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IMPACT OF THE VELOCITY ON THE FATE OF POLLUTANTS IN GABAL EL-ASFAR DRAIN

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ABSTRACT

Gabal El-Asfar drain (GAD) receives a secondary treated sewage effluent from Gabal El-Asfar wastewater treatment plant (GAWWTP). The design capacity of GAWWTP is 2.5 million m^3/d. The drain receives also agriculture drainage water from agriculture sub drain. The drain length is about 7.7 km starts from the GAWWTP and discharge in Belbeis drain. This study focused in the first 7 km of the GAD. The objective of this study is to develop a hydrodynamic model for GAD and simulate the fate of residual pollutants from GAWWTP and subdrains to study the effect of velocity variation within the drain channel GAD using a water quality module. Delft3D-FLOW software was used firstly to develop the hydrodynamic model of the drain based on the historical geometric and hydraulic data. hereafter, Delft3D-WAQ was used to simulate the fate of residual pollutants in terms of Biochemical, chemical, etc. based on water quality measurements that were conducted from February to May 2023 in the field. The calibrated model was used to study the impact of the drain velocity on GAD water quality. Many scenarios have been conducted assuming that the capacity of GAWWTP is varied from 1 to 3.5 million m^3/ day, which these capacity refer to longitudinal velocity in GAD from 0.3 to 0.8 m/s. The results showed that as the velocity in the drain increased, the removal rate of BOD5, COD and TSS were decreased. The reduction of BOD5, COD and TSS were 33.56, 3.12 and 71.30 % respectively for scenario 1 where the velocity is 0.3 m/s, While the reduction of BOD5, COD and TSS was 12.29, 1.31 and 23.81 % respectively for scenario 6 where the velocity is 0.8 m/s.

KEYWORDS: hydrodynamic model, water quality model, calibrated model, Delft3D-FLOW, Delft3D-WAQ, fate.

تأثير السرعة على مصير الملوثات في مصرف الجبل الأصفر

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الملخص

يستقبل مصرف الجبل الأصفر (GAD) مياه الصرف الصحي المعالجة الثانوية من محطة معالجة مياه الصرف الصحي بالجبل الأصفر (GAWWTP). تبلغ الطاقة التصميمية للمحطة 2.5 مليون م^3/ يوم. ويستقبل الصرف أيضًا مياه الصرف الزراعي من المصارف الزراعية الفرعية. ويبلغ طول المصرف حوالي 7.7 كم , يبدأ من محطة معالجة مياه الصرف الصحي و وينتهي في مصرف بلبيس. ركزت هذه الدراسة على أول 7 كيلومترات من GAD. الهدف من هذه الدراسة هو تطوير نموذج هيدروديناميكي لـ GAD ومحاكاة مصير الملوثات المتبقية من GAWWTP والمصارف الفرعية وذلك لدراسة تأثير اختلاف السرعة داخل قناة الصرف GAD باستخدام نمذجة جودة المياه. تم استخدام برنامج Delft3D-FLOW أولاً لتطوير النموذج الهيدروديناميكي للصرف بناءً على البيانات الهندسية

والهيدروليكية التاريخية. وبعد ذلك، تم استخدام Delft3D-WAQ لمحاكاة مصير الملوثات المتبقية من حيث العناصر الكيمياء الحيوية والكيميائية وغيرها. بناءً على قياسات جودة المياه التي أجريت في الفترة من فبراير إلى مايو 2023 في الميدان. تم استخدام النموذج المعاير لدراسة تأثير سرعة التصريف على نوعية مياه GAD. تم إجراء العديد من السيناريوهات على افتراض أن قدرة محطة معالجة مياه الصرف الصحي تتراوح من 1 إلى 3.5 مليون م^3/ يوم، وتشير هذه السعة إلى السرعة الطولية في GAD من 0.3 إلى 0.8 م/ث. أظهرت النتائج أنه مع زيادة السرعة داخل المصرف، فانه ينخفض معدل إزالة BOD5 و COD و TSS. حيث كان مقدار الازالة في BOD5 و COD و TSS 33.56 و 3.12 و 71.30٪ على التوالي للسيناريو 1 حيث كانت السرعة 0.3 م / ث، في حين كان معدل الازالة في BOD5 و COD و TSS 12.29 و 1.31 و 23.81٪ على التوالي للسيناريو 6 حيث السرعة 0.8 م/ث.

الكلمات المفتاحية : النموذج الهيدروديناميكي، نموذج جودة المياه، النموذج المعاير، Delft3D-FLOW، Delft3D-WAQ، مصير.

1. INTRODUCTION

Egypt has been suffering from serious issues such population expansion, the development of new industries, and a water resources shortage and limited facilities for treating the reused water from agriculture, industry and domestic activities [1-2]. The contamination of water bodies by discharged the effluents of waste water treatment plants (WWTP) has been classified as an issue of global concern, based on the ecological and human health risks associated with exposure to toxic chemicals [3 -5]. As an illustration, the threat to aquatic life caused by significant amount of organic pollutants discharged into estuarine water that led to reduction of dissolved oxygen in the water caused by aerobic decomposition [6]. The potential negative effects of pollutants from sewage effluents on the receiving water quality are manifold and depend on the volume of the discharge, the chemical composition and concentrations in the effluent. Additionally, it depends on the nature of the discharge, such as the quantity of suspended solids, organic matter, or potentially dangerous contaminants like heavy metals and organochlorines, as well as the characteristics of the receiving waters [7]. Surface water contamination is being reduced through a variety of measures. One option of these measure is to construct and locate the sewage outfall appropriately, allowing for rapid dilution of pollutants in the water receiver and, as a result, rapid reduction in their concentration [8].

Numerical simulation for water quality is particularly beneficial for the sake of a better environment. The spatiotemporal dynamics and variability of water quality are predicted and simulated by numerical models. Modelling is also useful for assessing the success of water management strategies and guiding water quality improvement practices [9]. The first models of surface water were proposed by Lotka–Volterra and Streeter–Phelps in the 1920s. In the 1970s, these approaches and their variations were used more extensively in environmental management [10, 11]. In recent years, hydrodynamic and water quality models have been developed, AQUATOX, CE-QUAL-W2, Delft3D, EFDC, MIKE, and WASP are examples of popular models [9]. For Example, to understand the dependence of primary production on abiotic parameters, the authors of [12] applied a physical and water quality model to a shallow lagoon (Ria de Aveiro); [13] used a model to evaluate the impact of extreme river discharge on the dynamics of nutrients and dissolved oxygen in two nearby estuaries (the Lima and Minho Estuaries); [14] used a 3D hydrodynamic and water quality model to understand the factors affecting the distributions of nutrients and dissolved oxygen throughout the Danshuei River estuary system.

The present study focused on simulating hydrodynamic and water quality model of GAD. Applications of Delft3D modeling for the simulation of the hydrodynamic and water quality modelling have been reported in the literature [15 -21].

The objective of this work is to develop a hydrodynamic and water quality model of GAD and simulate the fate of residual pollutants from GAWWTP and sub-drains to study the effect of velocity variation within the drain channel GAD by using a water quality module. For this purpose, hydrodynamics and water quality status of the GAD were investigated by using the Delft3D-WAQ. The calibrated model was used to study impact the velocity on the fate of pollutants in GAD.

2. MATERIALS AND METHODS

2.1. DESCRIPTION OF THE STUDY AREA

The GAWWTP is the largest facility of its kind in not only in Africa but also in the Middle East. It is located at the government-owned farm of Gabal El-Asfar, which is located northeast of Cairo in the eastern desert. It is called Khankah district, in the Al-Qalyubia Governorate which is located at the south of the Nile delta, Egypt. The GAWWTP was constructed in subsequent stages, the current capacity of GAWWTP is 2.5 million m^3/d with a maximum design capacity 2.8 million m^3/d and a capability to serve almost 12 million people. The total capacity will be 3.5 million m^3/day at Project Stage III. The GAWWTP is located at altitude 20 meters above sea level with an area around the station with almost flat land with no slopes. The outfall of GAWWTP release its effluents into the GAD, which in turn flows into the main Belbeis drain through Belbis siphon that crosses Ismailia canal. After that, Belbeis and Qaliobia drains merge together, forming the main stream of the Bahr al-Baqar drain.

2.2. GEOMETRIC AND WATER QUALITY DATA

The bathymetry of the drain and boundary conditions are essential parameters for the hydrodynamic model. The Drainage Research Institute - National Water Research Center (DRI-NWRC) provided the data used for the model. The measurements from the Acoustic Doppler Current Profiler (ADCP) equipment were collected during the survey work as shown in **Figure 1**. **Figure 2** displays the measured sectors that were investigated for the different sections along the drain under study. The ADCP measures the behaviors in the water sector from the right edge to the left edge or vice versa, and among these behaviors is the speed and depth of the water in the waterway, so that the measurement of the water sector is repeated several times and then the arithmetic average of these behaviors is calculated. Thus, the cross-section of the stream has been drawn during the measurement process and the directions of the water current, as well as a summary of the measured velocities and water depth. **Figure 3** shows the cross-sections topographic surveys that were used for establishing the bathymetric of the drain under this study.

Figure 1: Velocities and bathymetry measurements at the six cross sections using ADCP device.

Figure 2: Google earth photo showing the locations of the six measured sections and the four subdrains.

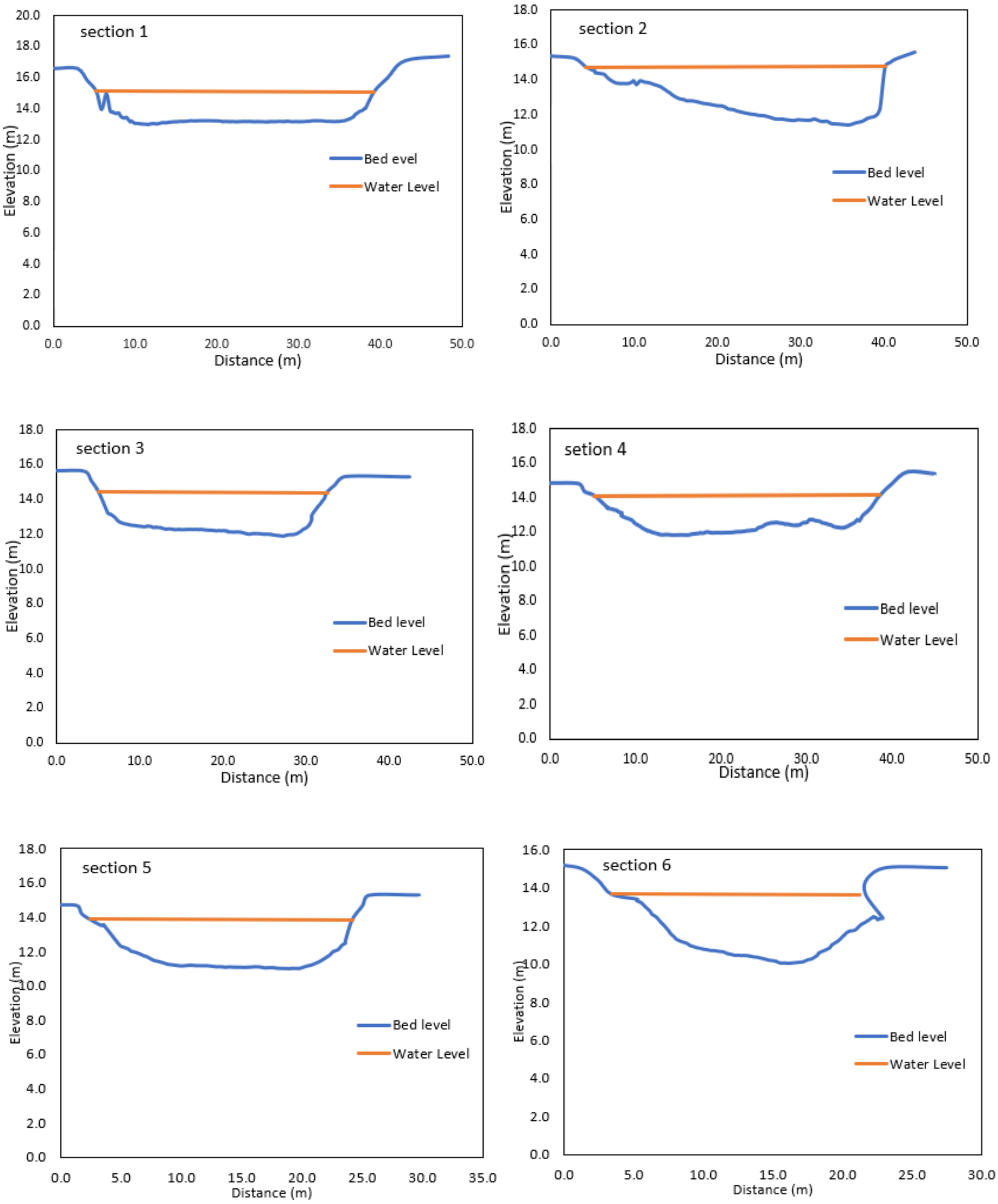

Figure 3: bathymetric survey of the six cross sections provided by (DRI-NWRC)

The water quality data for the six defined cross-sections along the GAD path and four sub drains locations shown in **Figure 1** were obtained from the field by collecting sample during four months period from February to May 2023. The collected samples were analyzed at the Central laboratory for environmental and water quality monitoring CLEQM, NWRC as shown in **Table 1**. This, presents the chemical laboratory for both suspended matter (TSS), biological oxygen consumed (BOD5), chemical oxygen demand (COD), Ammonium (NH4-N), Ammonia (NH3) and temperature.

Table 1-1: Water quality measurements from the field at six cross-sections and four sub drains along the Gabal El-Asfar drainage canal.

Station NO	Station m	Date	BOD5 mg/l	COD mg/l	TSS mg/l	NH3 mg/l	NH4-N mg/l	Temperature °C
Sub drain 1	1338	2/2023	67	768	155	1.5	37.5	16
		3/2023	119	1119	52	2.2	3.2	25
		4/2023	190	481	340	1.3	1.46	25
		5/2023	71	307	--	3	4.32	33
Sub drain 2	3567	2/2023	37	165	179	0.13	--	16
		3/2023	60	2526	448	2	2.8	25
		4/2023	10	198	27	0.38	0.46	25
		5/2023	25	967	--	0.15	0.216	33
Sub drain 3	4057	2/2023	397	877	227	16	--	16
		3/2023	500	926	276	8	11.5	25
		4/2023	--	--	--	--	--	25
		5/2023	464	771	--	11	15.84	33
Sub drain 4	6976	2/2023	49	81	34	12	192	16
		3/2023	70	83	39	15	21.6	25
		4/2023	85	119	33	16	19.5	25
		5/2023	50	81	--	16	23.04	33
Sec-1	1372	2/2023	25.8	119	34	12	17.3	16
		3/2023	140	178	22	15	21.6	25
		4/2023	100	132	10	15	18.3	25
		5/2023	66	74	--	15	21.6	33
Sec-2	3261	2/2023	23	134	19	11	15.8	16
		3/2023	120	218	58	15	21.6	25
		4/2023	120	238	16	15	18.3	25
		5/2023	65	76	--	15	21.6	33
Sec-3	4685	2/2023	34.7	165	9	11	15.8	16
		3/2023	130	248	49	15	21.6	25
		4/2023	70	147	20	15	18.3	25
		5/2023	60	85	--	15	21.6	33
Sec-4	5870	2/2023	25.3	151	7	12	17.3	16
		3/2023	140	220	63	15	21.6	25
		4/2023	120	221	30	15	18.3	25
		5/2023	55	61	--	15	21.6	33
Sec-5	6411	2/2023	35	126	5	12	17.3	16
		3/2023	140	210	34	15	21.6	25
		4/2023	100	313	48	15	18.3	25
		5/2023	74	94	--	15	21.6	33
Sec-6	6966	2/2023	23.6	145	4	12	17.3	16
		3/2023	150	208	41	0.24	21.6	25
		4/2023	80	310	31	15	18.3	25
		5/2023	66	86	--	15	21.6	33

2.3. NUMERICAL MODELING

In this study, hydrodynamics and water quality status of the GAD drainage canal were Carried out by using the Delft3D model. It is a quasi-two and three-dimensional modeling frameworks for simulating different physical, chemical and biological phenomena using several modules (Hydrodynamics – Water Quality – Waves – Morphology – Particle Tracking) at which the framework can be used to model complicated cases by coupling the results between these different modules [28 -31]. The main module is the hydrodynamic module, which shall run first, after that its results can be coupled to any of the other modules, except for the wave module, which can run separately independent of the flow module. In this study Delft3D-FLOW was used to develop the hydrodynamic model of GAD based on the historical geometric and hydraulic data, thereafter Delft3D-WAQ module coupled with the Delft3D-FLOW. The mathematical solution of Delft3D is based on the transformation of some partial differential equations to discrete equations. The hydrodynamic numerical solution of Delft3D solves the equations of motion in the horizontal direction, the continuity equation and the transport equations. The numerical modelling techniques and other mathematical formulations of Delft3D-FLOW are detailed in [28]. This research was performed using the Delft3D-FLOW and Delft3D-WAQ [29]. Delft3D-FLOW software was used to develop the hydrodynamic model of the GAD based on the historical geometric and hydraulic data. Then, Delft3D-WAQ was used to simulate the fate of residual pollutants in terms of BOD, COD, NH4 and TSS based on water quality measurement that were conducted in period from February to May 2023. Delft3D-WAQ model includes physical, biological, and chemical reactions and processes. It can be used to study bacterial pollution, eutrophication, heavy metal contamination, organic matter, and oxygen dynamics. Three nutrient cycles are covered in the module: silica, phosphorus, and nitrogen. The ANOVA technique is applied to compare the measured data and output parameter from WAQ-model

The inputs to the hydrodynamic model were created using the historical geometric and hydraulic data provided from the Drainage Research Institute (DRI) -National Water Research Center (NWRC); this was converted into a digital format that could be used by the Delft3D-FLOW module. **Figure 4** shows the bed levels at the starting point of the drainage canal was 14.00 m ASL and with a bed slope of 57 cm/km till reaching a bed level of 10.00 m ASL.

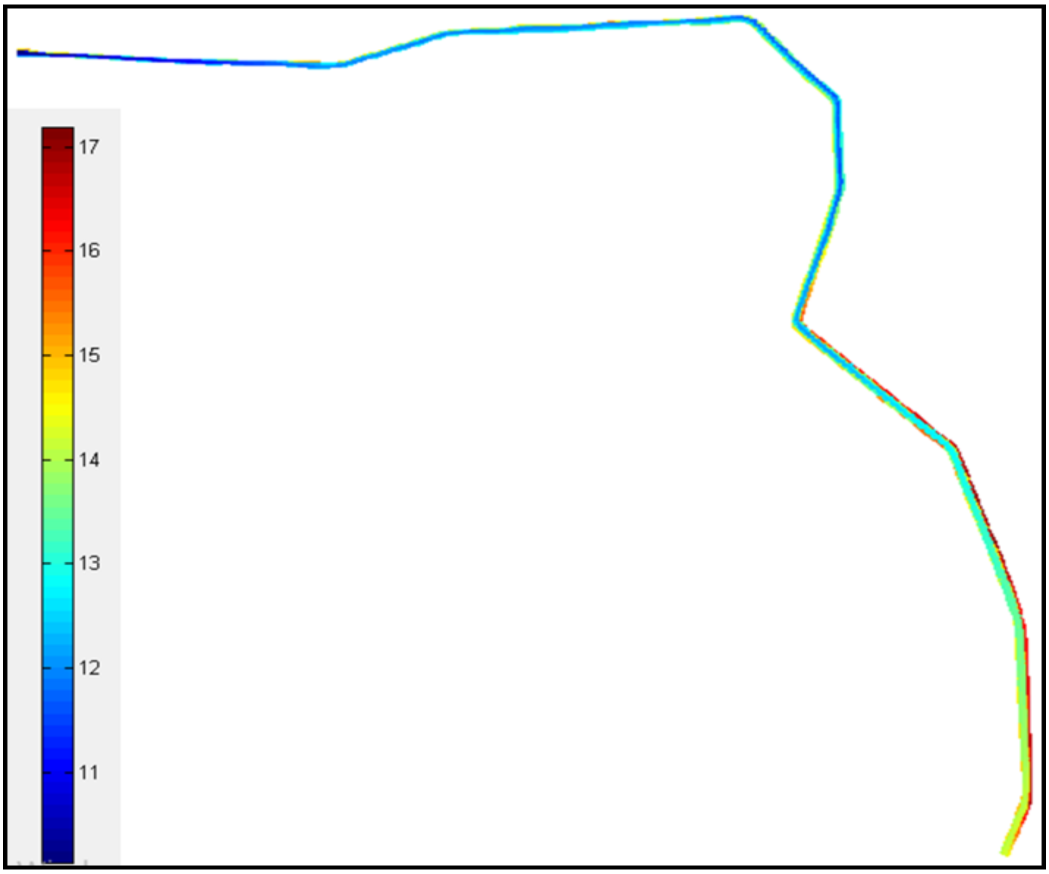

Figure 4: Delft3D showing bed level for the GAWWTP drainage canal

In order to describe the roughness of the GAD bottom, Manning coefficients 0.025 was used [28]. One of the most significant sources of water to GAD is GAWWTP and agriculture sub drains. The discharge value from sub drains to the GAD and the current flow for GAWWTP are shown in **Table 2**.

Table 1-2: water inflows to Gabal El-Asfar drain

Drain name	Discharge m^3/sec
Sub drain 1	1.70
Sub drain 2	0.062
Sub drain 3	1.00
Sub drain 4	0.754
GAWWTP	32.41

The calibration of the coupled hydrodynamic-water quality model was done in two stages; firstly, hydrodynamic model that was calibrated to adjust the model behavior concerning the water levels and water circulation from the sub-drains to GAD, once the model hydrodynamically was calibrated and the water quality module was coupled to the hydrodynamic module Water quality calibration was conducted to adjust the water quality simulation for GAD. Hydrodynamic calibration was conducted by comparison the depth average velocity over the six sections with the velocities measured at the site. It can be concluded that the values of both hydrodynamic model and measured data from the field are very close and shows minor difference, which indicate that the variance in the individual errors for each section is relatively small as shown the **figure 5**.

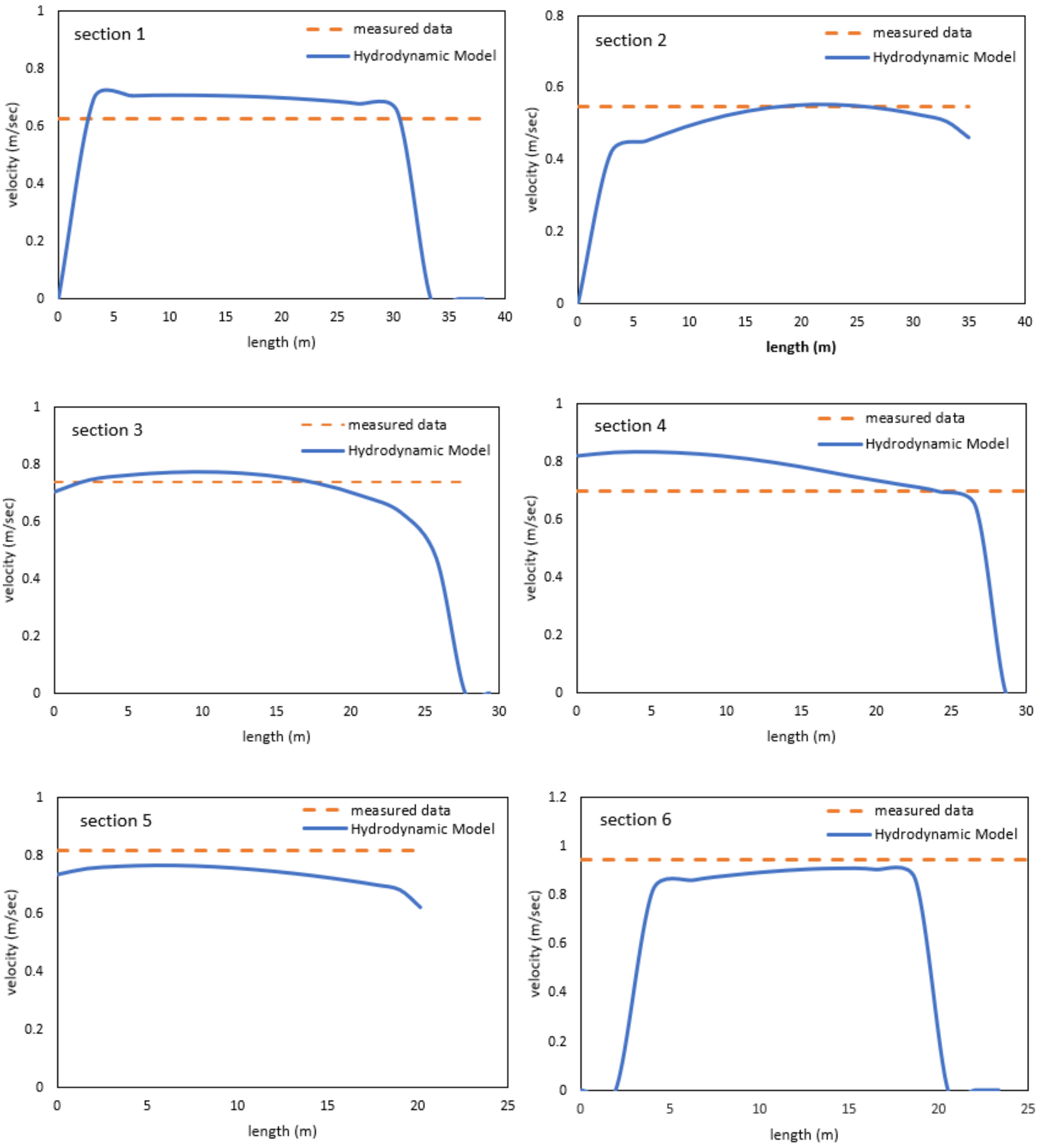

Figure 5: Comparison between the depth average velocity at the field and the model results for the six sections of the study area

The water quality calibration was conducting by adjusting the process parameters repeatedly and comparing the simulation results with the obtained water quality field measurements at the defined stations. **Table 3** presents the modelled substances and selected processes of the GAD water quality model. The calibrated state variables and process coefficients were shown in **Table 4**.

Table 1-3: Modeled parameters and processes of Gabal El-Asfar drain water quality model

Substance	Selected process
Dissolved oxygen	Uptake of nutrients Horizontal dispersion vertical dispersion Denitrification in water column Nitrification of Ammonium Reaeration of oxygen Oxidation/Mineralization of BOD5 and COD Mineralization of carbon in sediment Sediment oxygen demand
Ammonium	Uptake of nutrients Nitrification Mineralization detritus POC vertical dispersion Horizontal dispersion
BOD5	Mineralization Sedimentation vertical dispersion Horizontal dispersion
COD	Mineralization Sedimentation vertical dispersion Horizontal dispersion
TSS	Sedimentation vertical dispersion Horizontal dispersion

Table 1-4:State variables and process coefficients for the Delft3D-WAQ applied to Gabal El-Asfar drain

Process Parameter	Code	Value used	Value Range	Reference
Background Dispersion (m^2/s)	Dback	1	0-1000	[28]
Vertical Dispersion (m^2/s)	VertDisper	1	0.5	[22]
Ambient Water Temperature (°C)	Temp	20	-	from field data
First Order Denitrification Rate (1/d)	RcDenwat	0.1	0.1 0-0.1	[31], [23]
First Order Nitrification Rate (1/d)	RcNit	0.1	0.005-0.1 0-2	[24], [23; 31]
Wind Speed (m/s)	Vwind	4	-	from field data
Reaeration Transfer Coefficient (m/d)	KlRear	1	0.2-1000	[31]
Reaeration Temperature Coefficient (m/d)	TcRear	1.016	1.016-1.024 0.5–1.8	[31] [23; 24]
Rainfall Rate (mm/hr)	Rain	0.01	-	from field data
Decay Rate (BOD5) (1/d)	RcBOD5	0.3	0.05-0.4 0.02-0.5	[32] [33]
Decay Rate (COD) (1/d)	RcCOD	0.1	0.05-0.1 0-0.8	[31] [27]
First Order Mineralization Rate (1/d)	RcBOD5N	0.1	0.1-0.3	[22, 31]

A modeled output and measured data comparison was conducted with field measurements over a four-month during the period from February to May 2023. **Figures 6** present the average values and standard deviations of BOD5, COD, NH4-N and TSS at the six sections along the drain, which conclude that there is no significant difference between measured and model output.

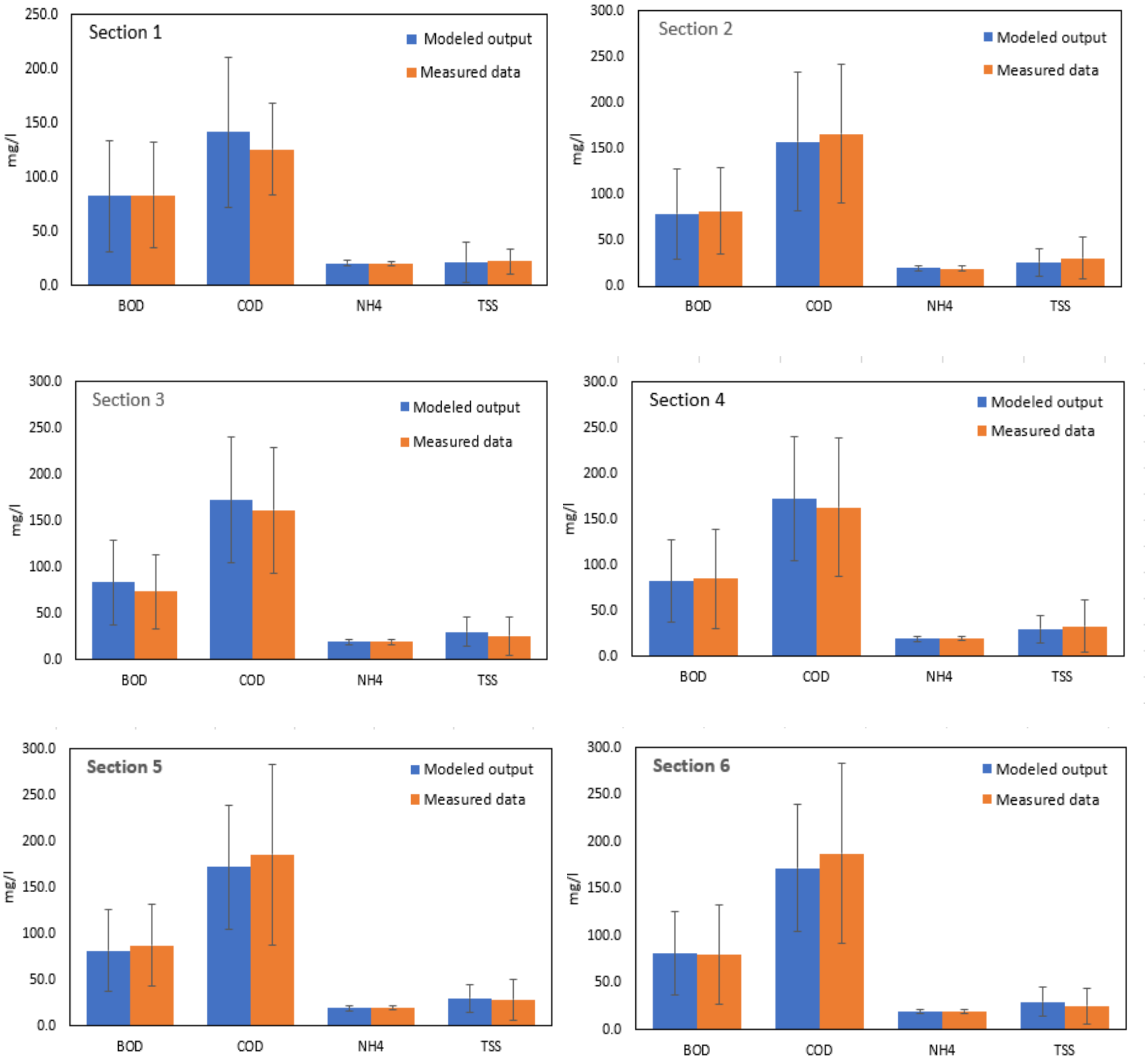

Figure 6: Average values and standard deviations of BOD5, COD, NH4-N and TSS at six sections along the drain

Variance between measured and output modeled data was studied using one-way ANOVA. The ANOVA technique applies to compare the measured data and output parameter from WAQ-model. If the p-value is less than 0.05, we reject the null hypothesis that there's no difference between the means and conclude that a significant difference does exist. If the p-value is larger than 0.05, that means there is no significant difference between measure and model output. **Table 5** showed the summary of ANOVA results, P-value for BOD5, COD, NH4-N and TSS. It was found that there is no significant difference between measure and model output.

Table 5: P-value of average measured and output modelled data for BOD5, COD, NH4-N and TSS

Section NO	BOD5	COD	NH4-N	TSS
1	0.98	0.71	0.74	0.97
2	0.94	0.87	0.87	0.79
3	0.75	0.82	0.97	0.78
4	0.93	0.87	0.85	0.87
5	0.86	0.82	0.85	0.95
6	0.97	0.81	0.87	0.76

3. RESULTS AND DISCUSSION

In order to understand the importance of studying the effect of velocity on GAD water quality, **Figure 7** present long profile for each parameter at February 2023 which the actual velocity in GAD was 0.66 m/s, the fate rate of BOD5 along the GAD is faster than COD and NH4-N. The sedimentation rate of TSS depends on the velocity of the water inside the drain.

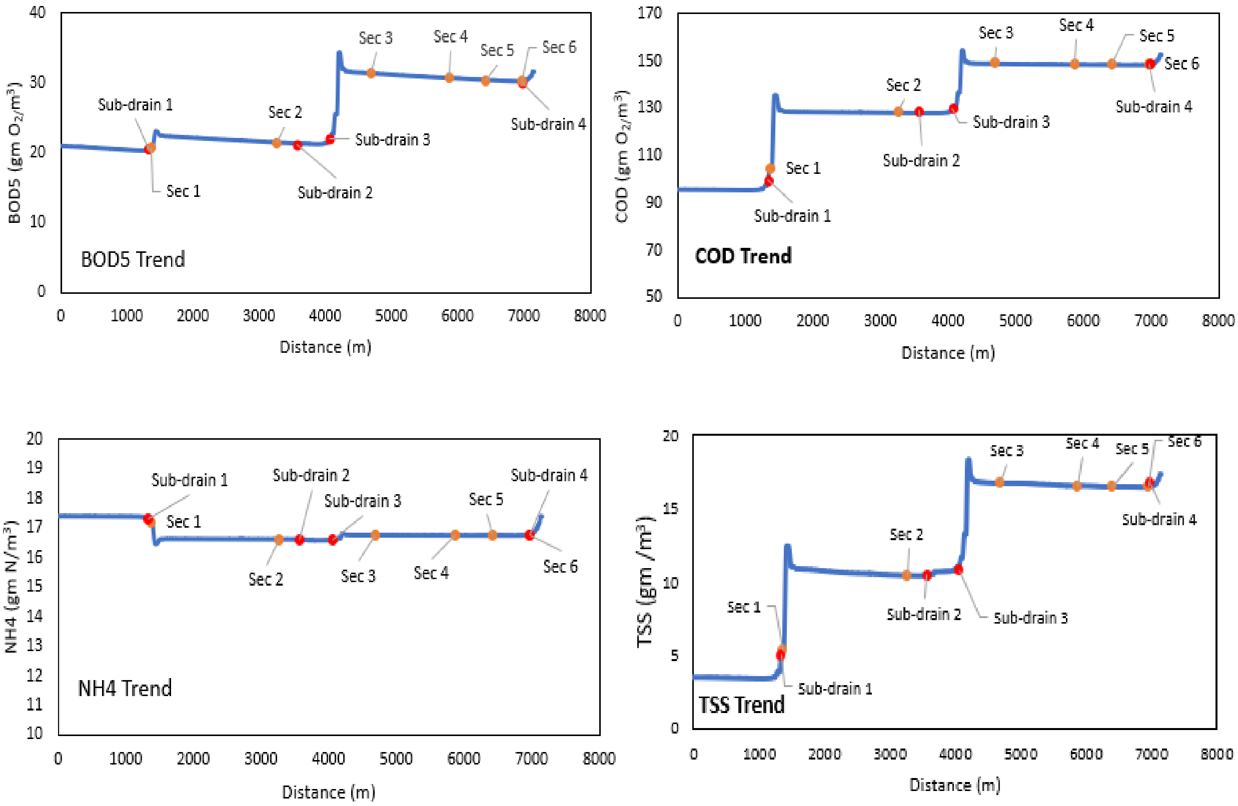

Figure 7: Long profile for each parameter at February 2023

The calibrated model was used to study the effect of velocity on GAD water quality. the capacity of GAWWTP will be increased in stage 3 to be 3.5 million m^3/d. regarding to Egyptian regulations for disposal of treated wastewater to receiving water the WWTP effluent is BOD5, COD and TSS 60, 80 and 50 mg/l respectively. Suggested scenarios to study the effect of velocity in the drain on water quality, assuming that the capacity of GAWWTP is varied from 1 to 3.5 million m^3/ day, which these capacity refer to longitudinal velocity in GAD from 0.3 to 0.8 m/s. **Table 6** summarizes the studied Scenarios. **Figures 8** shows BOD5, COD and TSS concentration trend along GAD for different velocity. The results showed, the reduction of BOD5, COD and TSS was 33.56, 3.12 and 71.30 % respectively for scenario 1 where the velocity is 0.3 m/s, While the reduction of BOD5, COD and TSS was 12.29, 1.31 and 23.81 % respectively for scenario 6 where the velocity is 0.8 m/s. The results concluded that as the velocity in the drain increased, the removal rate of BOD5, COD and TSS were decreased. **Table 7** summarized The results of the different scenarios which show the reduction of BOD5, COD and TSS for all scenarios.

Table 1-5: Proposed scenarios to study the impact of velocity change on water quality

Scenario	Longitudinal velocity m/s
Scenario 1	0.3
Scenario 2	0.4
Scenario 3	0.5
Scenario 4	0.6
Scenario 5	0.7
Scenario 6	0.8

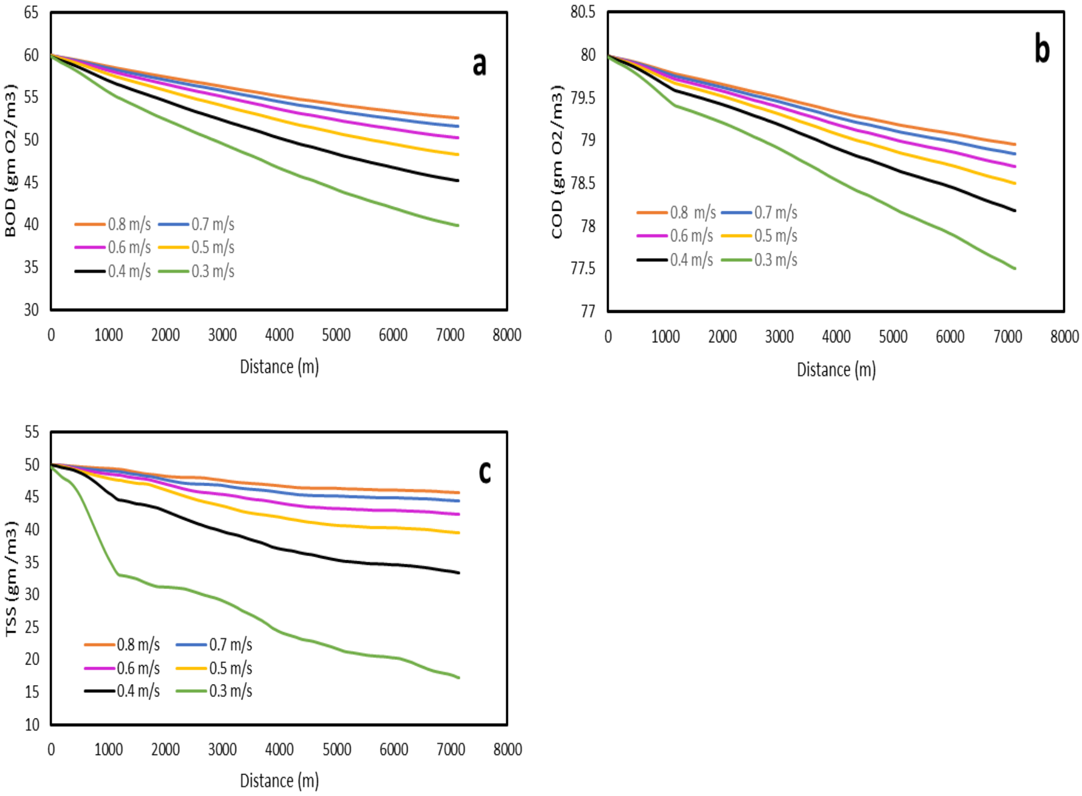

Figure 8: Long Profile for different velocity along GAD a BOD5 (mg/l) . b COD (mg/l). c TSS (mg/l)

Table 1-6: Reduction of BOD5, COD and TSS for different scenarios

Velocity m/s	Reduction %		
	BOD5	COD	TSS
0.3	33.56	3.12	71.30
0.4	24.72	2.28	44.56
0.5	19.55	1.88	34.14
0.6	16.29	1.62	29.43
0.7	13.97	1.44	25.88
0.8	12.29	1.31	23.81

4. CONCLUSIONS

- Delft3D is a useful tool for assessing the success of water management strategies and guiding water quality improvement practices. Delft3D-FLOW and Delft3D-WAQ are successfully able to model GAD from hydrodynamic and water quality point of views.
- The results showed that the values of both hydrodynamic model and measured data from the field are very similar with small difference. The results show that the depth average velocity for the measured and modeled at the end of the drain were 0.94 and 0.90 m/s respectively. The average measured values of the BOD5, COD, NH4-N and TSS at the end of drain were 79.9, 187.3, 19.7 and 25.3 mg/l and, modelled values were 81.1, 172.2, 19.4 and 30 mg/l, respectively.
- The fate rate of BOD5 along the GAD is faster than COD and NH4-N. The sedimentation rate of TSS depends on the velocity of the water inside the drain.
- The ANOVA technique is applied to compare the measured data and output parameter from WAQ-model, the ANOVA results concluded acceptable patterns compared to the field measurements. The P- values at end of drain for measured and output modeled data were 0.97 for BOD5, 0.81 for COD, 0.87 for NH4-N and 0.76 for TSS which means there is no significant difference between measure and model output.
- The calibrated model was used to study the impact of the drain velocity on the drain water quality.
- The results showed that as the velocity in the drain increased, the removal rate of BOD5, COD and TSS were decreased. The reduction of BOD5, COD and TSS were 33.56, 3.12 and 71.30 % respectively for scenario 1 where the velocity is 0.3 m/s, While the reduction of BOD5, COD and TSS was 12.29, 1.31 and 23.81 % respectively for scenario 6 where the velocity is 0.8 m/s.

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