International Journal of Advanced and Applied Sciences, 7(2) 2020, Pages: 99-112

Contents lists available at Science-Gate

International Journal of Advanced and Applied Sciences

Journal homepage: http://www.science-gate.com/IJAAS.html

Evaluation of water quality parameters using numerical modeling approach for the El-Salam Canal in Egypt

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ARTICLE INFO

Article history:
Received 24 September 2019
Received in revised form
18 December 2019
Accepted 21 December 2019

Keywords:
El-Salam Canal
Water quality
Eutrophication
AQUASIM
Water quality index

ABSTRACT

The El-Salam Canal was designed to supply irrigation water in the northern Delta and crossing the Suez Canal eastward to the northern Sinai Peninsula in Egypt. The canal receives both the Nile water and contaminated drainage water with a ratio of 1:1. The drainage water comes mostly from Hadous and El-Serw pumping stations. In this regard, the water quality of the El-Salam Canal can be estimated to check the level of usage. So, the water quality of the El-Salam Canal was simulated using the one-dimensional surface water quality model (AQUASIM). The water quality simulation focuses on five nutrients: chlorophyll-a (Chll-a), ammonia (NH4), nitrate (NO3), chemical oxygen demand (COD), and dissolved oxygen (DO), based on the kinetic rates of production-death-respiration of Chll-a, nitrification-denitrification of NH4 and NO3, reaeration-oxidation-deoxidation of DO and COD. The calibration and validation were performed for the model predictions along the El-Salam Canal. The accuracy of the AQUASIM model was evaluated applying various statistical rating tools. The water quality variation along the El-Salam Canal is evaluated using the water quality index (WQI). The results were affected by agricultural and domestic uses. The canal is acceptable for irrigation with much concern of pre-treatment in the Hadous drain (one of the main drainage providing the El-Salam Canal). Further, the El-Salam Canal showed a decline in DO with respect to the flow profile as a tropical zone of north Egypt especially in summer. The outcomes acquired in this study will facilitate the development of a policy for the operational enhancement of sustainable water quality in the El-Salam Canal.

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1. Introduction

The most important problem of water resources management in Egypt is the unbalance between increasing water demand and limited water supply. It has become a pressing need to reuse the drainage water for irrigation. El-Salam Canal project is one of those efforts that aim at using the available water resources together with the agriculture drainage water to establish new communities in that part of the Sinai Peninsula (El-Desouky, 1993; FAO, 2007). El-Salam Canal starts from Damietta river Nile branch with a quantity of 2.11 billion m^3 per year and runs south-east to mix with El-Serw drainage water with 0.435 billion m^3 per year then moves south-east to mix with Hadous drainage water with 1.905 billion m^3 per year then moves east under Suez Canal to Sinai Peninsula to convey the total quantity of nearly 4.45 billion m^3 per year with an approximate volumetric ratio of 1:1, Nile water to drainage water (Elkorashey, 2012). The flow of fresh water and drainage water supplied to the canal can be controlled by the automation system (Donia, 2012). This automatic control system is able to process data of various flows and water quality data along the canal and the feeding drains.

The water quality has been monitored along El-Salam Canal since 1998. A study has been conducted to estimate the BOD pollution rates along El-Salam Canal using the water quality data measured in the period of 1997-2001 by the Drainage Research Institute (DRI) of Egypt and the numerical model QUAL2E (El-Degwi et al., 2003). The statistical analysis of the study has been conducted to compute the upper and lower limits of BOD of El-Serw and Hadous drains. The results showed a good help for the prediction of possible water quality along the

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canal when it comes into full operation. In addition, a regression model has been developed to forecast the water quantity and quality of El-Salam Canal using the water quality model QUAL2K (Shaban and Elsayed, 2012). The study of the water quality of El-Salam Canal has been implemented to estimate the phytoplankton composition along El-Salam Canal (EL-Sheekh et al., 2010). In the study, it can be found 67 species of phytoplankton at the River Nile of Damietta Branch and 72 species at the Hadous drain. They estimated the total biomass along El-Salam Canal as ranged from a minimum value of 12 mg/l at the intake of Damietta Branch to a maximum value of 64 mg/l at Hadous drain. Further, the water quality of the El-Salam Canal during 2010 has been investigated according to the analysis of COD, BOD, and heavy metals (Elkorashey, 2012). The study emphasized the necessity of effective strategies to treat the sources of drainage water before mixing them with the Nile water. Another study has been introduced in Abukila et al. (2012) to evaluate the water quality of El-Salam Canal using the Canadian Council of Ministers of the Environment water quality index (CCME WQI) to use the canal for irrigation. Accordingly, the water quality of the El-Salam Canal ranged between good to fair based on their water quality. Another research has been studied the chemical properties along El-Salam Canal (Mohamed, 2013). The results showed that the EC values increased in summer after mixing with Hadous drain rather than after mixing with El-Serw drain. The results also showed that sodium and Chlorine increased progressively with increasing salinity levels in the irrigation water. In addition, the water quality of the El-Salam Canal has been evaluated using physicochemical and certain biological characteristics (El-Amier et al., 2017). The results showed that the increase of N, P, heavy metals and Water Quality Index (WQI) are due to the excessive input of wastewater from El-Serw and Hadous drains. Furthermore, the extent of water contamination in El-Salam Canal west of the Suez Canal has been studied as a result of mixing drainage water with Nile water (Ahmed et al., 2018). The results showed that the chemical analysis (salinity and alkalinity) of the studied locations of El-Salam Canal differs due to the ratio of mixed the drainage water with Nile water and also differs in different seasons (summer and winter). Higher values of heavy metal ions (Fe^{2+}, Zn^{2+}, Mn^{2+}, Cu^{2+}, Cd^{2+} and Pb^{2+}) were noted after the second mixed stage compared with the first stage at Damietta branch, especially in the summer season. Likewise, numerical/data-driven models have been developed to simulate El-Salam Canal under working conditions using real field data (Mohamed et al., 2018). The water quality parameters such as TDS, BOD were analyzed which would not significantly deteriorate the canal water. Another study has been presented in Assar et al. (2018) to evaluate the water quality of El-Salam Canal using the following parameters: PH, DO, Turbidity, TDS, COD, NO3, NH4, TSS, VSS, TOC, IC and TC. The results revealed that all parameters were in accordance with reuse in agricultural purposes except dissolved oxygen depletion due to discharge of domestic wastewater. In addition, another study has adopted the irrigation WQ index (IWQI) and an analogous index based on a fuzzy logic water reuse index (FWRI) to evaluate the water quality in El-Salam Canal (Assar et al., 2019). The simulated water quality data using a 1-D hydrodynamic model (MIKE 11) indicated that the deterioration towards the downstream of the canal due to the polluted water discharged from canal feeders (e.g., the El-Serw and Bahr Hadous drains). The results revealed that the FWRI had its capability and accuracy compared to the IWQI for the evaluation of water quality in the El-Salam Canal.

Surface water quality has considerable influence on organisms' wellbeing, global economic and social activities. Conversely, human actions, economic and social advancement have various effects on water quality. In the last few decades, surface water quality models have been developed to support decision making processes in water management. Most river water quality models can be found in Reichert et al. (2001). Most of the models are adaptable to various environments subject to appropriate definitions of boundary conditions, dimensional variation, and parameter characterization. The basic objective of River Water Quality Models (RWQM) was to simulate the spatial-temporal effect of organic pollution on the oxygen level because of its significance for aquatic life. The famous Streeter-Phelps model, describing the balance between deoxygenation and reaeration, is presented as in Chapra (1997). Another important example of RWQM is the simulation of toxic substances such as organic chemicals or heavy metals via the WASP model package (Ambrose et al., 2001). In recent decades, QUAL2K (Chapra et al., 2006) which is an enhanced version of the famous QUAL-2E (Brown and Barnwell, 1987), the 'EUTRO' module of WASP (Ambrose et al., 2001), are examples of more complex RWQM. A rather new simulation solving the complete hydrodynamic equations which are capable of handling stratified as well as vertically mixed systems is CE-QUAL-W2 (Cole and Wells, 2006). Another approach of RWQM is AQUASIM (Reichert, 1998) which allows multiple types of "reactors" to be simulated with respect to hydrodynamics and the dominant transport processes. By linking advective, dispersive, or advective-dispersive reactors, it becomes possible to approximate river-lake systems as well.

The water quality modeling accuracy performance measures and corresponding performance evaluation criteria have been synthesized as in Moriasi et al. (2015). The study recommended coefficient of determination (R^2), Nash Sutcliffe efficiency (NSE), index of agreement (d), root mean square error (RMSE), percent bias (PBIAS), and several graphical performance measures to evaluate model performance. The model performance can be judged as in "satisfactory" for monthly flow simulations if (R^2>0.70 and d>0.75) for field-scale models, and daily, monthly, or annual if ($R^2>0.60$, NSE>0.50, and PBIAS≤ ±15%) for watershed-scale models. Model performance at the watershed scale can be evaluated as "satisfactory" if monthly ($R^2>0.40$ and NSE>0.45) and daily, monthly, or annual if (PBIAS≤ ±20%) for sediment; monthly ($R^2>0.40$ and NSE>0.35) and daily, monthly, or annual (PBIAS≤ ±30%) for phosphorus (P); and monthly ($R^2> 0.30$ and NSE>0.35) and daily, monthly, or annual (PBIAS≤ ±30%) for nitrogen (N).

The water quality index (WQI) is commonly used for the detection and evaluation of water pollution and may be defined as a reflection of the composite influence of different quality parameters on the overall quality of water (Horton, 1965). The WQI reduces the long list of parameters to a single composite number in a simplistic reproducible sequence (Tomas et al., 2017; Zahedi, 2017; Sutadian et al., 2018; Wu et al., 2018). The WQI has been applied in the monitoring of water quality for rivers, playing a significant role in water resource management (Darapu et al., 2011; Sun et al., 2016; Misaghi et al., 2017; Ponsadailakshmi et al., 2018; Brhane, 2016; Olumuyiwa et al., 2017). WQI can be developed along the spatial profile of a river using the corresponding water quality results obtained from the best WQMs (Huang et al., 2010; Şener et al., 2017; Chandra et al., 2017). WQI is an efficient and effective way to describe and easily compare the characteristic state of water quality, which is crucial in water resource management (Iqbal et al., 2018a).

As well-known DO concentrations in rivers are influenced by environmental conditions of upstream and the sections of the river (Iqbal et al., 2018b). In the meanwhile, higher temperatures reduce the solubility of DO and re-oxygenation rate. Consequently, it is critical to impose the independent impact of feeding tributaries on river water quality along with other management strategies such as flow augmentation, aeration, and water treatment practices (Iqbal et al., 2018b). This evaluation is used to evaluate the spatial variation of water quality along the El-Salam Canal.

The goal of the present study can be divided into three objectives. The first one is to simulate the water quality parameters of El-Salam Canal; Chll-a, NH4, NO3, COD, and DO using the water quality data (El-Amier et al., 2017; Assar et al., 2019) and the performance of AQUASIM model is evaluated. The second target of the study presented is to evaluate the water quality of El-Salam Canal using the water quality index (WQI). The third objective is to investigate the spatial scale relationship of El-Salam Canal's water quality and flow toward the downstream end of the Canal profile over different climatic conditions.

2. Materials and methods

2.1. Study site

El-Salam Canal starts at the right bank of Damietta Branch (East branch of the Nile River at delta). The total length of the Canal is 252.750 km divided into two main parts. The first part is called El-Salam Canal which stretches for 89.750 km long and lies west of the Suez Canal. The second part is called El-Sheikh Gaber Canal which lies east of the Suez Canal with a total length of 163.000 km. Both parts are connected through a 770 m long siphon, under the Suez Canal (Elkorashey, 2012).

The present study concerns the west part of the Suez Canal. The study area receives a contaminated load from El-Serw and Hadous drains, which discharges domestic and agricultural wastewater. The spatial-temporal dynamics of flow was presented in Khalifa (2014). The physicochemical parameters were measured as in El-Amier et al. (2017). The selected five sampling stations along El-Salam Canal are shown in Fig. 1. The sampling station 1 lies on the Damietta branch of the River Nile (only Nile water). Therefore, Station 1 (0.00 km, 31º 23' 38" N, 31º 46' 09" E) can be considered as a reference station for all the other stations. The sampling station 2 (23.39 km, 31º 14' 07" N, 31º 50' 41" E) lies 5.0 km downstream the point of merging El-Salam Canal with El-Serw drain (18.39 km). Station 3 (59.87 km, 31º 03' 32" N, 32º 00' 37" E) lies 5.0 km downstream the merging point with Hadous drain (54.87 km). Station 4 (69.87 km, 31º 00' 48" N, 32º 04' 56" E) lies 10 km downstream the station 3. Station 5 (89.75 km, 31º 01' 07" N, 32º 18' 19" E) is located at the end of El-Salam Canal just before the siphon under Suez Canal.

Fig. 1: Sampling stations of El-Salam Canal

2.2. Water quality modeling

The study reach is modeled using the numerical modeling approach of AQUASIM. The model was compared for the simulation of water quality on the El-Salam Canal. The calibration and validation were performed over the selected stations of El-Salam Canal. The hydraulic equations of AQUASIM were presented in Khalifa (2014). The AQUASIM applies the conservation of mass governing relation as:

$$\frac{\partial AC}{\partial t} = -\frac{\partial (QC)}{\partial x} + \frac{\partial^2 AE(C)}{\partial x^2} + r + S_{qn} \quad (1)$$

Here (A) represents the cross-sectional area of the Canal. The first term of Eq. 1 represents the advection of concentration (C) with the water flow (Q). The second term represents longitudinal dispersion which is estimated in Fischer et al. (1979). The third term represents the transformation processes (r). The fourth term represents the lateral inflow or outflow (S_{qn}).

2.2.1. Modeling of water quality parameters

The parameters of water quality of El-Salam Canal are characterized by chlorophyll-a of phytoplankton compositions, NH4, NO3, COD, and DO. The chemical and biological transformation term (r) in Eq. 1 for the five parameters, can be modeled with AQUASIM (Khalifa, 2000). Such parameters would be summarized in sequence.

- Chlorophyll-a Modeling: The kinetics of Chlorophyll assumes the core of water quality and then affects all other parameters. The reaction term of phytoplankton (r_{Chll}) can be expressed as a difference between the growth rate of phytoplankton and their death and respiration rates as:

$$r_{Chll} = (G_P - D_P)C_{Chll} \quad (2)$$

The growth rate (G_P) can express the production rate of biomass as a function of the main environmental variables (temperature, light, and nutrients) as:

$$G_P = G_T G_I G_N \quad (3)$$

The temperature growth factor (G_T) can be reported in maximum rates as (1.5~2.5 day^{-1}) (Thomann and Mueller, 1987). AQUASIM can also present the daily depth-averaged growth rate reduction (G_I) (Di Toro et al., 1971) using the intensity of light estimation. Finally, the growth rate reduction of ammonia concentrations (G_N) can be considered as (Di Toro et al., 1971):

$$G_N = C_{NH4}/(K_{mn} + C_{NH4}) \quad (4)$$

A range value of the nitrogen Michaelis constant (K_{mn}) has been reported from 10 to 20 μg N/L (Thomann and Mueller, 1987). The second term of Eq. 2 is related to the total biomass reduction rate as:

$$D_P = D_R + D_D \quad (5)$$

The reported endogenous respiration rate (D_R) varies from 0.02~0.6 day^{-1} (Khalifa, 2000). The death rate of phytoplankton (D_D) is equal to 0.02 day^{-1} (Ambrose et al., 1993).

- Ammonia Modeling: The reaction term of ammonia (r_{NH4}) is given by:

$$r_{NH4} = a_{NC} f_{ON} D_P C_{Chll} - a_{NC} P_{NH4} G_P C_{Chll} - K_{nit} \frac{C_{O2}}{K_{NIT}+C_{O2}} C_{NH4} \quad (6)$$

The ratio of nitrogen to carbon for phytoplankton (a_{NC}) is reported a range of 0.1~0.35 with a mean value of 0.25 (Ambrose et al., 1993). The fraction of the cellular nitrogen recycled to the inorganic pool (f_{ON}) has been assigned at 50% (Di Toro and Matystik, 1980). The preference for ammonia uptake term (P_{NH4}) is reported a range of 0.22~0.83 (Ambrose et al., 1993). The nitrification rate (K_{nit}) is reported a range of 0.09~0.5 day^{-1} (Khalifa, 2000). The half-saturation constant (K_{NIT}) is reported as 2.0 mg O_2/L (Ambrose et al., 1993).

- Nitrate Modeling: The reaction term of nitrate (r_{NO3}) is given by:

$$r_{NO3} = K_{nit} \frac{C_{O2}}{K_{NIT}+C_{O2}} C_{NH4} - a_{NC}(1 - P_{NH4}) G_P C_{Chll} - K_{den} \frac{K_{NO3}}{K_{NO3}+C_{O2}} C_{NO3} \quad (7)$$

A range value of denitrification rate (K_{den}) has been reported as 0.1~0.5 day^{-1} (Thomann and Mueller, 1987). In addition, the denitrification rate has been reported as 0.09 day^{-1} and Michaelis constant for denitrification (K_{NO3}) as 0.1 mg O_2/L for (Ambrose et al., 1993):

- Chemical Oxygen Demand (COD) Modeling: The rate of oxidation of COD is the controlling kinetic reaction (r_{COD}) as:

$$r_{COD} = a_{OC} D_D C_{Chll} - K_D \frac{C_{O2}}{K_{O2}+C_{O2}} C_{COD} \quad (8)$$

The ratio of oxygen to carbon for phytoplankton (a_{OC}) has been reported as an approximation value of 2.7 and the deoxygenation rate (K_D) of about 0.1~0.5 day^{-1} (Thomann and Mueller, 1987). A range of (K_D) has been reported as 0.16~0.21 day^{-1} and Michaelis constant of oxidation (K_{O2}) as 0.5 mg O_2/L (Ambrose et al., 1993).

- Dissolved Oxygen (DO) Modeling: The oxygen balance is characterized by intense production-respiration-nitrification-deoxygenation processes. According to Eq. 1, it can be modeled the oxygen balance with these processes to formulate their kinetics explicitly using Eq. 9:

$$r_{O2} = K_a(C_{sat} - C_{O2}) + G_P(a_{OC} + a_{NC})C_{Chll} - a_{OC}D_R C_{Chll} - \frac{64}{14}K_{nit}\frac{C_{O2}}{K_{NIT}+C_{O2}}C_{NH4} - K_D\frac{C_{O2}}{K_{O2}+C_{O2}}C_{COD} \quad (9)$$

The physical reaeration estimations were included in Khalifa (2000). The Empirical formulas of the reaeration rate (K_a) values are ranging from 17.0~29.0 day^{-1} (Borchardt and Reichert, 2001). The concentration formula for oxygen saturation (C_{sat}) was given in APHA (1985). Fig. 2 shows the graphical illustration of the water quality parameter interactions involves in the AQUASIM model. The study adopted the 1-D model due to the availability of only the longitudinal water quality data of El-Salam Canal.

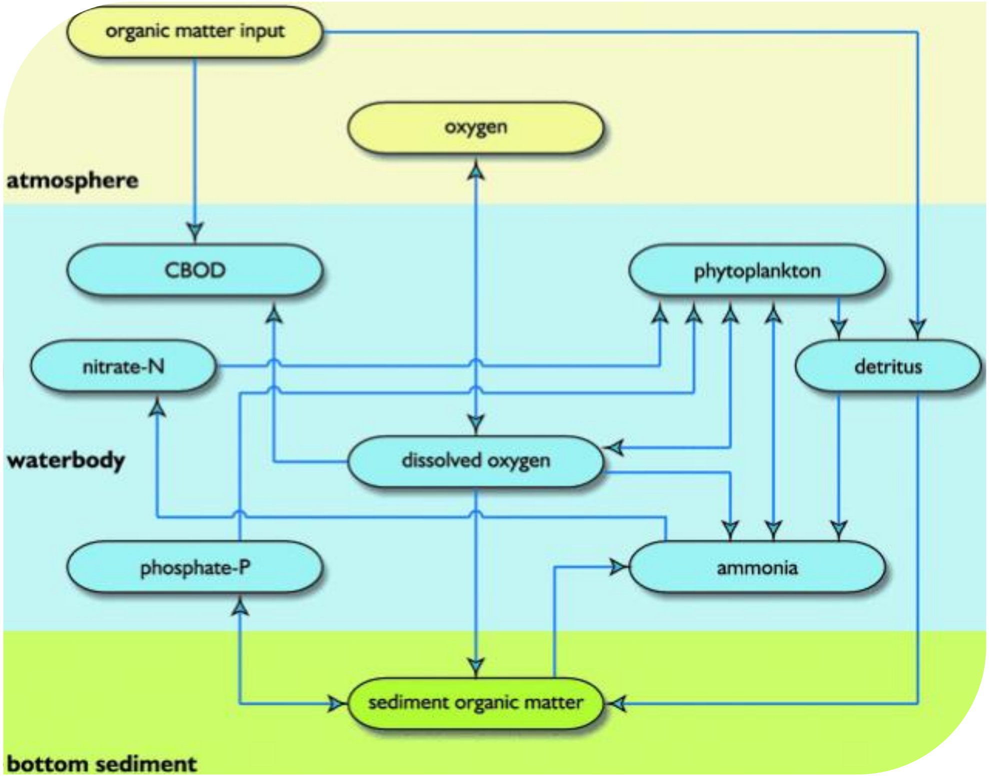

Fig. 2: AQUASIM graphical illustration of water quality parameters

2.3. Calibration and validation of AQUASIM model

Calibration and validation are fundamental processes used to demonstrate that the AQUASIM model can produce suitable results in a particular application. In this regard, the obtained data from El-Salam Canal were simulated for a period of 2013-2014 (El-Amier et al., 2017; Assar et al., 2019) by repetitive tuning of kinetic reaction constants and environmental parameters using the literature and other models and were then adapted to the local conditions. The calibrated constants and parameters were used for verification of AQUASIM results. The conditions of boundary reference, including Chll-a, NH4, NO3, COD, and DO were used along with the upstream as well as downstream sections and drains. The final output comprised a combination of the best cases of every constant controlled. The calibration and verification of AQUASIM were achieved in parallel.

2.4. Assessment of AQUASIM model accuracy

The model simulation accuracy is conducted by comparing the simulated data (predicted) with the corresponding observations (actual). In this study, six statistical rating tools were used to evaluate the accuracy of the AQUASIM model (Benedini and Tsakiris, 2013). The criteria of these statistical tools can be considered fair and provide unbiased indicators of AQUASIM performance (Moriasi et al., 2012). The first statistic tool used is the mean absolute error (MAE), which measures the deviation between predicted results and observed values. The MAE can be given as:

$$MAE = \frac{\sum_{i=1}^{N}|X_i^{mod} - X_i^{obs}|}{N} \quad (10)$$

Here, (X_i^{mod}) is the ith value predicted by the model, (X_i^{obs}) is the ith value of observations, and (N) is the number of observations. As well-known, it can be understood that the lower the value ofMAE, the better the performance of the model.

The second statistic tool used is the percentage bias of the model (BP), which is estimated by the percentage of the summation of residuals from the observed values in order to measure whether the model under or overestimates with respect to the observed values. The BP criterion is clearly, the lower theBP, the better the performance.

$$BP = \frac{\sum_{i=1}^{N}(X_i^{mod} - X_i^{obs})}{\sum_{i=1}^{N}X_i^{obs}} * 100 \quad (11)$$

The performance evaluation criteria have been reported that water quality models have been adopted as very good for (BP<15%), good for (15%≤BP≤25%), and fair for (25%≤BP≤35%). Some concerns of BP criterion can deceive the model performance rating where PB can close to zero however the model simulation is poor. So, it is recommended to use BP with other statistical analyses to determine the model performance (Moriasi et al., 2012).

The third statistic tool used is the root mean square error ($RMSE$), which represents the standard deviations of observed and predicted values. The $RMSE$ units are the same as the units of the model predictions and observations. The model performance indicates well when values of $RMSE$ are near to zero (Moriasi et al., 2012).

$$RMSE = \left[\frac{\sum_{i=1}^{N}(X_i^{mod}-X_i^{obs})^2}{N}\right]^{1/2} \tag{12}$$

The $RMSE$ has not been suggested a good indicator to evaluate the model performance and maybe a misleading indicator of average error, and the MAE has been suggested better criteria for that purpose (Willmott and Matsuura, 2005). While some concerns over using $RMSE$ are valid, the $RMSE$ is more suitable to represent model performance than the MAE (Chai and Draxler, 2014).

The fourth statistic tool used is the relative root mean square error ($RRMSE$) which is defined as:

$$RRMSE = \frac{1}{\overline{X^{obs}}}\left[\frac{\sum_{i=1}^{N}(X_i^{mod}-X_i^{obs})^2}{N}\right]^{1/2} \tag{13}$$

Here, ($\overline{X^{obs}}$) is the mean of observed values. $RRMSE$ is the same as$RMSE$, but normalized by the mean value of (X^{obs}), giving an indication of the scatter in relation to mean value. As the error lessens, the model prediction accuracy rises (Benedini and Tsakiris, 2013).

The fifth statistic tool used is the coefficient of determination (R^2), which evaluates the relative deviation of predicted results from the observed data obtained by the model. The (R^2) can be expressed by squaring the Pearson correlation coefficient (PCC) equation as:

$$R^2 = \left(\frac{\sum_{i=1}^{N}(X_i^{obs}-\overline{X^{obs}})(X_i^{mod}-\overline{X^{mod}})}{\sqrt{[\sum_{i=1}^{N}(X_i^{obs}-\overline{X^{obs}})^2]}\sqrt{[\sum_{i=1}^{N}(X_i^{mod}-\overline{X^{mod}})^2]}}\right)^2 \tag{14}$$

If (R^2) approaches 1, a strong positive relationship between the observed and predicted can be attained. The reported performance evaluation criteria for water quality models have been adopted as very good for (R^2>0.85), good for (0.75≤R^2≤0.85), satisfactory for (0.7<R^2<0.75), and poor for (R^2≤0.7) (Moriasi et al., 2012).

The sixth statistic tool used is Nash–Sutcliffe's model efficiency (NSE), which measures the ratio of the model deviation from the true (observed) data as:

$$NSE = 1 - \frac{\sum_{i=1}^{N}(X_i^{mod}-X_i^{obs})^2}{\sum_{i=1}^{N}(X_i^{obs}-\overline{X^{obs}})^2} \tag{15}$$

The value of NSE varies from -α to 1.0, with 1.0 being the optimal value. Values between 0 and 1 are generally considered acceptable, whereas negative values imply unacceptable model performance (Benedini and Tsakiris, 2013).

In general, the acceptable water quality model simulation has been reported as (R^2 ≥ 0.8, NSE ≥ 0.7, and BP≤15%) (Moriasi et al., 2012). In the meanwhile, the good water quality model performance is considered (BP<30%) for nutrients and (BP<50%) for phytoplankton (Moriasi et al., 2012).

2.5. Water quality index (WQI) development

WQI is a comparative single number that reflects the combined effects of several water quality parameters on the general quality of a certain location and time. This manner is easier to use and understand the characteristics of water quality parameters. As a whole, several institutions have developed WQI based on their priorities, institutional capacities, and levels of technology. There are several WQI methods, based on the weighted arithmetic index. The main weighted arithmetic means method for deriving WQI is the quality rating method (Wu et al., 2018; Bora and Goswami, 2017; Shah and Joshi, 2017). The WQI was deduced from the quality rating method (Horton, 1965) as:

$$WQI = \frac{\sum q_n W_n}{\sum W_n} \tag{16}$$

Here, (q_n) is the rating of the quality of nth water quality parameter and (W_n) is the unit weight of the nth water quality parameter. The rating of quality (q_n) is calculated using the expression given in Brown et al. (1972) as:

$$q_n = \left[\frac{(V_n-V_{id})}{(S_n-V_{id})}\right] * 100 \tag{17}$$

Here, (V_n) is the estimated value of nth water quality parameter at a given sample location, (S_n) is the standard allowable value of nth water quality parameter, and (V_{id}) is the ideal value for the nth water quality parameter in pure water. The unit weight (W_n) is calculated as:

$$W_n = \frac{k}{S_n} \tag{18}$$

Here, (k) is the proportionality constant and is calculated as:

$$k = \frac{1}{\sum(\frac{1}{S_n})} \tag{19}$$

The status of water corresponding to the WQI is categorized into five types which are given in Srinivas et al. (2016). The study has used basic sixteen physiochemical parameters which were presented in El-Amier et al. (2017).

3. Results and discussion

The present study includes three major objectives. The first one is the simulation of water quality of El-Salam Canal for the parameters: Chll-a, NH4, NO3, COD, and DO using the computer modeling program AQUASIM. The second target is to evaluate El-Salam Canal's water quality using the water quality index. The third objective is to study the effect of flow on the spatial profile of El-Salam Canal's water quality. In the subsequent articles, it can be possible to detail these targets.

3.1. AQUASIM model calibration and validation

The performance of the AQUASIM model has been evaluated based on the simulated and observed results of Chll-a, NH4, NO3, COD, and DO at their corresponding monitoring stations of El-Salam Canal. The AQUASIM hydraulic model calibration and the water level profile of the El-Salam Canal were early presented in Khalifa (2014). The basic water quality modeling capability of AQUASIM to predict the mean concentration field may be the inflow-outflow boundaries.

Based on these boundary conditions and all rates of production, respiration and death, nitrification and denitrification, oxidation and deoxygenation, and reaeration; the parameters are time-series estimated using the observed concentrations of Chll-a, NH4, NO3, COD, and DO (El-Amier et al., 2017). AQUASIM is prolonged to be validated using the data presented in Assar et al. (2019). In this regard, Table 1 lists the parameter values of the principal interest of the reaction of water quality parameters for the El-Salam Canal. Fig. 3, Fig. 4 and Table 2 show the summaries of the calibrated and confirmed water quality model parameters and statistical evaluations according to the observed data in El-Amier et al. (2017). In addition, AQUASIM extends to be validated by the data of water quality parameters (NO3, BOD5, and DO) which are implied in Assar et al. (2019) and shown in Fig. 5.

The performance of the modeling tools has been assessed via different statistical approaches to show a good agreement between the simulated results of the model's output and the observed values for different stations of El-Salam Canal. To reach the model performance evaluation solidly, six various statistical analyses were completely done. Fig. 3 shows the output water quality of the validated values for Chll-a, NH4, NO3, COD, and DO for El-Salam Canal. It is obvious that the water quality in terms of NH4, NO3, and DO degrades, especially in summer which reflects the impact of the environmental deterioration of El-Serw and Hadous drains. The spatial profile of El-Salam Canal concurs with findings of previous studies (El-Degwi et al., 2003; Abukila et al., 2012; El-Amier et al., 2017; Assar et al., 2018; Assar et al., 2019). In addition, Fig. 4 shows the mean values of water quality parameters during the summer and winter of all five stations of El-Salam Canal.

AQUASIM model is performed well to some extent for El-Salam Canal via the statistical analysis as shown in Table 2. All of the simulated water quality parameters (Chll-a, NH4, NO3, COD, and DO) show the lower values of MAE, $RMSE$, $RRMSE$, and NSE for the observed values using the AQUASIM model along El-Salam Canal (Table 2). Similarly, AQUASIM predictions have higher R^2-value with observations. Furthermore, statistical analysis employing BP revealed that AQUASIM shows better estimation (Table 2). These statistical results comparing simulated and observed values showed that AQUASIM is almost consistent in predicting El-Salam Canal water quality parameters. Moreover, this study reveals that significant changes were observed in DO profile due to temperature changes from summer to winter (Fig. 3 and Fig. 4). The summer has a warm temperature and the DO level reduced rapidly due to more consumption by the canal biomass and less reoxygenation (Wetzel, 2001). Moreover, Fig. 5 showed a good validation for AQUASIM according to the water quality parameters (NO3, BOD5, and DO).

Table 1: Water quality parameters estimation for El-Salam Canal

Parameter	Unit	Value	Parameter	Unit	Value
G_T	day^{-1}	2.0	K_{nit}	day^{-1}	0.05
K_{mn}	mg N/L	0.015	K_{NIT}	mg O_2/L	2.0
D_R	day^{-1}	0.35	K_{NO3}	mg O_2/L	0.1
D_D	day^{-1}	0.02	K_{den}	day^{-1}	0.0
a_{NC}	-	0.30	K_D	day^{-1}	0.2
a_{OC}	-	2.7	K_{O2}	mg O_2/L	0.5
P_{NH4}	-	0.77	K_a	day^{-1}	0.5

3.2. AQUASIM model accuracy evaluation

In this study, the calibration of the AQUASIM model was performed to obtain some rational results by comparing the model prediction and observation values of the water quality data of El-Salam Canal with statistical evaluation (Table 2). The profile of El-Salam Canal water quality has obtained reasonably by adjusting the environmental parameters including kinetics and stoichiometric constants (Table 1).

According to Moriasi et al. (2012), it can be observed from Table 2 that the PB criterion gives values less than 15% (accepted) except stations 3, 4, and 5 for NH4 in which their values consolidated around 50% (poor). Furthermore, statistical analysis employing R^2revealed that the model shows better appraisal as R^2 gives values more than 0.8 (accepted) except for station 4 for Chll-a (R^2=0.62678; poor) and station 4 for COD (R^2=0.58506; poor). The NSE values locate more than 0.7 (accepted). Some stations give poor evaluation as; stations 4 for Chll-a, stations 3, 4, and 5 for NH4, stations 2, 3, and 4 for NO3, and station 4 for COD. Overall, Table 2 shows the good fitness of the calibration. Therefore, the calibrated model's parameters, inclusive of the constants of kinetics and stoichiometry, were applied to verify the model as shown in Fig. 3 and Fig. 5.

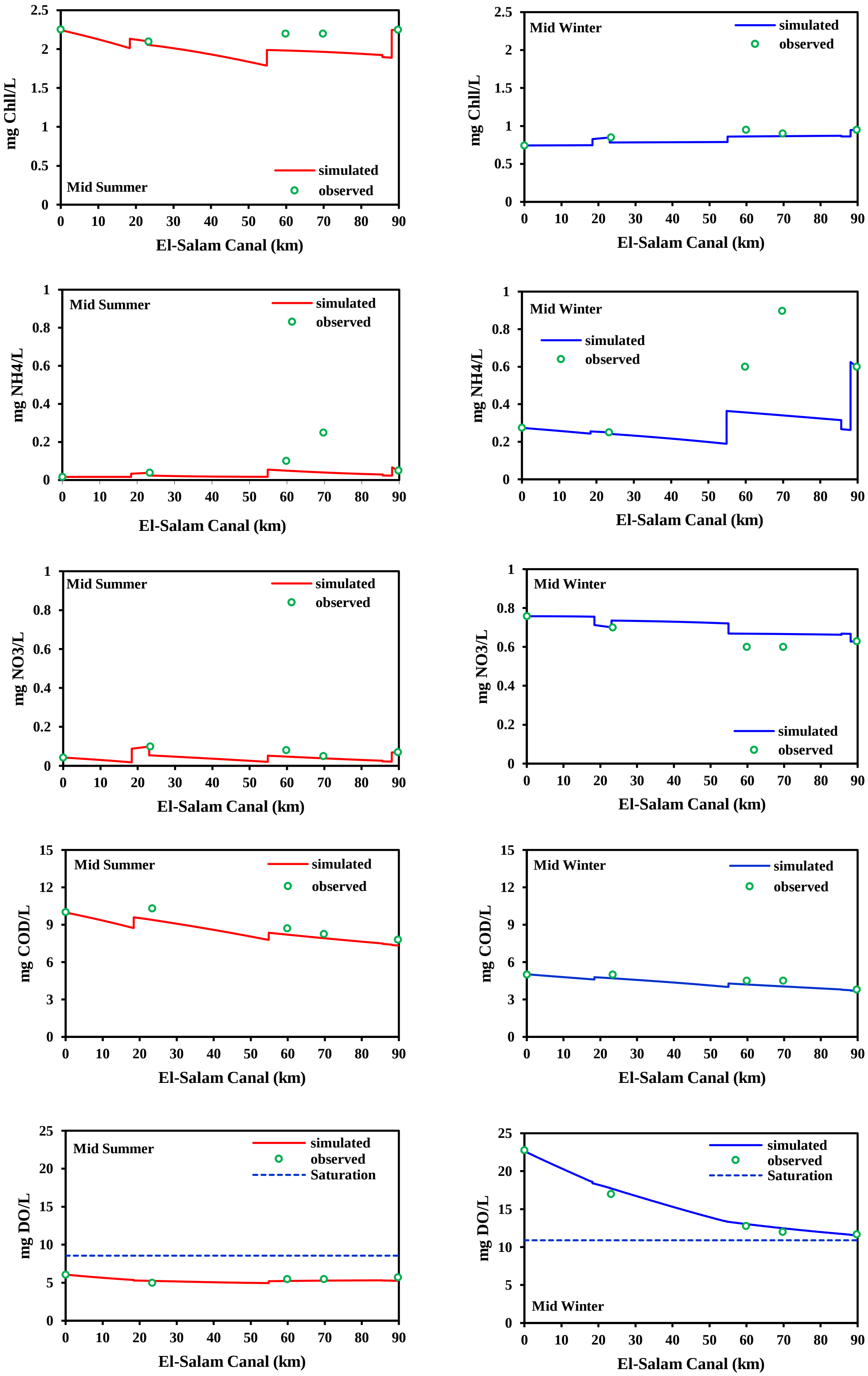

Fig. 3: Confirmation Results of AQUASIM model parameters for El-Salam Canal according to El-Amier et al. (2017)

Table 2: Statistical evaluation of calibrated and validation results for predicted and observed

Parameter	Location	MAE	BP%	RMSE	RRMSE	R^2	NSE
	Station 1	0.00026	0.02603	0.00062	0.00063	1.00000	1.00000
	Station 2	0.05752	5.47962	0.08419	0.08021	0.98403	0.96891
Chll-a	Station 3	0.05814	5.62298	0.09651	0.09334	0.97592	0.95829
	Station 4	0.15591	13.78702	0.37770	0.33400	0.62678	0.55013
	Station 5	0.08451	8.19838	0.13451	0.13049	0.98708	0.93021
	Station 1	0.00020	0.13481	0.00023	0.00158	1.00000	1.00000
	Station 2	0.01452	9.64065	0.01875	0.12445	0.99694	0.98212
NH4	Station 3	0.16193	45.39707	0.30526	0.85579	0.92184	0.58901
	Station 4	0.26552	58.96171	0.28063	0.62318	0.86498	-0.29928
	Station 5	0.15439	50.98510	0.27376	0.90408	0.87885	0.56645
	Station 1	0.00007	0.01636	0.00030	0.00074	1.00000	1.00000
	Station 2	0.03193	-9.21629	0.14117	0.40754	0.85267	0.51523
NO3	Station 3	0.03954	-12.8538	0.12455	0.40491	0.86556	0.50139
	Station 4	0.04547	-15.2052	0.11407	0.38148	0.88644	0.66543
	Station 5	0.04424	-14.6081	0.10044	0.33163	0.94322	0.78407
	Station 1	0.01180	0.13277	0.01411	0.00159	1.00000	0.99998
	Station 2	0.56667	6.57095	1.01914	0.11818	0.91801	0.87774
COD	Station 3	0.75126	9.80090	1.21720	0.15880	0.90072	0.80602
	Station 4	0.08018	-1.23491	1.33403	0.20546	0.58506	0.25652
	Station 5	0.23625	3.81386	0.49615	0.08010	0.95944	0.90712
	Station 1	0.02033	0.18227	0.02614	0.00234	1.00000	0.99997
	Station 2	0.11009	1.13446	0.85526	0.08822	0.94290	0.94161
DO	Station 3	0.16910	2.03189	0.49676	0.05970	0.96857	0.96223
	Station 4	0.20386	2.38767	0.71312	0.08374	0.90645	0.80528
	Station 5	0.18473	2.38319	0.57124	0.07373	0.92288	0.91079

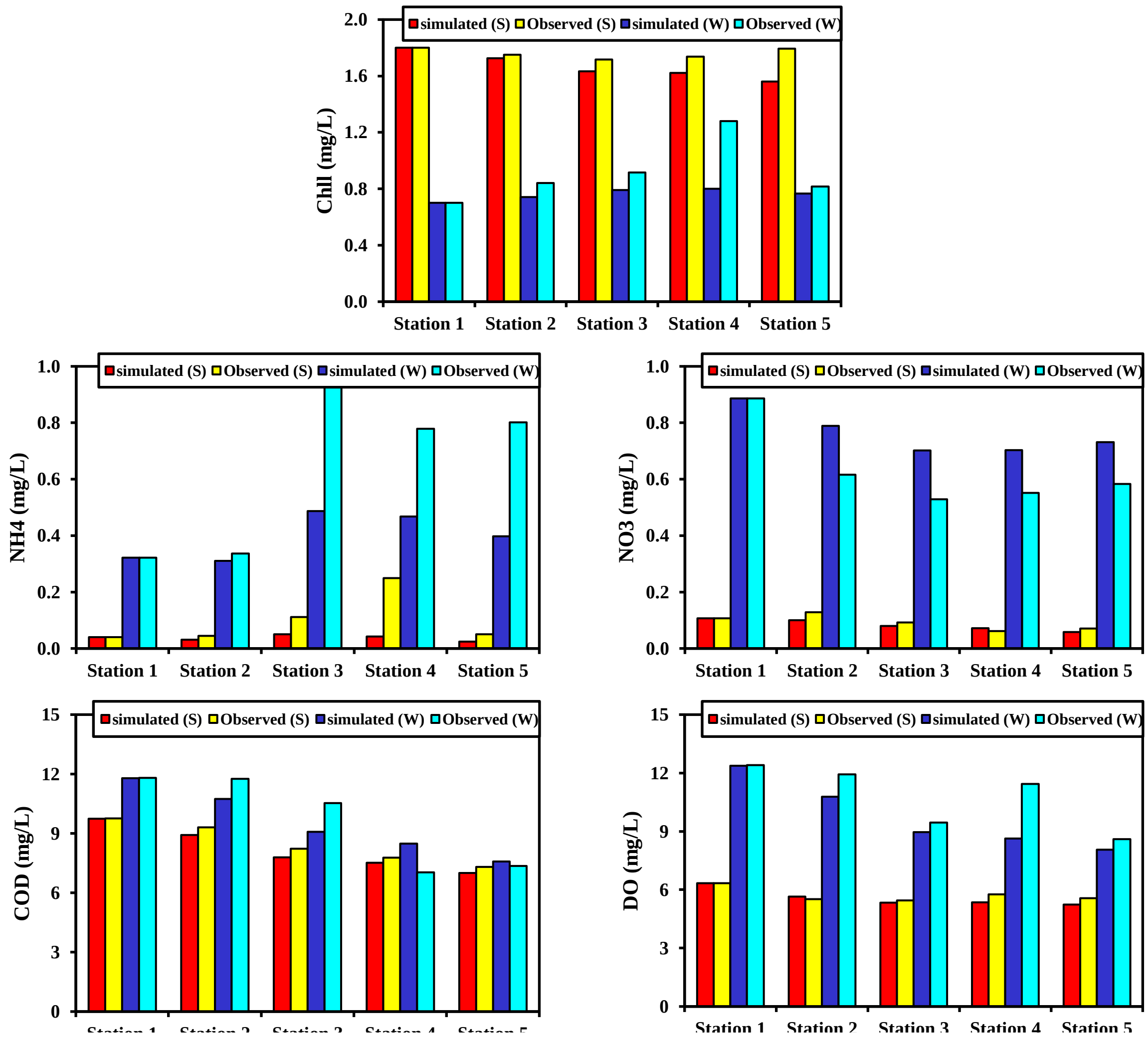

Fig. 4: Mean values of water quality parameters during summer and winter along El-Salam Canal according to El-Amier et al. (2017)

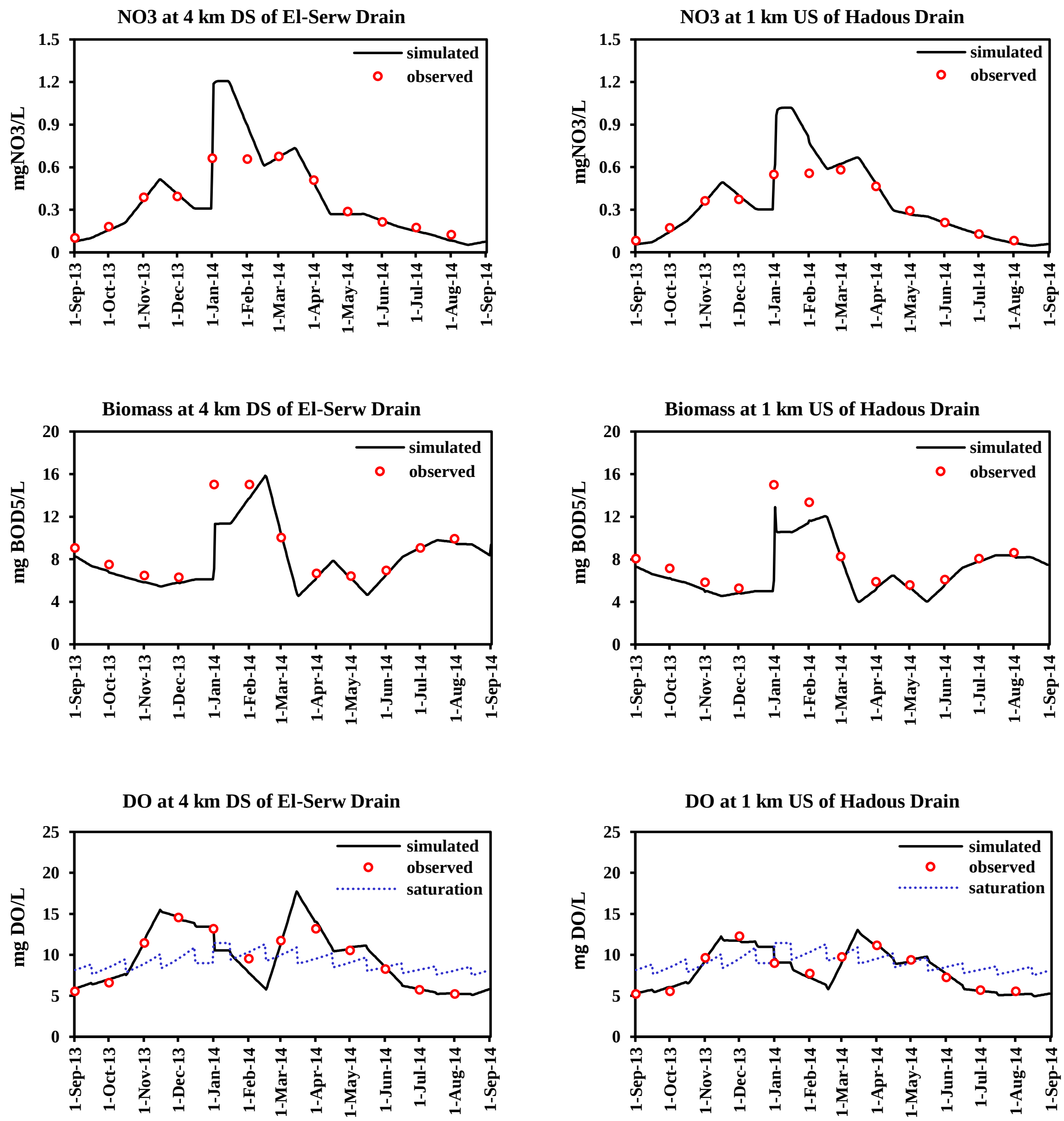

Fig. 5: Confirmation Results of water quality model parameters for El-Salam Canal according to Assar et al. (2019)

3.3. Water quality index (WQI) assessment

WQI is produced by using the physicochemical variables measured for El-Salam Canal as presented in El-Amier et al. (2017). Sixteen parameters have been selected as shown in Table 3. The standard values (S_n) are in mg/L except p forH, and can be estimated according to Egyptian Law (48/1982) in 1995 and its revision (48/1982) in 1999. Fig. 6 shows the pictorial depiction of the water quality index for El-Salam Canal. In this regard, it can be possible to summarize the water quality status for El-Salam Canal as shown in Table 4. It is clearly noticed that the water quality in station 3 (near Hadous drain), was affected by agricultural and domestic uses especially in winter due to the closure system (Abu-Zeid, 1995). Therefore, minimizing these pollution sources should be the priority to improve the water quality around this area.

3.4. Interrelationship of spatial scale among water quality parameters

Fig. 7 shows the interrelationship of spatial scale among the quantity of El-Salam Canal flow profile and the DO concentrations. Usually, the DO concentrations are improved by a high rate of fresh-water flow. However, exceptions of different climatic zone occur since the concentration of DO, COD, and nitrogen also depends on the different reaction rates. Fig. 7 shows that the concentration of DO declines with respect to the flow profile as a tropical zone of north Egypt (Khalifa, 2014). This study shows that the DO concentration increases in winter, while DO concentration declines clearly in summer (Fig. 3 and Fig. 4). The greater possibility of a high reoxygenation rate is also observed in winter than in summer (Fig. 3 and Fig. 4). Overall, the COD profile trend is increasing with increasing phytoplankton in summer which is due to the addition of El-Serw and

Hadous drains in El-Salam Canal. From this finding, it can be agreed that water quality is a function of both natural water climate and anthropogenic sources (Onuoha et al., 2018; Rashid and Romshoo, 2013; Ratemo, 2018; Liyanage and Yamada, 2017).

Table 3: Standard values of water quality parameters and unit weights for El-Salam Canal

S.N.	Parameter	Standard value (S_n) according to Egyptian Law 48/1982	Ideal value (V_{id})	$1/S_n$	k value ($k=1/\sum 1/S_n$)	unit weight ($W_n=k/S_n$)
1	TDS	500	0	0.002	0.00778477	1.56E-05
2	pH	8.5	7	0.11765	0.00778477	0.000916
3	Alkalinity	150	0	0.00667	0.00778477	5.19E-05
4	Hardness	300	0	0.00333	0.00778477	2.59E-05
5	Chlorides	250	0	0.004	0.00778477	3.11E-05
6	NH4	0.5	0	2	0.00778477	0.01557
7	NO2	1	0	1	0.00778477	0.007785
8	NO3	45	0	0.02222	0.00778477	0.000173
9	O2	5	12	0.2	0.00778477	0.001557
10	COD	10	0	0.1	0.00778477	0.000778
11	Fe	1	0	1	0.00778477	0.007785
12	Mn	0.5	0	2	0.00778477	0.01557
13	Zn	1	0	1	0.00778477	0.007785
14	Cu	1	0	1	0.00778477	0.007785
15	Pb	0.05	0	20	0.00778477	0.155695
16	Cd	0.01	0	100	0.00778477	0.778477
				$\sum 1/S_n$= 128.456		$\sum W_n$= 0.973097

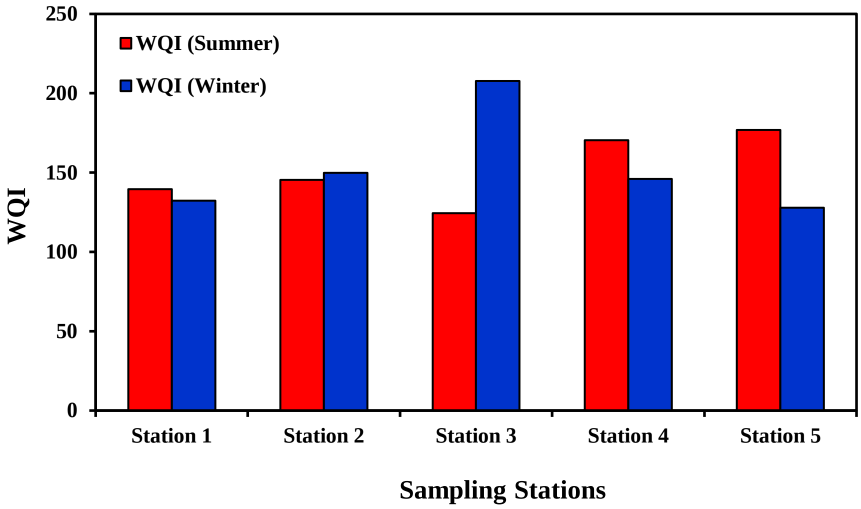

Fig. 6: Pictorial depiction of water quality index for El-Salam Canal

Table 4: Water quality status of El-Salam Canal (Srinivas et al., 2016)

Stations	WQI		Status	Possible usage
	Summer	Winter		
1	140	132	Poor (100<WQI<200)	Irrigation
2	145	150	Poor (100<WQI<200)	Irrigation
3	124	208	Poor (100<WQI<200)	Irrigation with restricted treatment in winter
4	170	146	Poor (100<WQI<200)	Irrigation
5	177	128	Poor (100<WQI<200)	Irrigation

The sustainable riverine ecosystem depends mainly on the DO and stream temperature of the aquatic biochemistry (Abdul-Aziz and Ishtiaq, 2014; Dick et al., 2016; Mader et al., 2017). The DO solubility is inversely affected by the temperature; therefore, higher stream temperature reduces the DO solubility thereby decreasing the DO. This is obvious in the observation of the instream DO in summer were lower compared to those in winter (Fig. 3 and Fig. 4). The minimum DO for the survival of the moderate aquatic life and river ecosystem is required for sustainable management practice for river water quality (Martin et al., 2013; Marzadri et al., 2013; Null et al., 2017; Lee et al., 2018). Therefore, the determination of the minimum DO level is required in warmer streams than in cold stream (Martin et al., 2013; Marzadri et al., 2013; Null et al., 2017; Lee et al., 2018; Williams and Boorman, 2012).

Many characteristics of quantity and water quality are coupled well. The ecosystem in water can importantly spatially vary depending on the actual quantity river flow profile, and rates of chemical reaction constant particularly in climatic regions. The health of water bodies and the river flow are incorporated with the mechanisms of the environment. The sustainability of the water environment is the objective of water quality conservation approaches such as the quantity and quality required to maintain water bodies at a safe level (Chen et al., 2013). In addition, most researches are concerned with the flow quantity to conserve the ecological health of a river (Scherman et al., 2003), which influence the water environment sustainability.

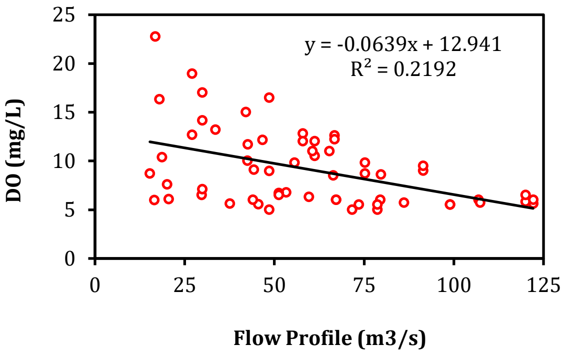

Fig. 7: DO concentration with respect to flow profile of El-Salam Canal

4. Conclusions

This study is approached for three main objectives. Firstly, the AQUASIM model is used to evaluate the spatially and temporal profiles of water quality of five parameters: Chlorophyll, ammonia, nitrate, chemical oxygen demand, and dissolved oxygen through El-Salam Canal in Egypt. The performance of AQUASIM predictions are assessed by applying various statistical rating tools such as MAE, BP, $RMSE$, $RRMSE$, R^2, and NSE. The simulation results showed a good agreement for almost all of the water quality parameters. The second target is to evaluate the water quality of El-Salam Canal using the water quality index (WQI) for selected sixteen parameters. The WQI showed that the water quality of the EL-Salam Canal was affected by anthropogenic activities of agricultural and domestic uses especially near the Hadous drain. Therefore, it is important for minimizing these pollution sources to maintain or improve water quality around this area. This leads to assist the process of decision-making for the water quality management in EL-Salam Canal. The third target of this study shows a decline in DO of El-Salam Canal with respect to the flow profile as a tropical zone of northern Egypt.

The cold conditions as in winter show an increase in DO, expressing high reoxygenation rates while the warm conditions as in summer show a decrease in DO, demonstration low reoxygenation and high biomass deoxygenation rates. The results of the present study are convenient in the observing and control of different nutrients loads of El-Salam Canal water quality. The outcomes acquired in this study will facilitate the development of a policy for the operational enhancement of sustainable water quality in El-Salam Canal.

Compliance with ethical standards

Conflict of interest

The authors declare that they have no conflict of interest.

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