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Assessment of Longitudinal Dispersion Coefficient Using One-dimensional Numerical Modeling Equation

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Abstract: *The determination of an accurate value of dispersion coefficient is highly important in studying the environmental impacts of pollutants spill into rivers. A one-dimensional module is created in HEC-RAS to simulate the hydrodynamics of the river and the water quality variability. Two scenarios of maximum and minimum flow cases were implemented. Equation of Fischer (1979) was built in HEC-RAS model to compute the longitudinal dispersion coefficients. In this study, two more equations were added to create two other calculation models for comparison; modified Fischer (1979) and Kashefipour & Falconer (2002). The three models were applied to a reach of 144 km long selected and schematized on the Nile River. A comparative analysis of the three equations was performed based on the real measured data at several monitoring stations located along the studied area. The results revealed that the equation of Kashefipour & Falconer (2002) gives calculated values of dispersion coefficient very close to the real measured values.*

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I. Introduction

The Nile River is the life artery of Egypt. It is the main resource of drinking, irrigation and industrial water demands. Nile River pollution comes mainly from domestic, industrial wastewater, and agricultural drainage.

To study the environmental impact of polluting effluents spill into a stream, accurate values of dispersion coefficients (D) are needed (David et al. 2002). An accurate investigation of (D) requires a precise knowledge of all the geometric and dynamic characteristics of the watercourse (Benedini and Tsakiris, 2013). Due to the nature of flow in rivers, the prevailing velocity can generally be accurately obtained by solving the one-dimensional equations of motion (Kashefipour & Falconer, 2002).

The transport of contaminants in surface waters is generally described with the advection-dispersion equation (ADE). ADE comes from the mass balance equation (Van Genuchten et al. 2013). The numerical solution of the advection-dispersion equation (ADE) is one of the most difficult numerical problems in the computational fluid dynamics area. HEC-RAS uses the QUICKEST-ULTIMATE explicit numerical scheme (Leonard, 1979, Leonard, 1991) for different water quality constituents to determine concentrations at each computational node (Zhonglong Zhang 2014).

Referring to (Szomorová & Halaj, 2015), HEC-RAS model responds to the changes in dispersion coefficient values adequately, suitably and proportionately. Therefore, HEC-RAS model has proved its applicability to simulate the contaminants spill in water streams, and it is an appropriate tool for decision making related to the quality of water resources (Szomorová & Halaj, 2015). The general form of ADE equation after Kashefipour & Falconer (2002) reads:

$$\frac{\partial CA}{\partial t} + \frac{\partial CAU}{\partial x} = \frac{\partial}{\partial x} AD \frac{\partial C}{\partial x} + S_T$$

Where;

A = The cross-sectional area of flow.
C = The cross-sectional average concentration
U = The cross-sectional average velocity
t = The time
X = The direction of mean flow velocity
D = The longitudinal dispersion coefficient
$\boldsymbol{S_T}$ = The Source Term.

The equation used in the internal computation of dispersion coefficient in HEC-RAS is based on the equation given by Fischer (1979). Fischer's equation is an estimate of shear flow dispersion based on hydraulic and geometric quantities (velocity, channel width, depth, and slope). Fischer's equation (1979) reads:

$$D = 0.011 \frac{u^2 w^2}{y\, u^*}$$

Where;

u = cross-sectional average velocity (m/s)
w = average channel width (m)
y = average channel depth (m)
u* = shear velocity (m/s)

In addition, Brunner (2016b) has modified the Fischer's (1979) equation by suggesting a multiplier factor of four based on field observations. Kashefipour & Falconer, (2002) developed an equation for predicting the longitudinal dispersion coefficient in river flows. They derived their equation based on 81 sets of measured data and obtained from 30 rivers in the USA. They found that, the average percentage errors between the predicted and measured field data for their developed dispersion equations were less than those obtained using the Fischer's (1979) equation.

Kashefipour & Falconer, (2002) equation correlates the dispersion coefficient to the hydraulic and geometric parameters of the flow. It has been obtained using dimensional and regression analysis, with a correlation coefficient of $R^2 = 0.84$.

Equation of Kashefipour & Falconer (2002) reads:

$$D = 10.612\, H\, U \left(\frac{U}{U_*}\right) \quad with\, R^2 = 0.84$$

Where;

H = Depth of flow (m)
U = Cross-sectional average velocity (m/s)
U_* = Shear Velocity (m/s)

In this research, the three mentioned equations; Fischer, modified Fischer, and Kashefipour & Falconer are used to form three models through the HEC-RAS module to assess their accuracy in estimating the longitudinal dispersion coefficient of the studied area. The different contaminants behaviors resulted from the three various equations, are compared with the real data measured at the water quality monitoring stations.

II. Material And Methods

A one-dimensional steady simulation model was built in HEC-RAS to simulate the hydrodynamics of the studied reach. The HEC-RAS module provides hydrodynamic and water quality modeling in this study. This model was developed by the United States Army Corps of Engineers to model the complex phenomena and processes occurring in surface waters of the river systems. It calculates the one-dimensional steady non¬-uniform and unsteady flow to solve hydraulic engineering tasks and pollution transport modeling.

Studied Reach:

The studied reach is about 144 km long extending at the Egyptian part of the Nile River. The reach starts at Assiut Barrage which is 544.78 km downstream the High Aswan dam and ends at El Menia Monitoring Station, located at 687 km downstream the dam as shown in Figure 1. The study area is extended through two Egyptian governorates; Assuit and El Menia governorates from (31.186843 E, 27.204039 N) to (30.754224 E, 28.117306 N).

Data Collection

The main data collected in this study can be summarized as follow:

The bathymetric data:

The bathymetric data was used to extract the topography of the river bed through nineteen cross sections along the studied reach.

The hydrological and hydraulic data:

The average 10 days of discharges records at downstream Assuit Barrage were used as upstream boundary condition for the model. In addition, the average 10 days of the water level upstream Menia gauge station was used as the downstream boundary condition. The water levels were collected at 4 gauging stations along the studied reach, and the velocity distributions were used for calibration purpose.

Water Quality Data

Three water quality monitoring stations located along the studied reach as: 1.The monitoring station at Assuit Barrage (544.78 km downstream High Aswan Dam), considered as the reference point for the quality of water entering the study reach, 2. The station located about 93 km downstream Assuit Barrage, 3. El Menia Monitoring Station (687.55 km downstream HAD), which is the downstream end of the studied reach. Water quality parameters concentrations at the three monitoring station were collected and used for water quality module calibration. Nineteen cross-sections representing the studied reach were presented. Figure 2 shows the studied reach with the associated cross-sections and monitoring stations.

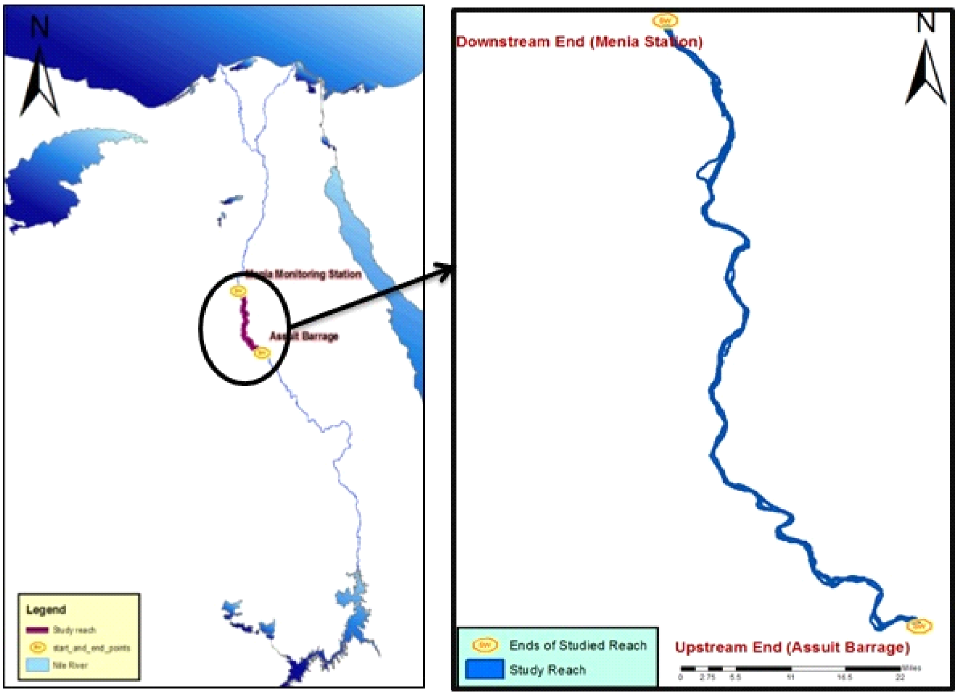

Figure 1: Location of the Studied Reach

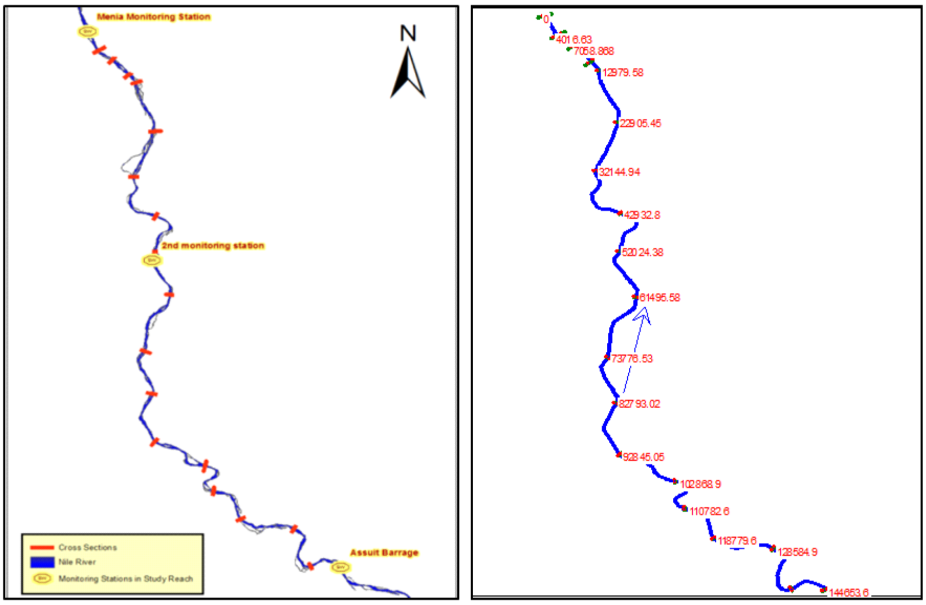

Figure 2: Studied Reach Associated with Cross-sections in Arc GIS and HEC-RAS

Point Source Pollution

The studied reach receives agricultural, industrial and domestic return flow from about eleven drains. Seven out of the eleven drains along the studied reach are located in Assuit Governorate. The remaining four drains are located in El Menia governorate. One of the major contaminants sources to the studied reach is the discharge of raw sewage, especially in rural areas. Most drains receive raw sewage either directly from housing units or sewage/sludge emptying trucks. Two villages, Tal Bani Omran and Qalandoul, discharge their raw sewage into the agricultural drains Khaity and El Serw drains, respectively. In the two villages, the people have no access to sewer systems or wastewater treatment facilities. Finally, Khaity drain and El Serw drain flow back into the Nile.

At 552 km downstream HAD, approximately 30,652 m3/d of industrial effluents are discharged to the Nile, from Manqabad fertilizer factory. However, most of Manqabad factory water quality parameters were in compliance with standards set in Law 48/1982. The wastewater treatments plants (WWTPs) located in the study area discharged their treated water indirectly into the Nile through the drains. For example, El Zinar El Raesy drain receives 120000 m3/d of secondary treated wastewater from Arab El Madabegh Extension treatment plant which in turn discharges to the Nile in the studied reach. Polluted loads of the drains were represented in the model as pollutants spill into the studied reach.

Calibration of Hydraulic and Water Quality Simulation modules in HEC-RAS

Model results are compared with the observed water levels in the cases of maximum and minimum flows. Figure 3 shows the resulted upstream water surface levels in the steady condition compared to the observed gauging levels revealing high accordance.

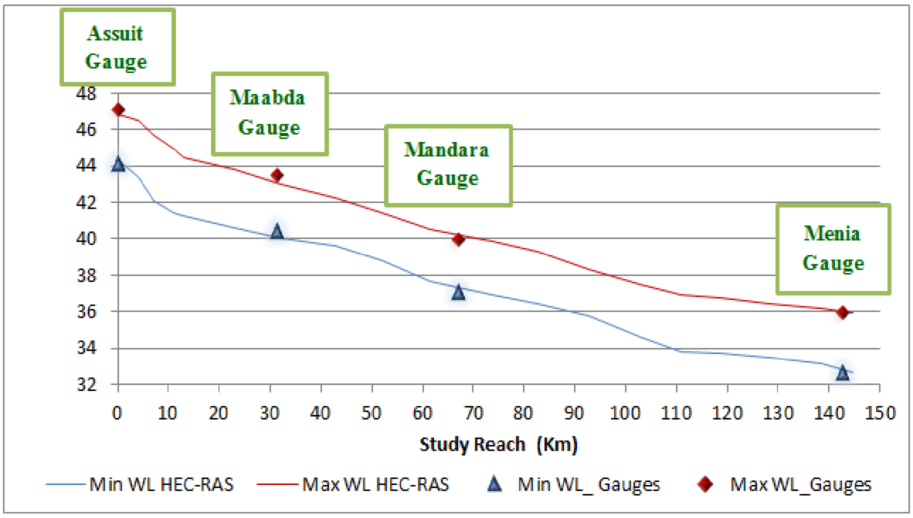

Figure 3: Calibration of Hydraulic Simulation

In addition, a water quality module was calibrated for maximum and minimum flow conditions. Figure 4 indicates the calibration of some parameters in the maximum flow condition. The resulted concentrations were found of high relevance with observed ones at the three monitoring stations.

As an Example, Figure 5 indicates the simulated BOD along the studied reach, represented in ArcGIS in maximum and minimum flow conditions. The maximum flow of 181 M.m3/d recorded in August and the minimum flow of 37.7 M.m3/d recorded in February. Pollutants' discharges are assumed to be released in the same time and the figure gives the results after 24 hrs. In Appendix A, Table A-1 indicates the point sources pollution along the studied reach and Table A-2 indicates the dispersion coefficient at the corresponding cross section.

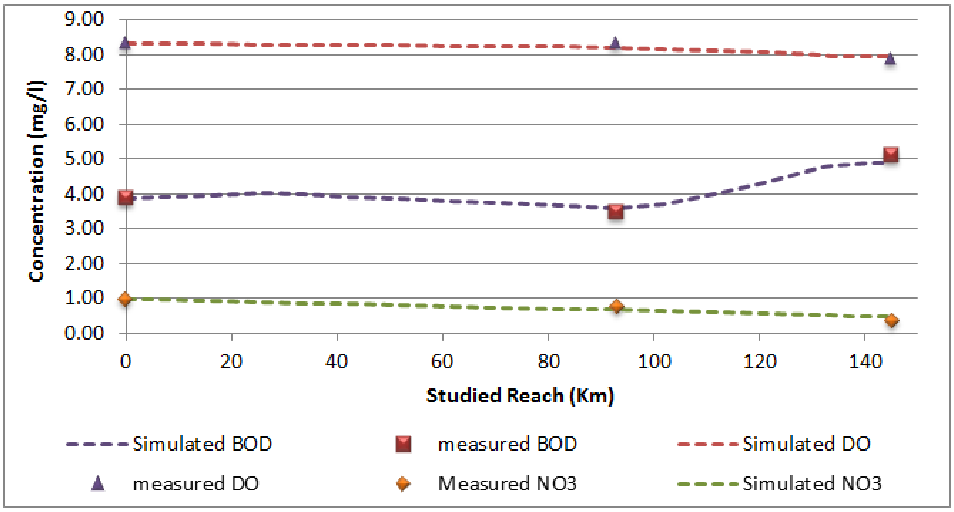

Figure 4: Calibration of Water Quality Simulation

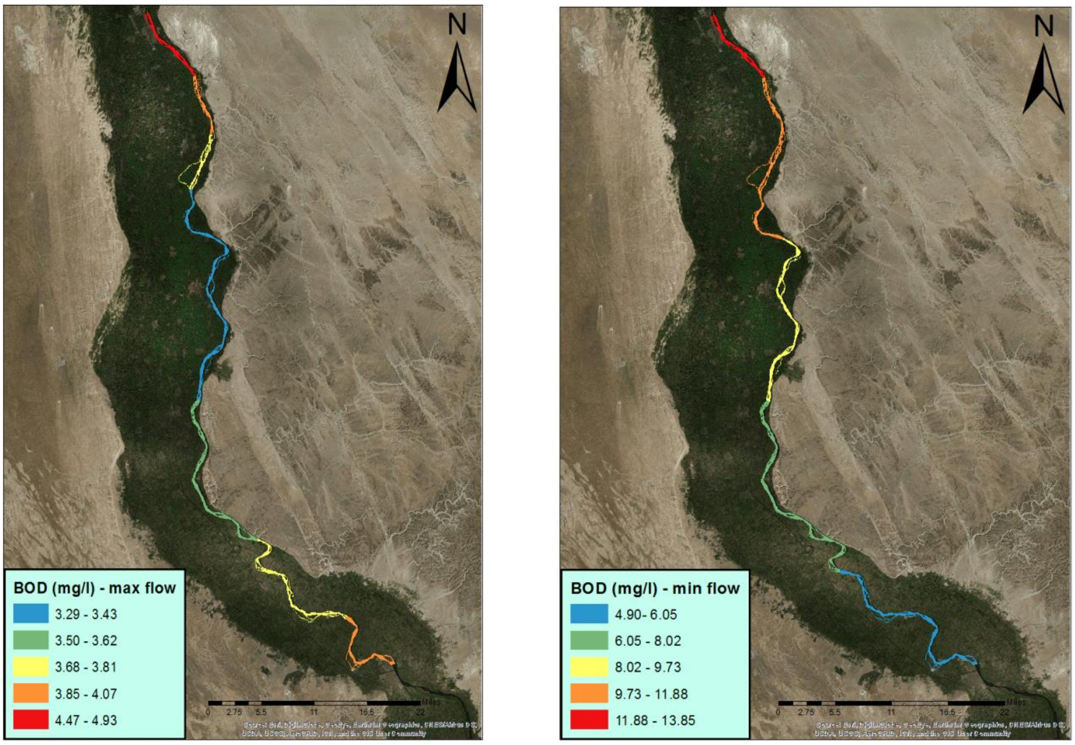

Figure 5: Simulated BOD in the Studied Reach (Maximum and Minimum Flow)

Three of the longitudinal dispersion coefficients computations are used. Model A: using Fischer (1979) equation, Model B: using modified Fischer (1979) equation, and Model C: using Kashefipour & Falconer (2002) equation.

Water quality simulations were performed for each of the three Models A, B and C. Concentrations of water quality parameters, due to different dispersion coefficients, were investigated and compared to the observed concentrations measured at the monitoring stations along the studied reach of the Nile River.

The water quality parameters assessed within this work are Dissolved Oxygen (DO), Biological Oxygen Demand (BOD), Nitrate (NO3), and Phosphate (PO4). These parameters were selected as being the most influencing parameters for the surface water.

III. Results and Analysis

Dissolved Oxygen (DO)

Initially, in maximum flow, DO concentration was measured as 8.32 mg/l at Assuit Barrage. With distance, DO concentration decreased. At the second monitoring station, DO concentration was recorded as 8.2 mg/l. The calculated values using Models A, B were 7.82 and 7.93 mg/l, respectively, while in Model C, DO record was 8.206 mg/l, which is almost the same observed DO value. At El Menia Monitoring Station, the measured DO was 7.90 mg/l. Results of Models A and B dropped below the observed value indicating 7.7 and 7.8 mg/l, respectively. In Model C, DO concentration was 7.91 mg/l, approximately the same as the observed value (see Figure 6).

In case of minimum flow, Figure 7 shows that Models A and B gave false calculated values regarding both values and trend. DO concentrations calculated by Models A, B showed increasing trend till they reached 8.68 and 8.64 mg/l at 93 km, respectively, which is above the observed DO of 7.6 mg/l. They also gave calculated values of 8.57 and 8.62 mg/l at the downstream end of the studied reach, respectively. These values are also far from the observed DO (7.4 mg/l). In Model C, calculated DO showed good agreement with values and trend of the observed DO values (see Figure 7).

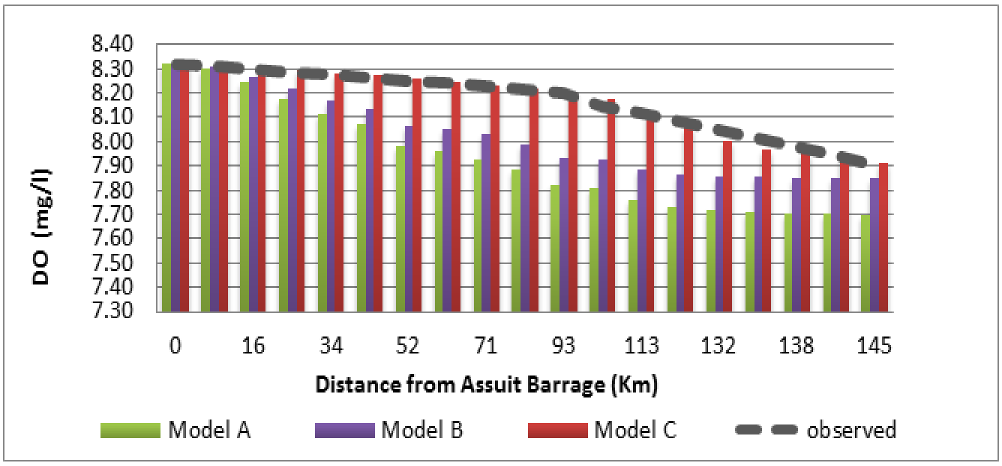

Figure 6: DO calculated concentration versus observed concentration - max flow

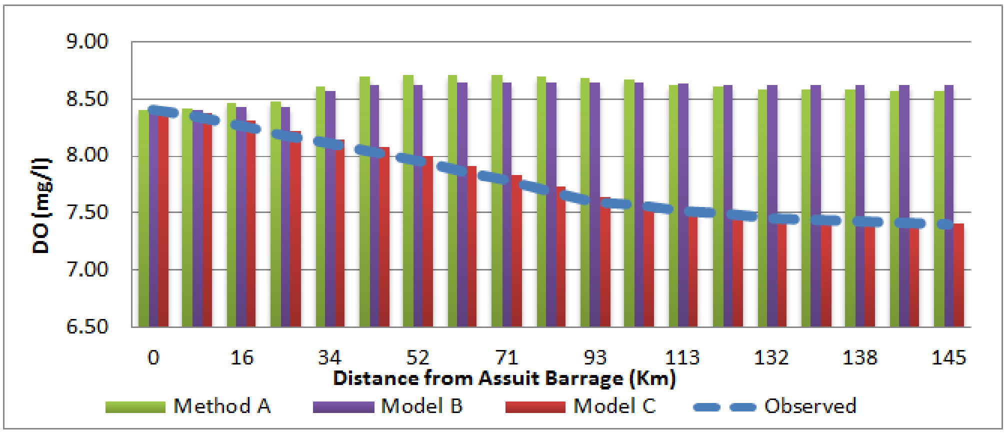

Figure 7: DO calculated concentration versus observed concentration - min flow

Biological Oxygen Demand (BOD)

In maximum flow, calculations using Models A, B gave false constant values of BOD. Model C gave approximately equal values and trends of the observed BOD. At 93 km, Model C gave value of BOD of 3.29 mg/l, almost the same as the observed BOD of 3.26 mg/l. At 144 km, Model C gave BOD value of 4.93 mg/l close to the observed value of 5 mg/l (see Figure 8).

Figure 9 shows the same results regarding the minimum flow condition. For example, the observed concentration was 10 mg/l at km 93, Models A, B, calculated the concentrations as 7.4 and 7.72 mg/l, respectively, while Model C result was approximately the same as observed.

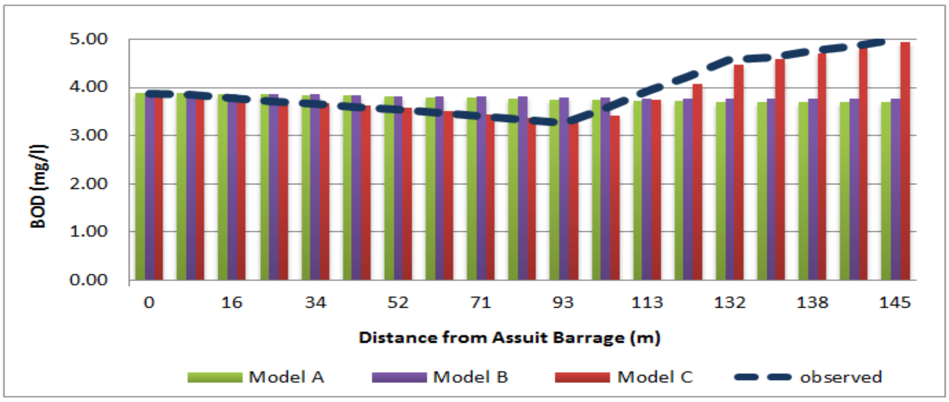

Figure 8: BOD calculated concentration versus observed concentration - max flow

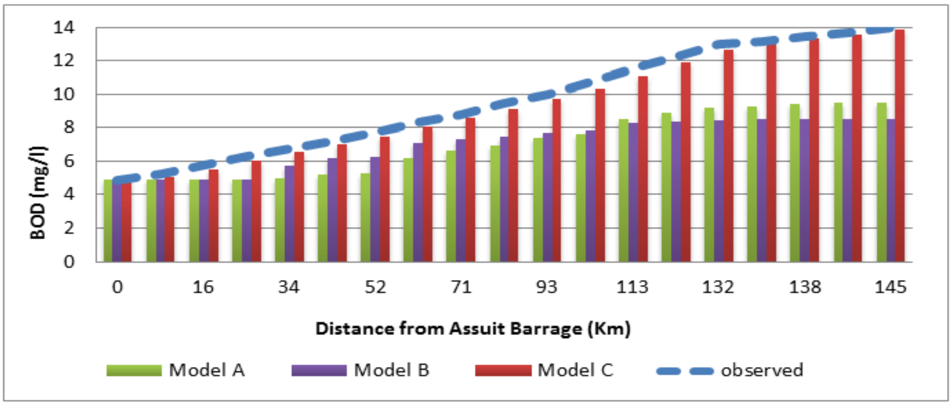

Figure 9: BOD calculated concentration versus observed concentration - min flow

Nitrate (NO_3)

Nitrate (NO_3) is associated with agricultural wastewater (Brunner, 2016b). At maximum flow, NO3 observed concentrations at 0, 93, 144 km were 0.97mg/l, 0.65 mg/l and 0.46 mg/l, respectively. Model A calculations were 0.97 mg/l, 0.89 mg/l, 0.78 mg/l. From 0 to 93 km Model B calculations were approximately the same as Model A. From 93 to 144 km, Model B calculations were more than Model A calculations showing a value of 0.85 mg/l at the end of the studied reach. Model C gave calculated concentrations in good agreement with the observed ones regarding values and trends (see Figure 10).

At the minimum flow case, the observed NO3 values at the monitoring stations along the studied reach were 0.93 mg/l at (km 0), 0.47 mg/l at (km 93) and 0.56mg/l at (km 145). In Model C, NO3 profile along the studied reach is very similar to the observed NO3, and the calculated values were 0.93 mg/l, 0.48 mg/l and 0.56 mg/l at the three successive monitoring stations on the studied reach, respectively (see Figure 11).

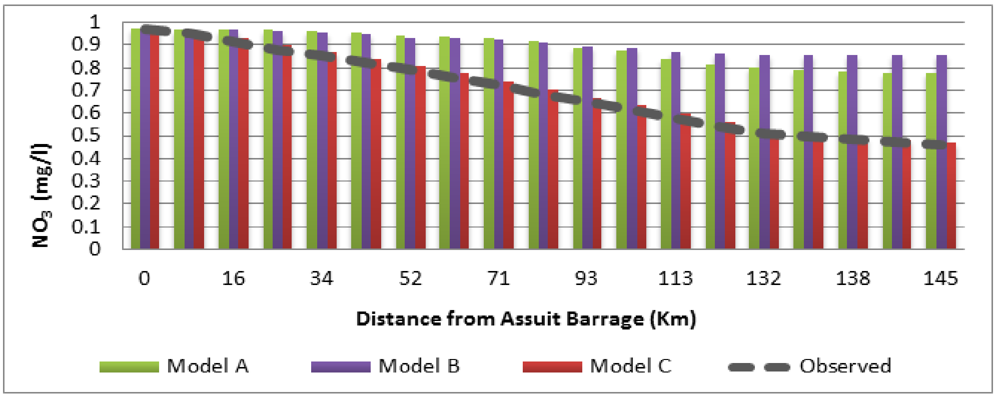

Figure 10: NO_3 calculated concentration versus observed concentration - max flow

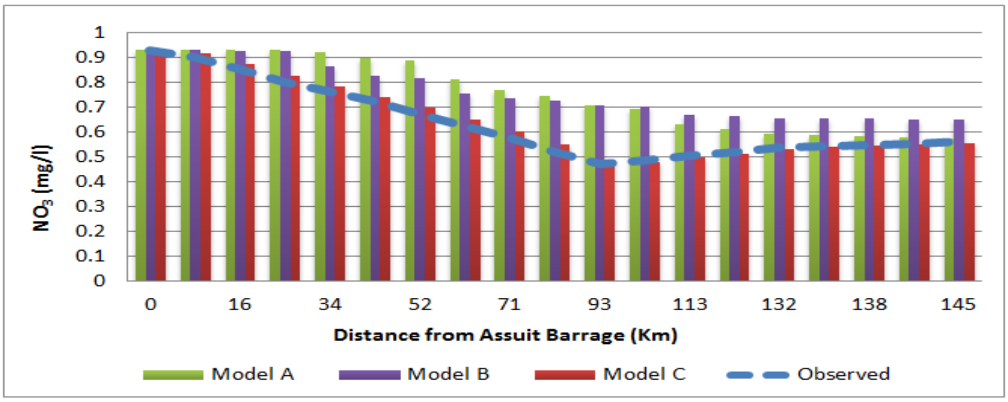

Figure 11: NO_3 calculated concentration versus observed concentration - min flow

Phosphate (PO_4)

At the maximum flow, the observed PO_4 started at 0.05 mg/l and took upward direction reaching its highest concentration of 0.06 mg/l, occurring at (km 93). At the reach from 93 to downstream end, PO_4 decreased and finally recorded 0.043 mg/l at El Menia Barrage.

Models A and B gave the same trends but with different values of PO_4. In both Models, PO_4 calculated concentrations were less than recorded ones from 0 to 93 km, and were more from 93 to 144 km. Figure 12 shows that results of Model C agreed well with observed values of PO_4 concentration.

At the minimum flow case, Figure 13 shows good agreement between Model C calculations and the observed ones, and the differences in values and trends of results of Model A and Model B.

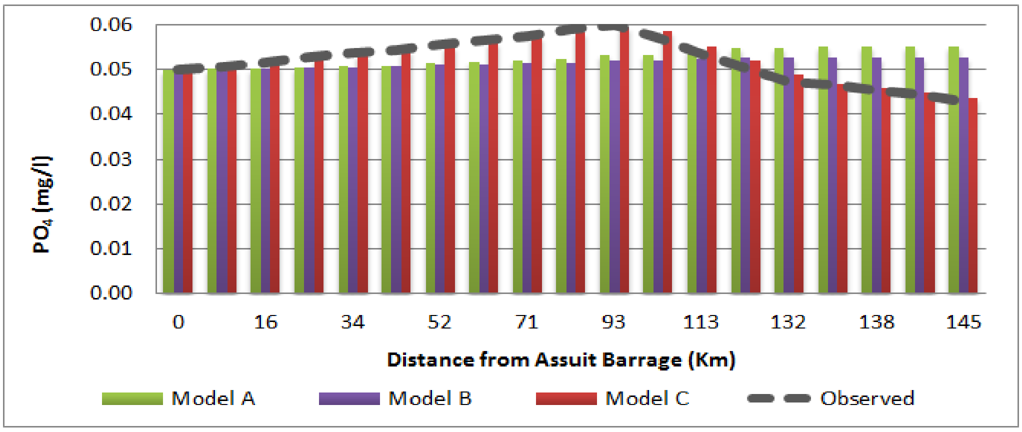

Figure 12: PO_4 calculated concentration versus observed concentration - max flow

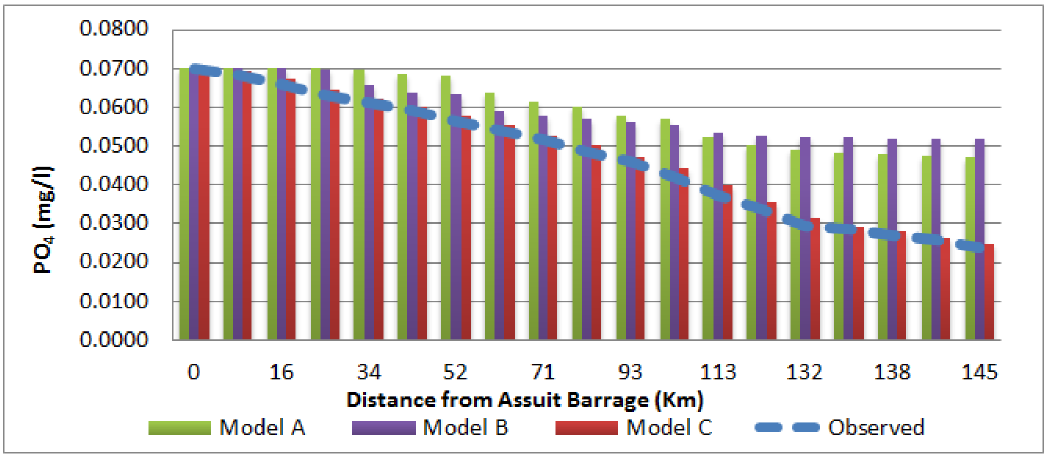

Figure 13: PO_4 calculated concentration versus observed concentration - min flow

General Comments

In the Models results regarding water quality results, the following may be noted. DO showed decreasing trends in maximum and minimum flow conditions, whereas, BOD has taken upwards trends. This was due to raw sewage discharges from surrounded villages to the agricultural drains then to the study area. Water quality parameters in Model C showed accurate values close to the measured values at monitoring stations.

IV. Conclusions

Dispersion Coefficient is the core element in estimating the dispersion effects on the contaminant concentration in water streams. Four selected water quality parameters were simulated along the studied reach using different dispersion coefficients calculated by three Models; A (Fischer equation), B (modified Fischer equation) and C (Kashefipour & Falconer equation).

Results showed that the simulated parameters obtained by using Models A and B differ a lot from the real observed parameters. On the other hand, the concentrations of different parameters obtained from Model C, were close to the observed concentrations at the monitoring stations along the studied reach in both maximum and minimum flow cases. This may be due to the Kashefipour & Falconer equation that was set based on high correlation between the dispersion coefficient and the best fitted combined hydraulic and geometric parameters.

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Appendix A: Table A-1: The point sources pollution along the studied reach.

Sub-reach	Point Source Pollution	Q source m3/d	Q Classifications (m3/d)		
			agriculture	municipal	industry
1	---	---	---	---	---
2	El Zinar El Raesy	662,688.00	592688	120000	---
3	Menqabad factory	30,652.05	---	---	30652.05
	Abnub El Quibly	191,808.00	191808	---	---
4	Manqabad El Raesy	138,240.00	138240	---	---
	Abnub El Bahary	260,064.00	260064	---	---
5	Manflout	84,672.00	84672	---	---
6	---	---	---	---	---
7	El Gabal El Raesy	1,209,600.00	1209600	---	---
8	---	---	---	---	---
9	Masara	112,320.00	112320	---	---
10	Khaity	86,400.00	86400		---
11	---	---	---	---	---
12	Dir Abu Henes	60,480.00	60480	---	---
13	---	---	---	---	---
14	El Serw	56,160.00	56160		---
15	---	---	---	---	---
16	---	---	---	---	---
17	---	---	---	---	---
18	Maqousa	342,144.00	342144	---	---

Appendix A: Table A-2: The dispersion coefficient at the corresponding cross section.

Cross-Section	D (m2/s) Min Flow	D (m2/s) Max Flow	Cross-Section	D (m2/s) Min Flow	D (m2/s) Max Flow
1	2.48	10.14	**11**	3.82	12.23
2	2.48	10.14	**12**	2.86	8.72
3	4.44	12.81	**13**	7.03	14.12
4	0.63	9.77	**14**	2.22	9.31
5	12.99	14.18	**15**	3.39	8.57
6	7.19	11.84	**16**	3.40	12.24
7	2.21	11.63	**17**	5.52	13.77
8	8.17	11.65	**18**	4.10	11.14
9	3.76	9.25	**19**	3.53	8.35
10	2.76	10.81			

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