Water Quality Assessment of Aswan High Dam Reservoir

M. Elshemy and G. Meon

Abstract Egypt is highly dependent on the River Nile as the main source of freshwater. The Aswan High Dam (AHD) was constructed to control the River Nile. AHD reservoir was formed due to the construction of the dam; it is considered as one of the largest man-made lakes in the world. There is currently rising awareness regarding the water quality status of River Nile and in particular the AHD reservoir, the sole reservoir in Egypt. In this work, a comparative study to assess the water quality and trophic state of the southern part of AHD reservoir, Lake Nubia, has been done during low flood periods of 3 successive years (2006–2008). Two water quality indices (NSF WQI and CCME WQI) and two trophic status indices (Carlson TSI and LAWA TI) were used. The results show that the water quality status of Lake Nubia ranges from excellent (according to the Egyptian water quality standards for surface fresh waterways) to good, while the trophic status of the reservoir is eutrophic. A spatial change in results can be noticed due to the morphological and hydrological characteristics of the reservoir. It is recommended that the reservoirs' different zones should be assigned to different water uses based on comprehensive water quality studies.

Keywords AHD reservoir, Lake Nubia, River Nile, TSI, WQI

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Abbreviation

AHD	Aswan High Dam
APHA	American Public Health Association
BCM	Billion cubic meter
CCME	Canadian Council of Ministers of the Environment
Chl-a	Chlorophyll a (mg/L)
DO	Dissolved oxygen (mg/L)
DO_{sat}	Dissolved oxygen saturation concentration (mg/L)
LAWA	Länderarbeitsgemeinschaft Wasser (German Regional Working Group on Water)
MWRI	Egyptian Ministry of Water Resources and Irrigation
NH_4	Ammonium (mg/L)
NO_2	Nitrite (mg/L)
NO_3	Nitrate (mg/L)
NSF	National Sanitation Foundation
OECD	Organization for Economic Cooperation and Development
pH	Potential of hydrogen (unit)
PO_4	Orthophosphate (mg/L)
St. n	Station number n
T	Temperature (°C)
TDS	Total dissolved solids (mg/L)
TI	Trophic level
TN	Total nitrogen (mg/L)
TP	Total phosphorus (mg/L)
TSI	Trophic status index
TSS	Total suspended solids (mg/L)
WQI	Water quality index

1 Introduction

The water quality state of a water body depends on a large number of physical, chemical, and biological indicators. Using an evaluation approach, such as the water quality index, can indicate the overall water quality condition.

Basically, there are four main approaches which are widely used to assess the water quality of a water body:

1. Water quality index approach
2. Trophic status index approach
3. Statistical analysis approaches of the water quality data such as correlation analysis [1–6] and fuzzy clustering analysis [7–11]
4. Biological analysis approaches such as genetic algorithms method and other different biological indices [12–33]

First, comprehensive studies are required to develop the statistical and biological approaches. This task was not within the frame of this research work but is recommended in future work. In this research work, water quality and trophic status indices will be used to assess the water quality state of Aswan High Dam (AHD) reservoir.

2 State of the Art

2.1 Water Quality Indices

A water quality index (WQI) can be simply defined as a mathematical approach which aggregates data on two or more water quality variables to produce a single number [34]. It consists of water quality variables such as dissolved oxygen, total phosphorus, and fecal coliform, each of which has specific impacts to beneficial uses. The water quality index concept was first introduced more than 160 years ago, in 1848, in Germany where presence or absence of certain organisms in water was used as an indicator of the fitness of a water source [35].

There are several water quality indices that have been developed to assess water bodies. In 1965, the first-ever modern WQI was developed and published by Horton [36]. Horton's index uses ten variables, including commonly monitored ones such as dissolved oxygen, fecal coliform, and temperature. It is computed as the weighted sum of subindices, which are calculated using a table of specific subindex values corresponding to range of each variable. Horton's index ranges from 0, representing poor water quality, to 100, representing perfect water quality [34].

Development of water quality indices has been discussed in numerous publications [37–42]. Abbasi and Abbasi [37] presented a comprehensive review for WQIs approaches, formulation, and types. Walsh and Wheeler [42] discussed the development of WQIs according to the applied aggregation methods. According to

Table 1 A statistical description of WQIs publications during the period (1974–2011) [40]

Type of water use	Public use	Agriculture	Water reuse	WTP	Fish farms
	76.3 %	19.8 %	13.5 %	8.01 %	5.9 %
WQI	Total number	New WQI	Most frequently used WQI		
	97 WQIs	20 %	NSF WQI		
Study region	India	China	Brazil	USA	Other
	38 %	9.6 %	5.5 %	4.5 %	42.4 %
Water body	Rivers and streams	Other			
	57 %	43 % (lakes, artesian wells, reservoirs, groundwater, flood plains then aquifers)			

Poonam et al. [39], WQIs can be classified into four main groups: public indices, specific consumption indices, planning indices, and statistical indices. The authors reviewed 13 frequently used WQIs. Ribeiro Alves et al. [40] discussed, in their review publication, the state of scientific literature on WQIs. The authors reviewed 554 articles which were published during the period (1974–2011). The main findings of this study can be seen in Table 1. In 2016, Sutadian et al. discussed the development and the application of WQIs for rivers during the period 1987–2014. Out of the 30 reviewed WQIs, the authors addressed seven WQIs as the most important indices, based on their wider use. These indices are ordered as the following: CCME WQI, NSF WQI, Oregon Index, Bascarón index, House's Index, Scottish Research Development Department index, and Fuzzy-based indices. The authors presented a list of the reviewed WQIs and their different applications [41].

For Egyptian water resources, different WQIs have been used. Table 2 shows a list of recent WQI applications for Egyptian water resources.

Since 1965, many different water quality indices have been addressed in the literature [62–80].

Two of the best known water quality indices, which have been frequently used, are the National Sanitation Foundation Water Quality Index (NSF WQI) and the Canadian Council of Ministers of the Environment Water Quality Index (CCME WQI). The two indices were chosen for this research work.

The NSF WQI has been widely applied to many water bodies [81–89]. NSF WQI, or variants of it, is used by a number of state agencies in the United States in their annual reports on the water quality of rivers and streams under their jurisdiction [73]. NSF WQI was used to represent the water quality profile of Yamuna River, India [87]. Bonanno and Lo Giudice [17] used the NSF WQI and a floristic quality index. The former enabled them to describe the water quality according to a spatial–temporal gradient, whereas the latter focused on the ecological quality of riparian vegetation.

Table 2 List of recent selected WQI studies for Egyptian water resources (2011–2016)

Year	WQI	Application	No. of WQ parameters	Reference
2011	Bascaron WQI	The beaches at Matrouh City	7	[43]
2012	EWQI (CCME)	Omar Bek drain and Damietta branch	17	[44]
2012	NSF WQI	Groundwater of eight rural governorates (Qena, Sohag, Kalubiya, Menofiya, Sharqiya, Gharbiya, Kafr El-Sheikh, and Daqahliya)	9	[45]
2012	PCA WQI	Kilo 21, Oumum, and Nubaria drains, Alexandria	33	[46]
2012	Bascaron WQI	Groundwater of Darb El-Arbaein area, South-western Desert	20	[47]
2013	CCME WQI	El-Nubaria and El Mahmoudia, El Hager, El Nassr, El Khandak, and Abo Diab Canals	17	[48]
2014	Bascaron WQI	Ismailia Canal	34	[49]
2014	Bascaron WQI	Groundwater of Darb El-Arbaein	8	[50]
2014	CCME WQI	Mahmoudia Canal	20	[51]
2014	EWQI (CCME)	El-Kurimat power steam plant on the River Nile	17	[52]
2014	PCA WQI	EL-Dekhaila Harbor, Alexandria	11	[53]
2014	PCA WQI	El-Mex bay, El-Umum Drain, El-Qalaa Drain, El-Noubaria Drain, and Marriott Lake, Alexandria	14	[54]
2014	Bascaron WQI	El-Omumm Drain and Nubaria Canal, Alexandria	19	[55]
2015	Bascaron WQI	Groundwater of Western Nile Delta	21	[56]
2015	Bascaron WQI	Rosetta Branch	6	[57]
2015	CCME WQI	20 drains discharging to Northern Egypt Lakes and the Mediterranean Sea	11	[58]
2015	CCME WQI	River Nile in Cairo governorate	9	[59]
2015	DWRI	Gharbia drain in the Nile Delta	5	[60]
2016	Bascaron WQI	Groundwater of Assiut governorate, Egypt	15	[61]

The CCME WQI has been applied to several data sets nationally (in Canada) and internationally [90–99]. In 2008, the CCME WQI was modified according to the Egyptian guidelines (for drinking surface water) and was applied at four stations of the River Nile, Egypt [100]. De Rosemond et al. [101] evaluated the ability of the CCME WQI to differentiate water quality from metal mines across Canada at exposure sites from reference sites using two different types of numeric water quality objectives. CCME WQI and NSF WQI were applied for the Karun River system which is considered as the most important river in Iran [102]. Boyacioglu [103] has modified the CCME WQI to meet requirements of classification of surface waters according to quality based on European legislation. Then, the developed WQI has been applied to assess the overall water quality in the Kucuk Menderes Basin, Turkey. The CCME WQI was used to assess the water quality of the River Chenab, Pakistan, during the low-flow months of 2006–2007 and 2007–2008 [104].

2.2 *Trophic Status Indices*

The trophic state does not directly imply the water quality but assigns the productivity of the water body due to the occurring biological and chemical activities and is dependent on nutrient concentrations and other characteristics. Lakes and reservoirs, according to their biological productivity and nutrient conditions, are commonly grouped into three different trophic states: oligotrophic, mesotrophic, and eutrophic. The trophic state falls under two terms “oligotrophic” (Greek for ‘little food’) or “eutrophic” (Greek for ‘well fed’) and was originally used to describe the soil fertility in northern Germany; subsequently, these terms were applied to lakes [105].

Numerous attempts have been made to define the trophic states in terms of both nutrient and productivity water quality parameters. Carlson [106] developed a numerical trophic state scale from 0 to 100 for lakes. The index number can be calculated from any of several parameters including Secchi depth transparency (SD), chlorophyll (Chl-a), and total phosphorus (TP). The Carlson TSI has been widely used to evaluate many lakes and reservoirs [107–114]. Galloway and Green [115] used TSI (TP) and TSI (CHL) to assess the trophic status of lakes Maumelle and Winona, Arkansas, USA. In 2010, Santhanam and Amal Raj [116] have used the Carlson TSI to determine the trophic status of Pulicat lagoon, India, for the years 2005 and 2006. All the values obtained for the TSI (SD) were higher when compared to the TSI (Chl-a), which may indicate that something other than algae, perhaps color or non-algal seston or the dominance by pico-plankton, is contributing to the light attenuation. The investigation relays the need to develop more modern and more accurate indices to represent water quality in a lagoon. The trophic status of Manzala Lake, Egypt, was evaluated using Carlson TSI [117–119]. N/P ratio also was calculated to determine the limiting nutrient for the lake. Ahmed et al. [117] concluded that the lake trophic state is eutrophic and hypereutrophic in those parts of the lake closest to the drain outlets, and most of the lake area (96%) is limited by the nitrogen. Chang and Liu [109] examined the influence of water turbidity on the reliability of Carlson TSI and used the Back-Propagation Neural Network model to create a new trophic state index. In 2016, Carlson TSI was used to investigate the phosphorus dynamics of the aquatic system (East Kolkata Wetlands, India) during the wastewater purification process [120]. The authors indicated that the wetland maintained a mesotrophic status after the onset of aerobic condition.

The Florida Department of Environmental Protection has developed a new trophic status index (using data for 313 Florida lakes), Florida Trophic State Index, which is based on the Carlson TSI but also includes total nitrogen as a third indicator [121, 122]. For Florida water quality assessment reports, the Secchi depth has been excluded as an indicator because of the associated problems which have been caused in dark-water lakes and estuaries, for which dark waters rather than algae diminish transparency. This index has been recently used [120, 123, 124].

In 1982, a detailed classification system based on the German technical standards was developed and has been used successfully for lakes and reservoirs located primarily in temperate zones as well as in some non-temperate situations [105, 125]. This detailed classification system evaluates the water quality of a water body by using three main criterion classes: hydrographic and territorial criterion, trophic criterion, and salt content, special, and hygienically relevant criterion [105].

The Organization for Economic Cooperation and Development [126] provides specific criteria for temperate lakes in terms of the mean annual values of total phosphorus, chlorophyll a, and Secchi depth (Table 3). These criteria have

Table 3 Trophic classification of temperate freshwater lakes, based on a fixed boundary system [126, 127]

	Trophic category				
	Ultra-oligotrophic	Oligotrophic	Mesotrophic	Eutrophic	Hypertrophic
Nutrient concentration (μg/L)					
Total phosphorus	<4	4–10	10–35	35–100	>100
Orthophosphate	<2		2–5	5–100	>100
DIN	<10		10–30	30–100	>100
Chlorophyll a concentration (μg/L)					
Mean concentration in surface water	<1	1–2.5	2.5–8	8–25	>25
Max. concentration in surface water	<2.5	2.5–8	8-25	25–75	>75
Secchi depth (m)					
Mean annual value	>12	12–6	6–3	3–1.5	<1.5
Minimum annual value	>6	>3	3–1.5	1.5–0.7	<0.7

limitations in practical use; some water bodies can be classified in one or another trophic category depending on which parameter is used. Lake Baikal, Russia, for example, is ultra-oligotrophic in terms of physicochemical characteristics but is close to mesotrophic on the basis of primary production [127]. To avoid this, a more flexible open boundary system has been developed by OECD by using a statistical fit to more open ranges of the parameters. OECD criteria have been used for estimating the trophic status of several lakes and reservoirs [112, 128–132].

For coastal marine waters, Vollenweider et al. [133] proposed a new trophic index (TRIX), which is based on Chl-a, oxygen saturation, mineral, total nitrogen, and phosphorus. This index has been frequently used to evaluate the trophic status of coastal marine waters, estuaries, and lagoons [134–140].

In 1999, a new trophic level index (TLI) was developed to estimate the trophic level of New Zealand lakes and reservoirs [141]. TLI is based on Chl-a, TP, SD, and TN. This index is used in recent studies [142, 143].

The OECD concept has been modified by the German Regional Working Group on Water, Länderarbeitsgemeinschaft Wasser [144]. The LAWA Total Index (TI) is more flexible and can be calculated by different methods. LAWA TI has been widely used in Germany; it has been used to assess 23 reservoirs in Saxony [145]. The Rappbode Dam reservoir in Saxony-Anhalt has been evaluated using LAWA TI. The reservoir trophic status was mesotrophic; LAWA TI was less than 2.0 [146]. The Ruhrverband [147] used the LAWA TI to assess eight reservoirs in different sites in Germany. The Hessian Agency for Environment and Geology [148] has applied LAWA TI to 90 water bodies (lakes and reservoirs) in Hessen for the water quality measurement in 2007. Scharf [149] used the LAWA TI to evaluate the Wupper Reservoir which is situated in central western Germany.

For reservoirs, based on their morphological characteristics, there is often a spatial gradient in sediment and nutrient concentration patterns along the body of a reservoir, especially in long, narrow, dendritic reservoirs. This gradient is accompanied by a spatial gradient in biological productivity and water quality in the reservoir [105]. The trophic status may range from nutrient rich (eutrophic) in the upper reaches of the water body to nutrient poor (oligotrophic) at locations closer to the dam wall [150]. Lind et al. [151] suggested that according to the gradient in trophic status in reservoirs, a corresponding zonation exists in the relative suitability of various portions of reservoirs for different uses (e.g., water supply, fishing, and recreational activities). Moreover, they stated that two different methods should be used for estimating the trophic status of reservoirs.

Some interesting trials to develop a new trophic index to evaluate tropical/subtropical reservoirs were done in Brazil [152–154]. The Trophic Status Index for tropical/subtropical reservoirs (TSI_{tsr}) is the most recently developed one in Brazil [152]. This index, which is considered as a calibrated version of Carlson TSI, is based only on Chl-a and TP. Secchi depth (SD) was excluded as this parameter is affected by turbidity due to suspended material which is common in reservoirs. The data of 18 tropical/subtropical reservoirs in Brazil were used for developing this index which has been used to evaluate different reservoirs in Brazil [78, 155, 156].

In the literature, many different trophic indices have been developed [8–10, 26, 157–171].

Two trophic status indices were chosen for this research work: Carlson TSI and LAWA TI.

3 Case Study: Aswan High Dam Reservoir

3.1 Study Area

Egypt is extremely dependent on the River Nile; the country hardly has any other freshwater resources [172]. Full control of the Nile water discharge was achieved in the 1970s after the construction of the Aswan High Dam (AHD). As a result, the AHD reservoir was formed. The reservoir extends about 500 km upstream from the Aswan High Dam between the latitudes 23° 58′ and 20° 27′ N and between longitudes 30° 35′ and 33° 15′ E (Fig. 1). The current length of the submerged area is about 500 km, of which 350 km are within the Egyptian territory and is known as Lake Nasser. The 150 km stretch which lies in the northern part of Sudan is known as Lake Nubia. Generally, the reservoir is also known as Lake Nasser reservoir. AHD reservoir has a long, narrow shape with dendritic side arms or bays (Khours) extending in both the Egyptian and Sudanese stretches of the Nubian Nile (Fig. 2).

Lake Nasser reservoir is situated in a desert area; the climate is extremely arid. The area is in the transition zone between the tropical climate with summer rain and the Mediterranean climate with winter rain [173]. This area receives virtually no

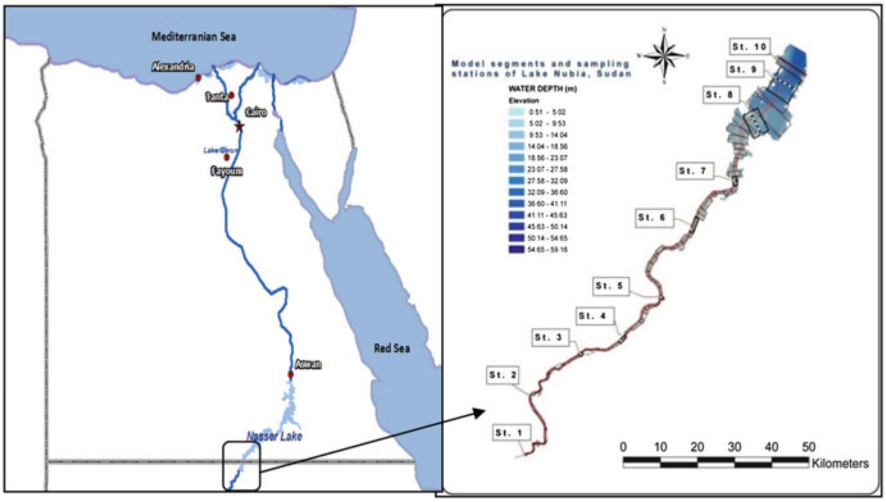

Fig. 1 Map of Lake Nubia and its selected sampling stations (control stations)

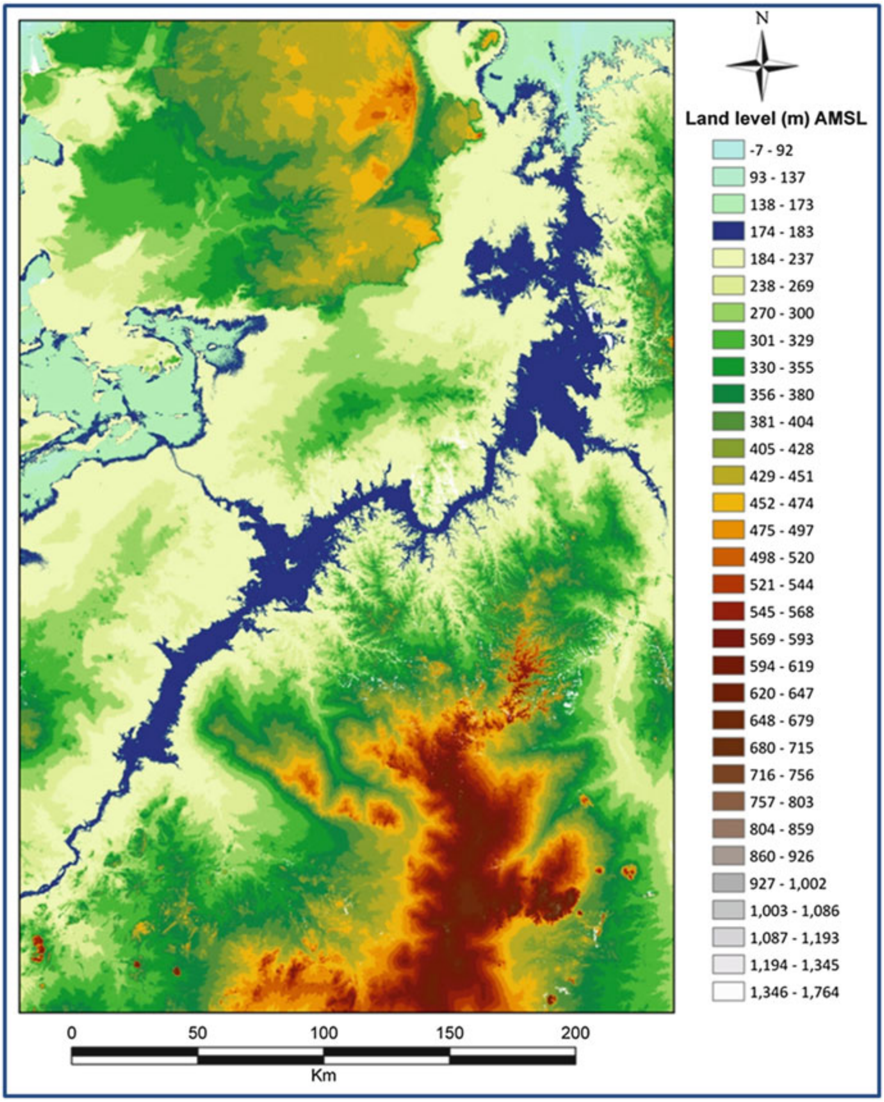

Fig. 2 AHD reservoir region topography

rainfall, except for occasional thunderstorms in winter, roughly once every 10 years [174, 175]. The relative humidity is highest (40–41 %) in December and January and lowest in the May and June (13–15 %). The wind speed does not vary greatly all over the year, as the mean ranges from about 15 to 19 km/h. Its direction is mostly NW-NE [175]. Evaporation is very high, approximately 3,000 mm/year [176].

The reservoir has a maximum water depth of 130 m (the mean depth is about 25 m), or 182 m above mean sea level (AMSL), and a total capacity of 162 BCM (about 15 % of that for Lake Nubia). At this level the reservoir has a length close to 500 km (about 150 km for Lake Nubia) and an average width of 12 km. The surface area of the reservoir at this maximum water level is 6,540 km^2. Lake Nubia has about 14.8 % of the total surface area. Figure 2 shows the topography of the reservoir region, while Fig. 3 shows the water level – reservoir volume – surface area curve. Further details about the reservoir morphology can be found in [174, 175, 177–179].

Lake Nubia can be divided into two sections: the riverine section and the semi-riverine section [175]. The riverine section, with all-year riverine characteristics, comprises the southern part of the lake, from the southern end to Daweishat (St. 5), as shown in Fig. 1. The semi-riverine section, with riverine characteristics during the flood season (from the second half of July to November) and lacustrine characteristics during the rest of the year, covers the northern part of the lake extending from Daweishat. The study area has a desert climate. This area receives virtually no rainfall, except for occasional thunderstorms which may sporadically penetrate the area in winter roughly once every 10 years [175].

The reservoir water velocity decreases as it approaches the High Dam. At the entrance of the reservoir, the flow velocity is about 0.5 m/s. This velocity is gradually reduced within a few kilometers to 0.1–0.2 m/s and in Lake Nasser to 0–0.03 m/s [176]. The Nile flood usually carries about 134 million tons of suspended matter (silt) per year, based on the average yearly inflow of 84 km^3 [180]. It is heavily loaded with inorganic clay, silt and sand, and organic debris (detritus) [177]. About 98 % of the annual sediment load occurred during the flood season [175]. Almost all the silt brought by the River Nile is deposited within Lake

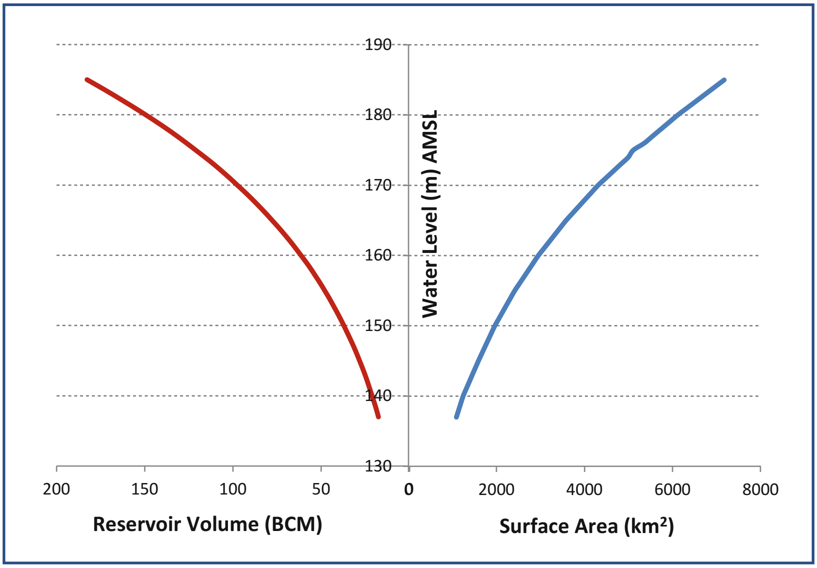

Fig. 3 AHD reservoir water level – volume – surface area curve

Nubia, most of it being deposited south of Haifa, where a new delta is in formation, and only the fine silt enters Lake Nasser [173]. Deposition in the reservoir is governed by a number of factors; the major factor is the sudden decrease of flow velocity as soon as it reaches the open area of Lake Nubia. The water losses of the reservoir are mainly due to evaporation and seepage. Annual evaporation losses are estimated at about 9.6 km^3, while annual seepage losses are estimated at 0.05 km^3 [180]. AHD reservoir has only one inflow source, the River Nile, at its upstream end. The inflow data were specified as daily average values from one gauging station at the upstream end of the reservoir. Figure 4 shows AHD reservoir inflows, monthly average, through the period from August 1998 to November 2007, as typical inflow for the reservoir. The reservoir inflow for successive 2 years is enlarged, as can be seen in Fig. 4. Typical flood period is from July to November, as can be seen in Fig. 4, while typical low flood period is from December to June.

The Egyptian Ministry of Water Resources and Irrigation, MWRI, has implemented an environmental monitoring program for AHD reservoir water quality [181]. MWRI realized the importance of protecting the reservoir from pollution, as it is almost the sole source of freshwater to the country. MWRI suggests that AHD reservoir and a strip of 20 km wide on both sides should be announced as a natural protectorate. Generally, from samples collected before and after the flood, the reservoir water has good physical and chemical characteristics for use [180]. The thermal pattern of the reservoir is warm monomictic; the reservoir stratifies in summer, and mixing occurs in winter [182]. Transparency is affected by the turbidity caused by silt and clay of riverine origin. It is particularly strong in the flood season. Water temperature ranges between 15.0°C in February and 32.4°C in August, pH is normally alkaline, and the reservoir trophic status is

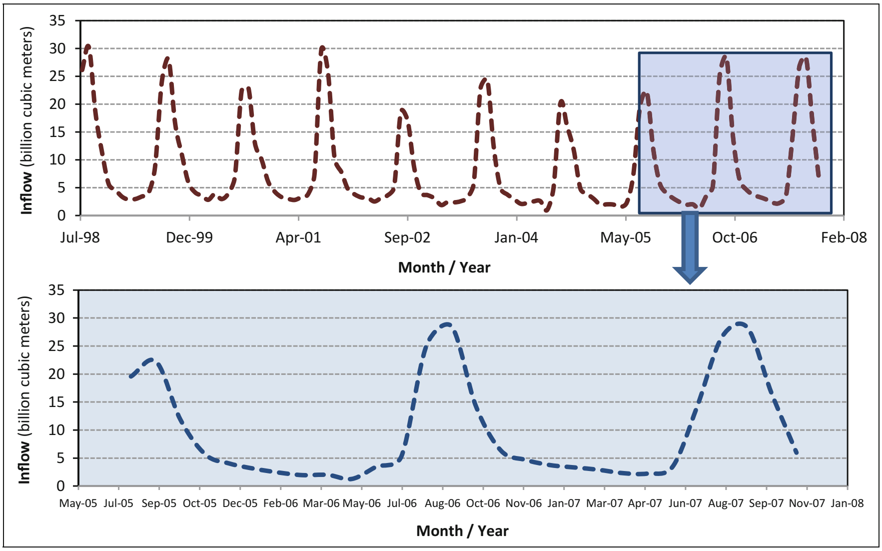

Fig. 4 AHD reservoir monthly inflows (1998–2007)

eutrophic [176]. Dissolved oxygen is usually high during November–April and low during May–October. In surface waters, concentrations often vary between 3 and 12 mg/L, but in deeper layers, they may be much less: 0–8 mg/L. Salinity is low at all times and generally <200 mg/L. Recorded concentrations for orthophosphate have ranged from 0.001 to 2.2 mg/L [182]. The phytoplankton community is composed of blue-green algae, diatoms, green algae, and dinoflagellates. Blue-greens dominate the community during spring and summer, while diatoms dominate the community only in winter [183]. Further details about the reservoir water quality can be found in [174, 184–186].

3.2 Data Collection

The southern part of Lake Nasser (AHD) reservoir which lies in Sudan, Lake Nubia, was chosen as the case study of this work due to the availability of different required data. Hydrodynamic and water quality data of Lake Nubia for January 2006, February 2007, and March 2008 were provided by Nile Research Institute (NRI) and National Water Research Center (NWRC), Egypt. The measured hydrodynamic and water quality data consist of water temperature, dissolved oxygen, chlorophyll a, orthophosphate, total phosphorus, nitrate–nitrite, ammonium, total dissolved solids, total suspended solids, turbidity, fecal coliform, and pH. In site parameters have been analyzed in a mobile Water Quality Laboratory, while other parameters have been analyzed in the NRI Water Quality Laboratory. The collected samples were analyzed using standard methods of American Public Health Association (APHA) [187].

In-reservoir temperature and constituent concentration profiles were measured at 18 sampling stations positioned along the longitudinal axis of Lake Nubia, as seen in Fig. 5. At each station, the water samples were collected from the surface and at 25, 50, 65, and 80 % of depth at three different vertical axes (east, middle, and west). Chlorophyll a samples were collected from different two zones, lighted and dark zones. Fecal coliform samples were collected from the surface and at 50 and 80 % of depth. Figure 6 shows surface measured concentrations of two selected parameters, DO and TSS, at different sampling stations along Lake Nubia, as examples.

3.3 Historical Review and Research Deficits

Studies regarding water quality evaluation of Aswan High Dam (AHD) reservoir in the literature are limited. Most of these studies were based on statistical approaches [188–191] or biological approaches [192–194].

In 1995, Awadallah and Soltan used a statistical approach to follow up the distribution of physical and chemical components between surface and bottom

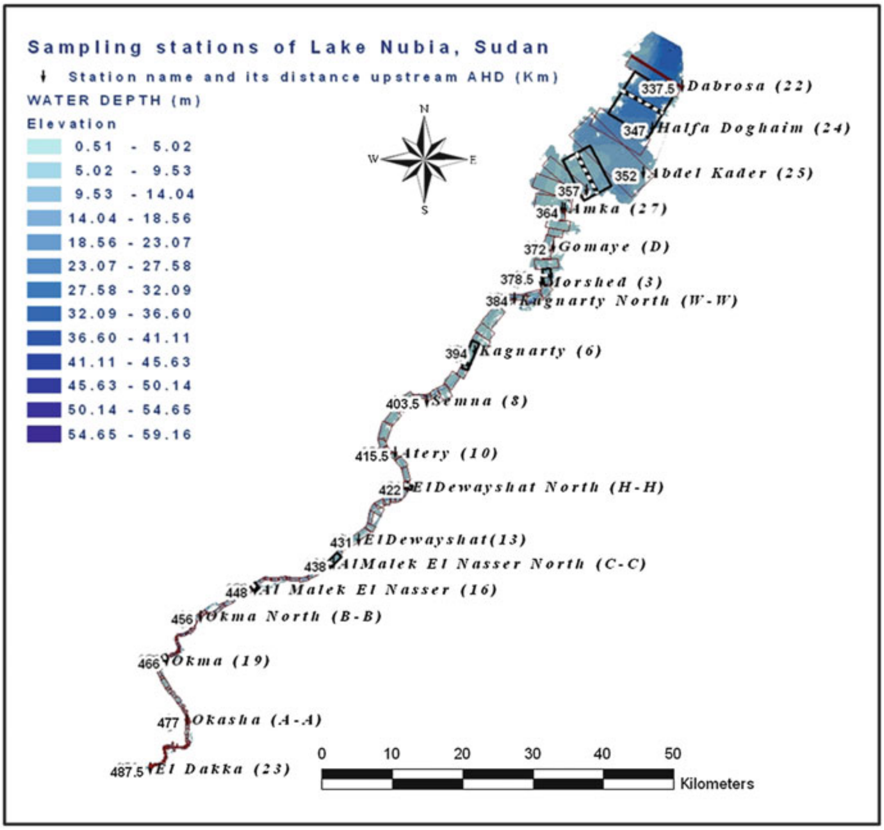

Fig. 5 Lake Nubia sampling stations

water of the AHD reservoir and their effects on the water quality and on the life of biota [195]. The samples were collected between Daal Cataract in Sudan and the AHD in the most southern part of Egypt, during the period from 23 November to 18 December 1992, at five different water depths. The statistical analysis of the database exhibited positive and significant correlation coefficient values. The results show that there was stratification in the water column of the reservoir.

The NSF WQI has been used by Abdel Rehim et al. [81] during the stratification period, extending from May to July, and turnover period, extending from September to December. The results revealed that the quality of water in Lake Nasser is improved during turnover and mixing periods. Average NSF WQI results were ranged between 62.00, medium, in July to 79.64, good, in November. The measured data were collected from one site in Lake Nasser, Abu Simbel (281 km upstream AHD), for 1 year (September 2000 to August 2001), and at different depths.

Abou El Kheir et al. [196] studied the seasonal variations of physical–chemical characteristics and phytoplankton growth at seven stations along Lake Nasser

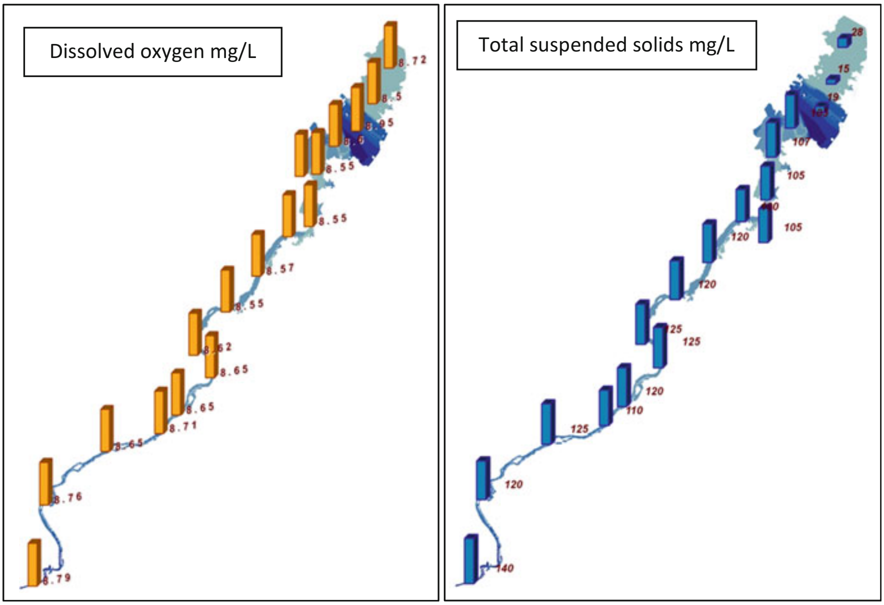

Fig. 6 Surface measured concentrations of some selected parameters at different sampling stations along Lake Nubia, January 2006

during the period 2001–2002. They stated that phosphorus is the limiting nutrient around the year. The Carlson TSI was used. The results show that Lake Nasser is a mesotrophic lake; its average TSI values range from 40 to 60. The TSI based on CHL was considerably lower than the TSI based on SD, especially in the south part of the lake. These results indicate that particles other than phytoplankton may be contributing to the light attenuation, where in this part of the lake, the water is turbid due to suspended sediment because of the flood or due to re-suspension from the bottom by turnover process.

A statistical mathematical model, based on regression relations of water quality parameters, was built up to estimate daily water quality parameters [197]. A fixed laboratory at the entrance of the reservoir was assumed using the available data (1977–2001). A physical, chemical, and biological analysis of the water quality was performed at 25 sections distributed along the lake using the World Health Organization (WHO) standards. According to WHO standards, the average water quality results before the flood are good, while during the flood are satisfactory except for the turbidity.

Gharib and Abdel-Halim [198] used statistical regression models to study the species composition, abundance, and phytoplankton biomass, supported by some physicochemical environmental parameters, in Lake Nasser during the highest flood season in autumn 1999. The results showed that the most relevant physicochemical factors affecting the growth of phytoplankton abundance were pH values, dissolved phosphate, and reactive silicate.

Heikal et al. [84] investigated the temporal and spatial variation of water quality status along the River Nile and the agricultural drains, which are the main sources of pollution along the Nile, during high- and low-flow periods from 2000 to 2005. Statistical analysis and NSF WQI were used. The results showed that the overall water quality status of the River Nile and the agricultural drains during the low-flow period is generally better than during the high-flow period. They concluded that the temporal and spatial variations in the water quality parameters along the River Nile are mainly affected by the quality of water discharges from agricultural drains as well as the magnitude of the River Nile flow.

Toufeek and Korium [6] studied the variations of physicochemical parameters in the main channel of Lake Nasser during the year 2005. Results indicated wide variations in the concentrations of different physicochemical parameters between surface and bottom layers during summer season especially in the northern part of the Lake. During winter, the variation in concentrations of these parameters between surface and bottom layers was modest. Correlation coefficient matrices between each two pairs of parameters were estimated to throw light on relationships between different physicochemical parameters. It was concluded that the various parameters under investigation in different seasons and regions in Lake Nasser lie within the permissible range, and the reservoir water quality status for drinking, irrigation, and fish culture purposes is good.

Heikal [199] investigated the quality of water in the main side branches (Khors) of Lake Nasser and its main channel during periods of low and high water levels for the years 2001 and 2005, respectively. He has used the NSF WQI and Carlson TSI to assess the water quality and trophic states, respectively, of Lake Nasser and main Khors. The results showed that the reservoir water level drop led to a decline in the water quality state of Lake Nasser and Khors from the order of good to medium. Also the trophic state index (TSI) values revealed that the productivity of the lake changed from mesotrophic during the high water level season to eutrophic during the low water level season.

NSF water quality index (WQI) and Carlson trophic status index (TSI) are the most frequently used indices for Egyptian water resources (see the previous section). In this research work, a comparative study has been done by applying other different two indices (additional to NSF WQI and Carlson TSI). These indices are CCME WQI and LAWA TI. The comparative study is essential to evaluate the water quality and trophic status for reservoirs in particular [151]. CCME WQI was developed according to the Egyptian water quality standards for surface fresh waterways. Carlson TSI was calculated for each of two water quality parameters, total phosphorus, and chlorophyll a, while the average Carlson TSI was calculated using both parameters, as recommended for reservoirs by Lind et al. [151].

3.4 Methodology

3.4.1 NSF WQI

The NSF WQI has been developed by the National Sanitation Foundation (NSF) in 1970 [62]. A survey of 142 water quality scientists was conducted to conclude which water quality tests should be included in an index, out of about 35 tests. Nine water quality variables are used for the index: dissolved oxygen (DO), fecal coliform, pH, biochemical oxygen demand (BOD), temperature change, total phosphate, nitrate, turbidity, and total solids. The index is computed as the weighted sum of subindices. Each parameter has a weight factor based on its importance in water quality (Table 4) and a rating curve gives a subindex quality value, which ranges from 0 to 100, corresponding to the field measurements. The NSF WQI can be calculated as follows:

$$\text{NSF WQI} = \frac{\sum_{i=1}^{n} W_i{*}Q_i}{\sum_{i=1}^{n} W_i} \tag{1}$$

where:

W_i	Weight factor of the *i*th parameter
Q_i	Quality of the *i*th parameter can be obtained from the appropriate subindex rating graph

The WQI ranges have been defined as [62]:

- 90–100: Excellent
- 70–90: Good
- 50–70: Medium
- 25–50: Bad
- 0–25: Very bad

Table 4 NSF WQI weight factors

Parameter	Weight factor
Dissolved oxygen (%sat)	0.17
Fecal coliform (#/100 mL)	0.16
pH (standard units)	0.11
Biochemical oxygen demand (mg/L)	0.11
Temperature change (°C)	0.10
Total phosphate (mg/L)	0.10
Nitrates (mg/L)	0.10
Turbidity (NTU)	0.08
Total suspended solids (mg/L)	0.07

According to the available water quality parameter measurements of Lake Nubia, eight parameters were used to apply NSF WQI to Lake Nubia. The used parameters are dissolved oxygen (% sat), fecal coliform (colonies/100 mL), pH (standard unit), temperature change (°C), total phosphate (mg/L), nitrate (mg/L), turbidity (NTU), and total solids (mg/L).

For temperature change, it is calculated as the difference between the water temperature value of the intended control station and its reference water temperature value. An expression for the dissolved oxygen saturation concentration ($\mathrm{DO_{sat}}$) at sea level for freshwater as a function of water temperature which is given in APHA [187], Eq. (2), was used to calculate DO (% sat) at different control stations, Eq. (3). The used expression was as follows:

$$\ln \mathrm{DO_{sat}} = -139.34411 + \frac{1.575701 \times 10^5}{T_\mathrm{w}} - \frac{6.642308 \times 10^7}{T_\mathrm{w}^2} + \frac{1.243800 \times 10^{10}}{T_\mathrm{w}^3} - \frac{8.621949 \times 10^{11}}{T_\mathrm{w}^4} \tag{2}$$

And then:

$$\mathrm{DO}\ (\%\ \mathrm{sat}) = \left({}^{\mathrm{DO}_i}/_{\mathrm{DO_{sat}}}\right)\% \tag{3}$$

where:

$\mathrm{DO_{sat}}$	Freshwater DO saturation concentration in mg/L at sea level
T_w	Water temperature in (°K) ([°K] = [°C] + 273.150)
DO_i	Measured or simulated DO concentration at the control station St. *i*

3.4.2 CCME WQI

In 1997, the Canadian Council of Ministers of the Environment (CCME) developed a WQI to simplify the reporting of complex and technical water quality data. The WQI Technical Subcommittee adopted the conceptual model from the British Columbia index [63].

The application of the CCME WQI provides a measure of the deviation of water quality from water quality guidelines or objectives. Therefore, for each site and water use, different sets of parameters can be used depending upon the availability of data and regulatory standards.

The CCME WQI consists of three measures of variance from selected water quality objectives (scope, frequency, amplitude). These three measures of variance are combined to produce a value between 0 and 100 that represents the overall water quality. The CCME WQI values are then converted into rankings by using an index categorization schema that can be customized to reflect expert opinion by users. The detailed formulation of the WQI is described in the Canadian Water Quality Index 1.0 – Technical Report [63].

After the body of water, the period of time, the variables, and the objectives have been defined, each of the three factors that make up the index must be calculated as follows:

F_1 (scope) represents the percentage of variables whose objectives are not met in terms of "failed variables":

$$F_1 = \left(\frac{\text{Number of failed variables}}{\text{Total number of variables}}\right)100 \tag{4}$$

F_2 (frequency) represents the percentage of individual tests that do not meet objectives in terms of "failed tests":

$$F_2 = \left(\frac{\text{Number of failed tests}}{\text{Total number of tests}}\right)100 \tag{5}$$

F_3 (amplitude) represents the amount by which failed test values do not meet their objectives. F_3 is calculated in three steps:

1. The number of times, by which an individual concentration is greater than (or less than, when the objective is a minimum) the objective, is termed an "excursion" and is expressed as follows.
   When the test value must not exceed the objective:

$$\text{Excursion}_i = \left(\frac{\text{Failed test value}_i}{\text{Objective}_j}\right) - 1 \tag{6}$$

   For the cases in which the test value must not fall below the objective:

$$\text{Excursion}_i = \left(\frac{\text{Objective}_j}{\text{Failed test value}_i}\right) - 1 \tag{7}$$

2. The collective amount by which individual tests are out of compliance. This variable, referred to as the normalized sum of excursions, or nse, is calculated as:

$$\text{nse} = \frac{\sum_{i=1}^{n} \text{excursion}_i}{\text{Total number of tests}} \tag{8}$$

3. F_3 is then calculated by an asymptotic function that scales the normalized sum of the excursions from objectives (nse) to yield a range between 0 and 100.

$$F_3 = \left(\frac{\text{nse}}{0.01\text{nse} + 0.01} \right) \tag{9}$$

The CCME WQI is then calculated as:

$$\text{CCME WQI} = 100 - \left(\frac{\sqrt{{F_1}^2 + {F_2}^2 + {F_3}^2}}{1.732} \right) \tag{10}$$

The WQI values are then converted into rankings by using the index categorization scheme as presented in Table 5. The rankings range from poor to excellent based on the WQI scores.

The CCME WQI was developed to estimate the overall water quality status of Lake Nubia. Seven water quality parameters, measured and simulated (January 2006), have been used. These parameters are dissolved oxygen (mg/L), total dissolved solids (mg/L), nitrate–nitrite (mg/L), ammonium (mg/L), total phosphorus (mg/L), fecal coliform (colonies/100 mL), and pH (standard unit). The CCME WQI has been developed according to the Egyptian water quality standards for surface fresh waterways (objectives), decree No. 49 – Law 48/1982 – Article No. 60 amended in 2013 [48]; see Table 6.

For fecal coliform, as there is no Egyptian standard for it, the used objective was previously used by Heikal et al. [84].

Table 5 CCMEWQI categorization scheme [63]

Rank	CCME WQI Score	Description
Excellent	95–100	Water quality is protected with a virtual absence of threat or impairment; conditions very close to natural or pristine levels. These index values can only be obtained if all measurements are within objectives virtually all of the time
Good	80–94	Water quality is protected with only a minor degree of threat or impairment; conditions rarely depart from natural or desirable levels
Fair	65–79	Water quality is usually protected but occasionally threatened or impaired; conditions sometimes depart from natural or desirable levels
Marginal	45–64	Water quality is frequently threatened or impaired; conditions often depart from natural or desirable levels
Poor	0–44	Water quality is almost always threatened or impaired; conditions usually depart from natural or desirable levels

Table 6 Egyptian water quality standards for surface fresh waterways (objectives)

Parameter	DO (mg/L)	TDS (mg/L)	NO_3 (mg/L)	NH_4 (mg/L)	TP (mg/L)	FC (N/100 mL)	Ph (unit)
Objective	>6	<500	<2	<0.5	<2	<2,000	$6.5 < \ldots < 8.5$

3.4.3 Carlson TSI

The concept of trophic status is based on the fact that changes in nutrient levels (measured as total phosphorus) cause changes in algal biomass (measured as chlorophyll a) which in turn cause changes in lake clarity measured as Secchi disk transparency [165]. The Carlson TSI clearly represents this relationship. It offers the most suitable and acceptable method for trophic classifications of lakes [169]. The Carlson TSI is independently calculated from Secchi depth (SD), chlorophyll a concentration (CHL), and total phosphorus concentration (TP).

The Carlson TSI can be calculated by using one of the following equations [106, 200]:

$$\mathrm{TSI(SD)} = 60 - 14.41\ \ln[\mathrm{SD}\ (m)] \tag{11}$$

$$\mathrm{TSI(CHL)} = 9.81\ \ln[\mathrm{CHL}\ (\mu\mathrm{g/L})] + 30.6 \tag{12}$$

$$\mathrm{TSI(TP)} = 14.42\ \ln[\mathrm{TP}\ (\mu\mathrm{g/L})] + 4.15 \tag{13}$$

According to the TSI value, lakes or reservoirs can be trophically classified as one of the following classes:

- $\mathrm{TSI} < 40$ oligotrophic
- 40–50 mesotrophic
- 50–70 eutrophic
- $\mathrm{TSI} > 70$ hypereutrophic

If the three TSI values are not similar to each other, Pavluk and Vaate [165] return this to the possibilities that the algal growth may be light limited or nitrogen limited instead of phosphorus limited or, among other reasons, that the Secchi disk transparency is affected by erosional silt particles rather than by algae. They recommend using the average of TSI values as an indicator of the water trophic status in general.

The Carlson TSI was used to evaluate the trophic state of Lake Nubia. Two water quality parameters were used to estimate the Carlson TSI for 2006 and 2008 records: total phosphorus (μg/L) and chlorophyll a (μg/L). While for 2007 records, only one parameter was used, chlorophyll a (μg/L), as TP was not available. The Secchi depth was excluded because the lake transparency is affected by suspended particles rather than by algae; the southern part of AHD reservoir, Lake Nubia, has a high total suspended solid concentration.

3.4.4 LAWA TI

The German Regional Working Group on Water LAWA, Länderarbeitsgemeinschaft Wasser, has modified the OECD concept to develop a new trophic index which meets the current German conditions [144]. A data base of 117 reservoirs in Germany was used. The index depends on three parameters;

chlorophyll a (Chl-a), Secchi depth (SD), and total phosphorus (P_S for summer and P_F for spring). The LAWA TI depends on the parameter subindices, which should be calculated as follows [144, 201]:

$$\text{Index Chl-a} = 0.560 + 0.856\ \ln[\text{Chl-a}\ (\mu\text{g/L})] \tag{14}$$

For other parameters subindices, the equations vary according to reservoir morphology. Deep reservoirs, with maximum water depth between 14 and 77.5 m, and parameter subindices are calculated as follows:

$$\text{Index SD} = 3.739 - 1.27\ln[\text{SD}\ (m)] \tag{15}$$

$$\text{Index } P_F = -0.155 + 0.813\ln[P_F\ (\mu\text{g/L})] \tag{16}$$

$$\text{Index } P_S = -0.939 + 1.066\ln[P_S\ (\mu\text{g/L})] \tag{17}$$

Consequently, the LAWA Total Index (LAWA TI) can be calculated as follows:

$$\begin{aligned}\text{LAWA TI} = 0.939 &+ 0.285(\text{Index Chl-a}) - 0.301(\text{Index SD}) \\ &+0.136(\text{Index } P_F)\ + 0.249(\text{Index } P_S\ )\end{aligned} \tag{18}$$

For small reservoirs, maximum water depth < 13.5 m, parameters subindices are calculated as follows:

$$\text{Index SD} = 3.607 - 0.984\ln[\text{SD}\ (m)] \tag{19}$$

$$\text{Index } P_F = 0.014 + 0.803\ln[P_F\ (\mu\text{g/L})] \tag{20}$$

$$\text{Index } P_S = 0.548 + 0.722\ln[P_S\ (\mu\text{g/L})] \tag{21}$$

Then the LAWA Total Index (LAWA TI) can be calculated as follows:

$$\begin{aligned}\text{LAWA TI} = 1.279 &+ 0.285(\text{Index Chl-a}) - 0.262(\text{Index SD}) \\ &+ 0.134(\text{Index } P_F) + 0.168(\text{Index } P_S)\end{aligned} \tag{22}$$

If the parameters subindices values are not similar to each other, another flexible method of the LAWA TI calculation can be used, in which the irregular parameter subindex can be excluded. This method of calculation depends on parameter weight factors (Wf) according to Table 7.

Then LAWA TI can be calculated as follows:

$$\text{LAWA TI} = \frac{(\text{Index Chl-a})\,\text{Wf}_{\text{Chl}} + (\text{Index SD})\,\text{Wf}_{\text{SD}} + (\text{Index} P_F)\,\text{Wf}_{\text{PF}} + (\text{Index} P_S\,)\,\text{Wf}_{\text{PS}}}{\sum \text{Wf}} \tag{23}$$

According to LAWA TI value, lakes or reservoirs can be trophically classified as one of the following classes (Table 8).

Table 7 LAWA TI parameter weight factors

Parameter	Weight factor (Wf)
Chlorophyll a (Chl)	10
Secchi depth (SD)	8
Total phosphorus – spring (P_F)	5
Total phosphorus – summer (P_S)	7

Table 8 LAWA TI trophic status category

Deep reservoirs		Small reservoirs	
Trophic status	LAWA TI	Trophic status	LAWA TI
Oligotrophic	0.5–1.5	Eutrophic 1	2.6–3.0
Mesotrophic	1.6–2.5	Eutrophic 2	3.1–3.5
Eutrophic 1	2.6–3.0	Polytrophic 1	3.6–4.0
Eutrophic 2	3.1–3.5	Polytrophic 2	4.1–4.5
Polytrophic 1	3.6–4.0	Hypertrophic	4.6–5.0

As in Carlson TSI, two water quality parameters were used, total phosphorus (μg/L) and chlorophyll a (μg/L), for 2006 and 2008 records. While for 2007 records, only one parameter was used, chlorophyll a (μg/L), as TP was not available. Secchi depth was excluded because transparency is affected by suspended particles rather than by algae.

3.5 Results and Discussions

Four indices have been developed to evaluate the water quality and trophic status of the southern part of AHD reservoir (Lake Nubia) during low flood periods for 3 successive years: January 2006, February 2007, and March 2008. Two of these indices are the water quality indices NSF WQI and CCME WQI (described in the previous section). The other two indices are the trophic status indices Carlson TSI and LAWA TI. Ten control stations along Lake Nubia, Fig. 1, were chosen to evaluate the reservoir water quality.

3.5.1 NSF WQI

The measured water quality parameters were used to obtain NSF WQI. Figure 7 shows the longitudinal profiles of the developed NSF WQI along Lake Nubia at different stations for measured water quality parameters for 3 successive years. The results show that the water quality status of Lake Nubia, according to NSF WQI, is good. The water quality status of the reservoir varies spatially; NSF WQI increases from St. 2 to St. 9. This increase in the water quality returns to the decrease of water turbidity and fecal coliform concentration due to the change in the reservoir geometric properties. For 2008 longitudinal profile, a decrease in NSF WQI at

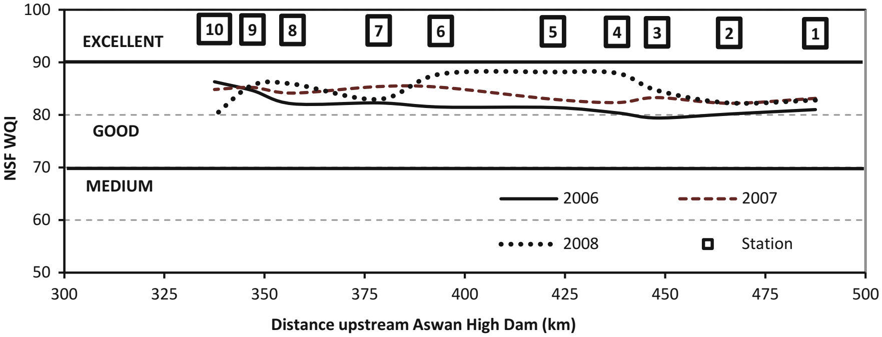

Fig. 7 Lake Nubia NSF WQI longitudinal profiles at different stations for measured water quality parameters during low flood periods, 2006–2008

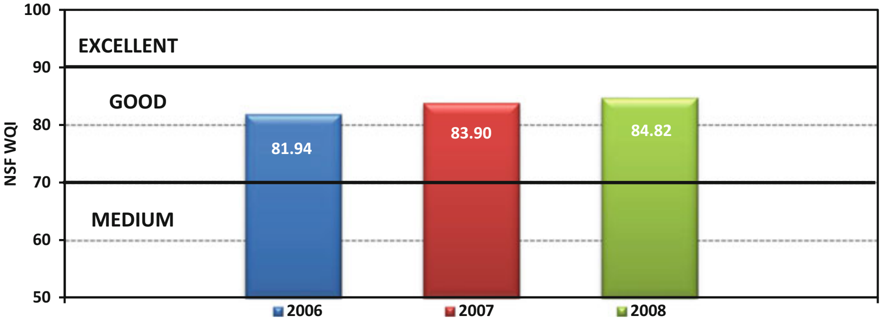

Fig. 8 Lake Nubia average NSF WQI for measured water quality parameters during low flood periods, 2006–2008

station 10 returns to increase in fecal coliform and pH and a decrease in DO concentrations. The average NSF WQI for the reservoir in low flood periods of 3 successive years can be seen in Fig. 8. It can be noticed that the average NSF WQI of 2008 is slightly greater than that of 2007, which in turn is slightly greater than that of 2006. These slight differences may return to the decrease in the flow (see Fig. 4).

3.5.2 CCME WQI

Figure 9 shows the overall CCME WQI of Lake Nubia for measured water quality parameters for 3 successive years, during low flood periods. The results show that the water quality status of the Lake Nubia is excellent for 2006 and 2007 and good for 2008. These results are based on the selected measured parameters and according to the Egyptian standards for surface fresh waterways. All measured water quality parameters values are in the objective range, for 2006 and 2007.

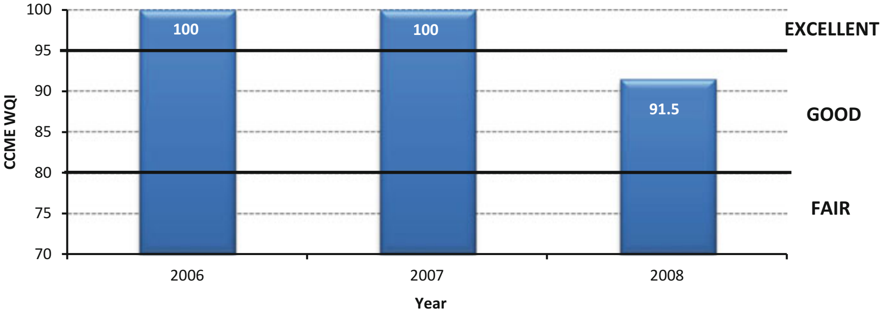

Fig. 9 Lake Nubia CCME WQI for measured water quality parameters during low flood periods, 2006–2008

While for 2008, CCME WQI is reduced as the measured records of pH were greater than the objectives at three different stations (St. 8, St. 9, and St. 10).

3.5.3 Carlson TSI

Figure 10 shows the Carlson TSI longitudinal profiles of Lake Nubia for measured total phosphorus only, January 2006 and March 2008. The results show that, according to Carlson TSI, the trophic state of Lake Nubia is hypereutrophic. The Carlson TSI varies spatially. This corresponds with the total phosphorus decrease due to increase of algae activity.

Lake Nubia Carlson TSI longitudinal profiles for measured chlorophyll a parameter only (January 2006, February 2007, and March 2008) are shown in Fig. 11. The results show that Lake Nubia trophic state, according to Carlson TSI, is almost eutrophic. The index slightly varies along Lake Nubia until station 8 where it starts to increase due to increase of algae activity.

The difference between Carlson TSI, based on total phosphorus, and that one based on chlorophyll a may return to phosphorus surplus in the water column [196]. This difference can be frequently noticed in reservoirs, in particular the riverine zone. For that it is recommended to use a comparative study (e.g., Carlson and LAWA), and both parameters (TP and Chl-a) should be used together (average) to estimate the trophic status of the reservoir.

Figures 12 and 13 show the average Carlson TSI longitudinal profiles of Lake Nubia for the measured water quality parameters in January 2006, February 2007, and March 2008. According to Carlson TSI, the Lake Nubia trophic state is eutrophic. For average Carlson TSI of February 2007, it can be noticed that it is clearly smaller than others, as it is based on one parameter only (Chl-a).

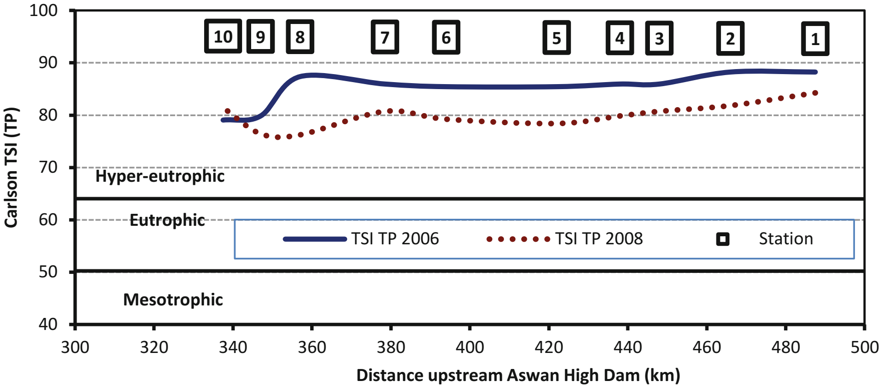

Fig. 10 Lake Nubia Carlson TSI longitudinal profiles for measured total phosphorus parameter during low flood periods in 2006 and 2008

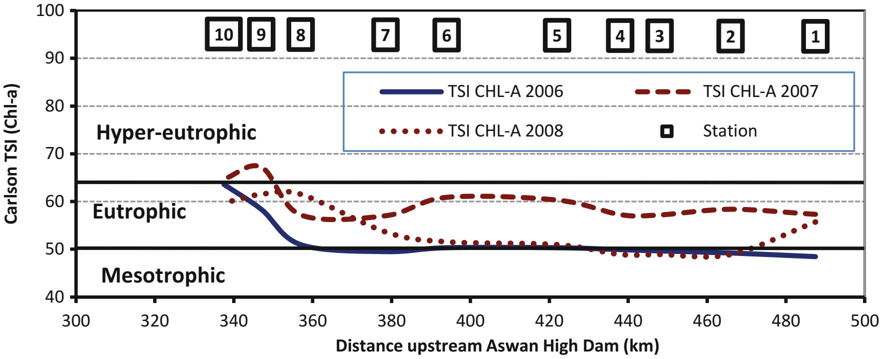

Fig. 11 Lake Nubia Carlson TSI longitudinal profiles for measured chlorophyll a parameter during low flood periods, 2006–2008

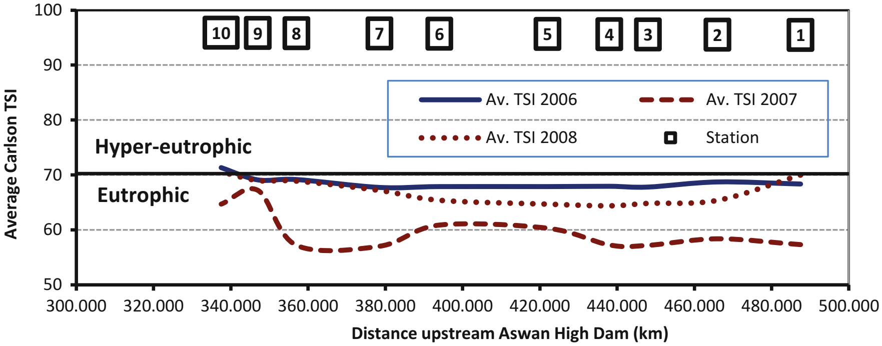

Fig. 12 Lake Nubia average Carlson TSI longitudinal profiles for measured water quality parameters during low flood periods, 2006–2008

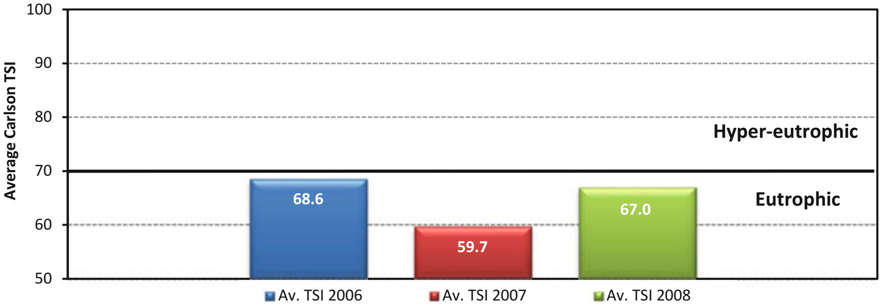

Fig. 13 Lake Nubia average Carlson TSI for measured water quality parameters during low flood periods, 2006–2008

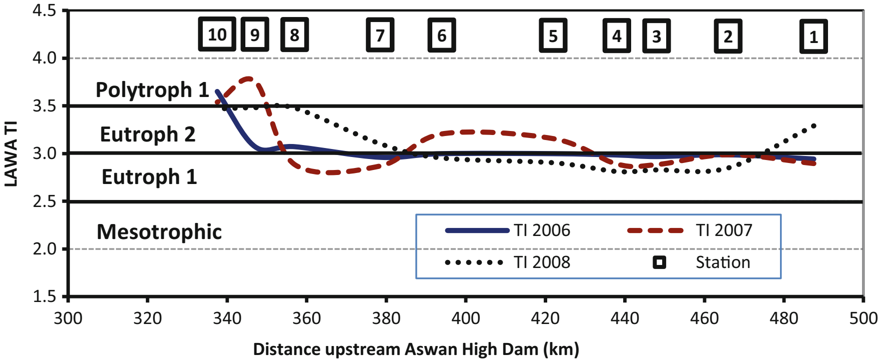

Fig. 14 Lake Nubia LAWA TI longitudinal profiles for measured water quality parameters during low flood periods, 2006–2008

3.5.4 LAWA TI

Figure 14 shows the Lake Nubia LAWA TI longitudinal profiles for measured parameters, January 2006. The results show that the Lake Nubia trophic state is eutrophic. The index slightly varies spatially until station 8 where it starts to increase due to algae activity.

The Lake Nubia average LAWA TI for measured water quality parameters, January 2006, February 2007, and March 2008, is shown in Fig. 15. According to LAWA TI, the Lake Nubia trophic state is eutrophic, and average LAWA TI is about 3.1. It can be noticed that, although average LAWA TI for February 2007 is based only on one parameter (Chl-a), the results do not differ much from others (comparing to Fig. 13). This may return to the flexibility design of this index which is mainly developed for reservoirs.

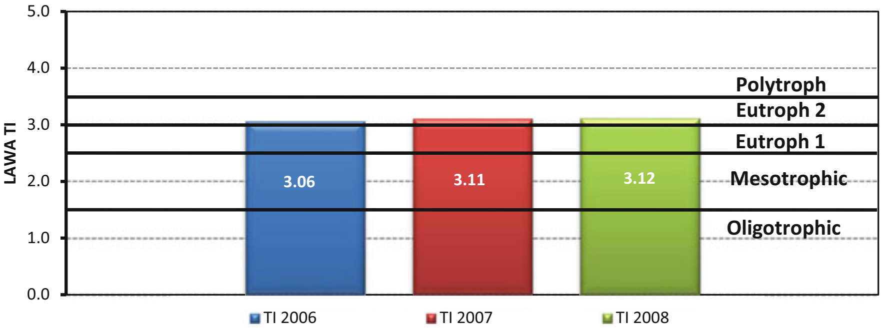

Fig. 15 Lake Nubia average LAWA TI for measured water quality parameters during low flood periods, 2006–2008

Table 9 A summary of average WQI and TSI study results for Lake Nubia during low-flow periods in 2006, 2007, and 2008

	Water quality indices (WQIs)		Trophic status indices (TSIs)	
Year	NSF WQI	CCME WQI	Carlson TSI	LAWA TI
2006 records	Good	Excellent	Eutrophic	Eutroph 2
	81.9 %	100 %	68.6	3.06
2007 records	Good	Excellent	Eutrophic	Eutroph 2
	83.9 %	100 %	59.7	3.11
2008 records	Good	Good	Eutrophic	Eutroph 2
	84.8 %	91.5 %	67	3.12

3.5.5 Results Summary

Table 9 summarizes the results of the application of the four water quality and trophic status indices for Lake Nubia during low flood periods, 2006–2008, based on the measured water quality characteristics.

3.6 Conclusions and Recommendations for Future Work

3.6.1 Conclusions

Two water quality indices, NSF WQI and CCME WQI, were developed to assess water quality state of the southern part of AHD reservoir, Lake Nubia, during low flood periods (January 2006, February 2007, and March 2008). Moreover, another two trophic status indices, Carlson TSI and LAWA TI, were developed to evaluate trophic status of Lake Nubia during the same periods.

1. According to the developed water quality indices results, Lake Nubia has a good water quality state during the low flood period. The modified CCME WQI, based on the measured data, indicates that the Lake Nubia water quality state ranges from excellent to good, according to the Egyptian water quality standards for surface fresh waterways.
2. Results of the applied trophic status indices show that the Lake Nubia trophic status is eutrophic. The Carlson TSI, based on total phosphorus, indicates that the trophic status of Lake Nubia is hypereutrophic.
3. The morphological characteristics of Lake Nubia affect water quality and trophic states of the reservoir; the transition zone of the reservoir (starts from St. 7) has a better water quality state and a somewhat worse trophic state than the riverine zone (upstream St. 7). This indicates that reservoir zones should be assigned to different water uses according to its water quality and trophic states.
4. For the AHD reservoir, Secchi depths should not be used to estimate the trophic status of the reservoir especially in the riverine and transitional zones where the water transparency is affected by suspended particles rather than by algae.

3.6.2 Recommendations for Future Work

1. A scientific study of the long-term trend of the water quality and trophic status should be performed for the AHD reservoir using a detailed database. Such a study could be the basis for a control management of the reservoir water quality.
2. Egyptian water quality standards for different uses (e.g., irrigation water, fishing, swimming) should be developed and used as guidelines in different water quality indices.
3. The NSF WQI should be developed according to different water uses instead of the general water quality state.
4. The CCME WQI procedure should have more guidelines about parameter choice and a more detailed ranking for the water quality state especially if all variables do not exceed the guidelines.
5. For trophic status indices, more than one parameter should be used. Moreover, a newer index should be developed for subtropical lakes and reservoirs such as the AHD reservoir.
6. As the trophic status is an aspect of water quality, a detailed study should be done to investigate the relation between water quality and trophic status indices.

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