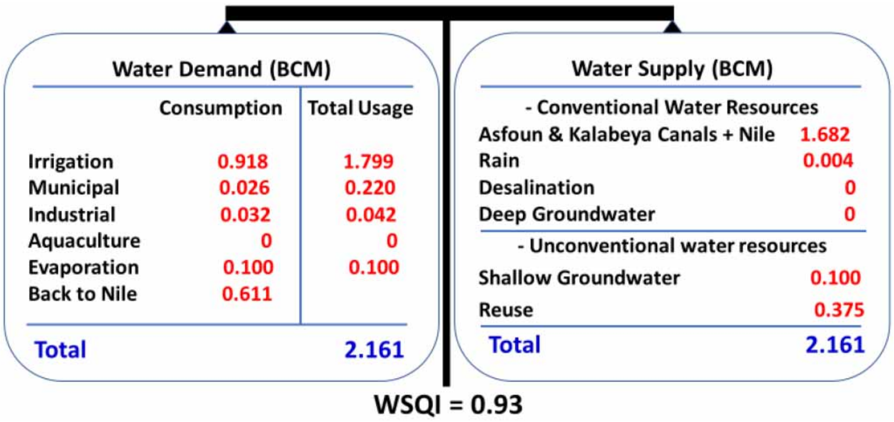
As shown in Figure 4, the total household usage in Qena in 2020 amounted to be 0.220 BCM, of which 0.026 BCM was consumed, while 0.111 BCM of untreated sanitation, 0.037 BCM of treated sanitation and 0.05 BCM of losses returned to the system. Agriculture usage reached 1.799 BCM, of which 0.918 BCM was consumed, and the rest returned to the system. Industrial usage outside drinking water networks reached 0.042 BCM, of which 0.010 BCM was consumed, and the rest returned to the system again. Based on the data collected from the Irrigation Directorate in Qena, the reused shallow groundwater quantity was 0.100 BCM. According to the mathematical model, the amount of drainage water reused to fill the water deficit was estimated at 0.376 BCM. Based on the estimation of *Fq* subindices values for different parameters, the WSQI for this scenario indicating a low water insecurity in the current scenario (Table 5).

3.2.2. Scenario 1 with Nile reduction in 2050

The output of the WB model of this scenario shows that the total traditional water resources were 1.265 BCM, while the total water needs increased to 2.529 BCM, and thus the water deficit was filled by reusing 1.011 BCM of drainage water and 0.253 BCM of shallow groundwater (Figure 5). As a result of increasing the drainage water reuse, the WSQI showed high water insecurity in this scenario.

3.2.3. Scenario 2 with adaptation measures in 2050

This scenario had the same Nile flow reduction of scenario 1 but with adaptation measures. The output of the WB model shows that the total traditional water resources were 1.265 BCM, while the total water needs decreased from 2.529 BCM in scenario 2–2.109 BCM due to the adaptation measures (Figure 6). The water deficit was filled by reusing 0.675 BCM of drainage water and 0.169 BCM of shallow groundwater. The WSQI showed a medium water insecurity in this scenario. This scenario showed a better status than scenario 1.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	Consumption	Total Usage
Irrigation	0.918	1.799
Municipal	0.026	0.220
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Aquaculture	0	0
Evaporation	0.100	0.100
Back to Nile	0.611	
Total		2.161

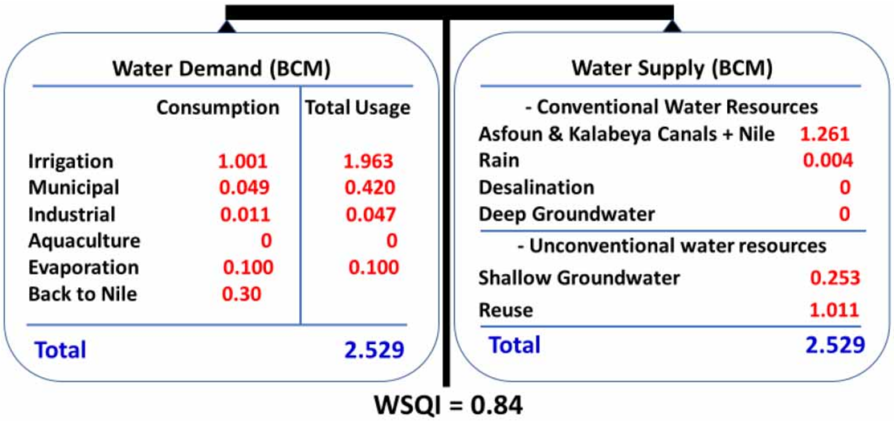
Water Supply (BCM)

- Conventional Water Resources	
Asfoun & Kalabeya Canals + Nile	1.682
Rain	0.004
Desalination	0
Deep Groundwater	0
- Unconventional water resources	
Shallow Groundwater	0.100
Reuse	0.375
Total	2.161

Figure 4 | Water supply and demand sides and WSQI in the Base Case Scenario.

Table 5 | Water Security Quality-based Index for the three tested scenarios

Scenario	Water supply type	Water quality sub-indexes	Fq	Supply quantity	Water demand	WSQI
Base Case Scenario	Nile water	DO: 1, pH: 1, BOD: 1, NO_3: 1, TP: 1, TDS: 1	1	1.682	2.162	0.93
	Rain	DO: 1, pH: 1, BOD: 1, NO_3: 1, TP: 1, TDS: 1	1	0.004		
	Shallow groundwater	DO: 1, pH: 1, BOD: 1, NO_3: 1, TP: 1, TDS: 0	0.833	0.100		
	Drainage water	DO: 0, pH: 1, BOD: 1, NO_3: 1, TP: 1, TDS: 0	0.666	0.376		
Scenario 1 in 2050	Nile water	DO: 1, pH: 1, BOD: 1, NO_3: 1, TP: 1, TDS: 1	1	1.261	2.530	0.84
	Rain	DO: 1, pH: 1, BOD: 1, NO_3: 1, TP: 1, TDS: 1	1	0.004		
	Shallow groundwater	DO: 1, pH: 1, BOD: 1, NO_3: 1, TP: 1, TDS: 0	0.833	0.253		
	Drainage water	DO: 0, pH: 1, BOD: 1, NO_3: 1, TP: 1, TDS: 0	0.666	1.011		
Scenario 2 in 2050	Nile water	DO: 1, pH: 1, BOD: 1, NO_3: 1, TP: 1, TDS: 1	1	1.261	2.109	0.88
	Rain	DO: 1, pH: 1, BOD: 1, NO_3: 1, TP: 1, TDS: 1	1	0.004		
	Shallow groundwater	DO: 1, pH: 1, BOD: 1, NO_3: 1, TP: 1, TDS: 0	0.833	0.169		
	Drainage water	DO: 0, pH: 1, BOD: 1, NO_3: 1, TP: 1, TDS: 0	0.666	0.675		



Water Demand (BCM)

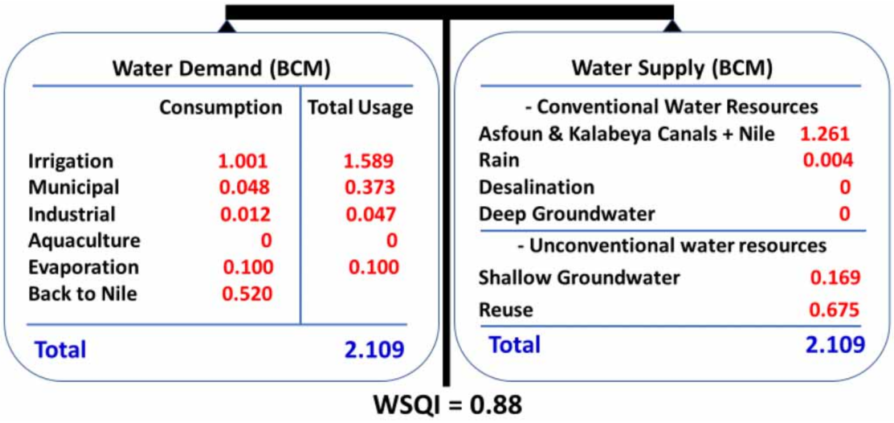
	Consumption	Total Usage
Irrigation	1.001	1.963
Municipal	0.049	0.420
Industrial	0.011	0.047
Aquaculture	0	0
Evaporation	0.100	0.100
Back to Nile	0.30	
Total		2.529

Water Supply (BCM)

- Conventional Water Resources	
Asfoun & Kalabeya Canals + Nile	1.261
Rain	0.004
Desalination	0
Deep Groundwater	0
- Unconventional water resources	
Shallow Groundwater	0.253
Reuse	1.011
Total	2.529

WSQI = 0.84

Figure 5 | Water supply and demand sides and WSQI in the Realistic Scenario 2050.



Water Demand (BCM)

	Consumption	Total Usage
Irrigation	1.001	1.589
Municipal	0.048	0.373
Industrial	0.012	0.047
Aquaculture	0	0
Evaporation	0.100	0.100
Back to Nile	0.520	
Total		2.109

Water Supply (BCM)

- Conventional Water Resources	
Asfoun & Kalabeya Canals + Nile	1.261
Rain	0.004
Desalination	0
Deep Groundwater	0
- Unconventional water resources	
Shallow Groundwater	0.169
Reuse	0.675
Total	2.109

WSQI = 0.88

Figure 6 | Water supply and demand sides and WSQI in the Optimistic Scenario 2050.

4. DISCUSSION

The study assessed the current and future water resources system in Qena Governorate under water supply reduction conditions and with several agronomic adaptation measures based on the developed WB Model and WSQI.

This study found that the current water shortage quantity in Qena Governorate was completely fulfilled by reuse of drainage water and shallow groundwater, but nevertheless, the WQSI indicated a low water insecurity when water quality was considered. However, the Nile flow reduction will increase the water shortage and the reuse quantity of drainage water and shallow groundwater. As a result, the WSQI indicated an absolute water insecurity. This study proposed a set of adaptation measures enacted to Nile flow reduction including serving 100,000 feddans with laser-leveling, use of sprinkler irrigation in 70,000 feddans, and lining the total length of 2,977 km of canals. These measures increased the water use efficiency in agriculture from 51% to 63%, reduced the water shortage quantity and dependence on reuse, and improved the water insecurity level from absolute to medium.

This study concluded that the adaptation measures in case on Nile flow reduction will improve the status of the water resources system and the water security in Qena Governorate. This is in agreement with Omar *et al.* 2021 who found that an increase in Nile flow would have more positive effects on food security and the socioeconomy than the cropping pattern adaptation measures on the national scale.

5. CONCLUSION AND RECOMMENDATION

The current study investigated the impacts of Nile flow reduction, and several adaptation measures enacted in case of Nile flow reduction. The authors developed the WB Model and WSQI index to assess the water resources system in Qena Governorate and to assess the impacts of different adaptation measures. The current and future water shortage quantities in Qena Governorate are completely compensated by reuse of drainage water and shallow groundwater. But, in terms of merging water quantity and quality, there is a low water insecurity in the current scenario. The water insecurity level deteriorated to the high level in case of Nile flow reduction with continuation of current policies. The package of adaptation measures in this study includes laser land leveling, application of sprinkler irrigation method, and lining of irrigation canals. This package will enhance the water use efficiency in agriculture, which reduces the water shortage and dependence on reuse of drainage water. The suggested adaptation will also improve the water insecurity status from absolute to medium level. The water security in Qena Governorate will not only be achieved by covering the water shortage quantity, but also by providing acceptable quality of water supplies. The current study recommends further trials to develop new water resources including mainly increasing the Nile flow to Egypt as a priority. The study recommends the extension of current adaptation measures for rationalizing the water resources use. The study also recommends upscaling the use of the developed WSQI for the remaining governorates and the entire country to ensure considering the water quality in the water security status assessment.

DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

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