Assessment of Water Quality of Taunsa-Panjnad (TP) Link Canal Using HEC-RAS

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Abstract

This paper investigates about water quality assessment system through the implementation of HEC-RAS 5.0.6. Due to rapid evolution, urbanization, mechanization, and over-population, the water demand has increased and the quality of water deteriorates year after year, leading to water-borne diseases and several other adverse effects. So, it is imperative to check the quality of the water as water plays an important role in our human society. Taunsa-Panjnad (TP) link canal, is a 62 km long canal, which was designed to deal with water scarcity at Panjnad headworks by diverting water from Mighty River Indus to river Chenab for irrigation purposes. To predict the values of some water quality parameters along TP link canal during a simulation period of twelve weeks, a water quality model was developed through the implementation of HEC-RAS 5.0.6 software. Such numerical water quality model (HEC-RAS) was developed to imitate different water quality parameters like algae, dissolve oxygen (DO), carbonaceous biochemical oxygen demand (CBOD), organic nitrogen, ammonium nitrogen, nitrite nitrogen, nitrate nitrogen, organic phosphorous and orthophosphate within the under-study reach of the TP link canal. Similarly, different sets of data were collected from previous studies for calibration & validation purposes of the model. The HEC-RAS software can be considered as a powerful tool to maintain the water quality of any water body as according to this study it delivers a successful and energy-efficient solution in water quality monitoring phenomena and if deviation of water quality parameters occurs, it also serves as an alarm for a remote user.

1 Introduction

Water, a prime natural resource, is the most basic need for mankind and both human life & the health of the environment depend on it. Recognizing the importance and scarcity of resources to meet biological needs and maintaining various economic and growth activities is a major issue. Constantly increasing population, industrialization, concentrated agricultural actions, industrialization, and urbanization resulted in a massive decline in freshwater availability during recent years. For industrial use, agricultural use, domestic use and to maintain a healthy and hygienic ecosystem, regular water quality monitoring of the water resources is essential. Using composite parameters to assess water quality can be a complex practice and raise any concerns about the overall water quality [1]. It is a quite difficult task to evaluate water quality because of various samples having accumulation of different constituents. Experimentally calculated parameter results and existing instructions are traditionally compared to evaluate water quality.

Taunsa Panjnad (TP) Link Canal having designed discharge 12000 cusecs at its head lead off from left flank of Mighty River Indus at Taunsa Barrage. Panjnad head works faced serious shortage of water supply as a result of operationalization of Indus-Basin Treaty between Pakistan and India. Taunsa-Panjnad Link Canal was constructed in early 1970’s under Indus Basin Replacement Works by WAPDA [2] and upon completion this link canal was handed over to Taunsa Barrage Division. This 62 km link canal diverts irrigation water from Mighty River Indus to river Chenab to cop up with the scarcity of water at Panjnad head works. TP Link Canal is fulfilling the desire water requirements since its construction and supplying water at Panjnad head works for 1.4 Million acres of fertile lands of District Bahawalpur and Rahim Yaar Khan. Similarly, such channel is maintaining water supply chain in southern Punjab and playing a prime factor role of sustainability of social as well as economic life of two Districts of southern Punjab. Likewise, TP link canal also provides supply to Rangpur canal at Head Muhammad Wala for District Muzaffargarh. In addition, such long channel has earthen prism and it runs in sand dunes in its course of alignment. Moreover, three cross regulators are provided in canal to maintain water levels in various reaches for stability of earthen prism of channel against sloughing as well as scouring.

Another challenge is to choose a suitable water quality model (WQM) because of the development of various WQMs such as QUAL series, SIMCAT, MIKE-11, HEC-RAS, WQRRS, WASP, MONERIS, etc. for the water quality assessment during the recent years and also each WQM has a different formulation and has its pros & cons. Critical parameters that must be simulated, the availability of input data, the model's use, the model's availability (public domain), and supporting materials (such as manuals) can be considered as a criterion in the selection of an appropriate WQM [3]. Water quality model selection is usually governed by the following factors: research aims, application of conclusions, target-related attributes of the system, required level of information (space and time), relevant chemical and physical processes, the calibration needs, accessibility of input information, past model experiences & scientific community approval, serviceability, susceptibility to the process of interest, time and resources at hand [4].

There are a number of well-known and extensively used software packages that incorporate physics-based equations, including the Hydrologic Engineering Centre-River Analysis System (HEC-RAS), developed by the US Army Corps of Engineers which is not only most extensively applied in the study-based literature but also in application as well [5]. Due to utilization of graphical user interface (GUI) in HEC-RAS 5.0.6, which standardizes several aspects of data entry, provides an efficient display of model outputs, and facilitates communication between sub-components of model, authors selected it for their research project. For water quality modeling data required includes; geometric data, flow data and water quality simulation data. In steady flow modeling, geometric data and flow data are both utilized which can be obtained from respective irrigation department. Water quality simulation data includes boundary conditions, initial conditions, meteorological data sets, and observed conditions. Meteorological datasets can be get from meteorological department while literature work and different testing can be utilized for the rest of the data required. Also modelled results and observed data are compared visually and quantitatively for the calibration and verification process of model.

HEC-RAS offers three types of modeling; Water temperature modeling, Nutrient simulation module (NSM-I) modeling and arbitrary constituent modeling. Authors opted NSM-I modeling for their water quality assessment research and it is also to be noted that water temperature modeling is compulsory for NSM-I modeling. With the help of NSM-I [6], due to biochemical reactions, kinetic processes and corresponding time rates of change of concentration can be determined separately. The NSM-I modeling consists of only those processes that deposit or transfer material onto the sediment bed, but the constituents which are already in the bed cannot be modelled through such modeling. The rate at which a kinetic process progresses is determined by the input of kinetic data from the users. The one of the benefits of NSM-I modeling is that aquatic water quality simulation can be conducted with the aid of simplified processes and minimum state variables because of the design of NSM-I. It simulates carbonaceous biological oxygen demand (CBOD), dissolved oxygen (DO), simplified nitrogen and phosphorus cycles, resulting in the additional state parameters such as organic nitrogen, ammonium nitrogen, nitrate nitrogen, nitrite nitrogen, organic phosphorus, orthophosphate, and algae.

In the present paper, the HEC-RAS (version 5.0.6) model was used to analyze the water quality of the Taunsa-Panjnad link canal. WQM was chosen in compliance with the proposed methodology [3]. HEC-RAS is an integrated system of software that was conceptualized for collaborative usage in a multi-tasking environment. It mimics the hydraulics of water flow in natural rivers and other channels. The main aims of the present study are to simulate the algae, DO, CBOD, ammonium nitrogen, organic nitrogen, nitrite nitrogen, nitrate nitrogen, organic phosphorous, and orthophosphate for a selected reach of the Taunsa-Panjnad link canal using the HEC-RAS model during twelve weeks' period, to determine the model's performance during water quality simulation and to assess the water quality in the understudy reach of the Taunsa-Panjnad link canal.

The study's objectives are as follows:

- To determine the current state of water quality by evaluating chosen water quality parameters such as algae, DO, CBOD, ammonium nitrogen, organic nitrogen, nitrite nitrogen, nitrate nitrogen, organic phosphorous, and orthophosphate.
- To compare the findings with the international research.
- To forecast the concentrations of specified water quality parameters from the simulation model, including algae, DO, CBOD, ammonium nitrogen, organic nitrogen, nitrite nitrogen, nitrate nitrogen, organic phosphorous, and orthophosphate.

The purpose of this work is to investigate and simulate several water quality parameters along the under-study length of the Taunsa-Panjnad link canal, as well as to forecast the water quality status.

2 Literature Review

At present observing and dealing with the water quality in the streams and canals is contemplated as a concerned issue as water is essential component for proper functioning of earth ecosystem. According to [7], incredibly expanded anthropogenic exercises and nonstop abuse of natural resources has immensely enhanced the pressure on accessibility of quality water, which further results in shortage of quality water for suitable operation of ecosystem. Similarly, it was found that both point source and non-point source can cause water contamination and municipal sewage & industrial effluent like heavy metals, hydrocarbons etc. are among mostly recognized point source whereas non-point source includes agriculture runoff. However, it is discovered that non-point source contamination is the principal reason for shabby water quality in aquatic systems when we constructed wastewater treatment plants for controlling the point source pollution. However, agriculture runoff that is a non-point source polluter causes the enrichment of streams and canals with the sedimentation of nitrogenous & phosphorous compounds and pesticides residues which causes surface water bodies to get eutrophicated [8].

According to [9], a systematic strategy of analyzing water quality and the consequences of human actions on streams and canals would be much problematic and quite expensive because when an issue in a fluid body is identified, there is huge possibility that it may have passed the point where it is possible to make a move to address it. Therefore, predicting the impacts of various practices on water quality in streams and canals using mathematical models can be considered a better solution as such approach involves immediate action prior to recognizing an issue, which might be extremely hard to determine subsequently. Water quality modeling is done through the implementation of a model using related software which predicts the location and value of pollutants through different mathematical techniques like finite difference method.

The HEC-RAS programme, created by the Hydrological Engineering Center (HEC) of the United States Army Corps of Engineers, is extensively used by researchers to predict both steady and unsteady circulation in rivers. The appropriateness of the HEC-RAS model for modelling water surface patterns for the river Jhelum, which flooded the whole valley of Kashmir [10]. Additionally, [11] also utilized the HEC-RAS model to characterize the hydraulic behavior of the Anambe River reach in Senegal, which is located between the convergence and Kounkane dams. For the purpose of determining channel roughness, the HEC-RAS model was contrasted to the hydraulic programme MIKE11 [12].

[13], with the help of HEC-RAS software developed a Water Quality Model in Bhima River located in India by gathering samples through dividing a 800 km study reach into five stations during 2017 and results were found within the permissible limits. For the upper reach of Al-Gharraf River that extended from Kut to Hay City a one-dimensional sediment transport model was developed through implementation of HEC-RAS software version 5.0.4. and sediment samples were collected from 13 equally distributed stations for a period extended from February 2019 to July 2019. Also one and two-dimensional unsteady-state hydraulic models were developed through the implementation of HEC-RAS program in the under-study reach of Al-Gharraf River that lies between Kut and Hay City. For the unsteady state in the river the Manning roughness value was estimated to 0.025 through calibration and validation of hydraulic models [14].

According to [15], from March 2018 to March 2019 various samples were gathered on monthly basis from a 59 km study reach consisting of five stations located between Qalat sukar and Shatrah Town to assess the water quality in Al- Gharraf River in Dhi Qar Governorate and it was found polluted in the selected region through analysis of collected samples. Water quality index for the Tigris River and its branches was assessed with the information of 27 parameters through principal component analysis (PCA) and it was classified as good for Diyala, poor for Al- Gharraf River, and bad for Shatt Al-Arab [16]. [17], conducted research for assessing the water quality in a mining- influenced watershed located in Colorado. To evaluate and compare the relationships between the TDS & TSS concentrations values, the watershed was divided into 14 stations. [18] investigated and developed the one-dimensional hydraulic model by implementing HEC-RAS software version 5.0.3 on the upstream section of Al Gharraf River and estimated the Manning roughness values for steady-state between 0.025 and 0.027 while for unsteady-state were ranged from 0.024 to 0.026.

To estimate sediment rate for the reach in Al-Gharraf River located between Al-Nasar City and Badaa Regulator, [19], developed an empirical formula using the SPSS program. Required information was gathered from 13 stations available on a 14 km reach under study. During 2013 & 2014, data of 17 parameters was gathered from five stations located on Al-Gharraf River for its WQI evaluation and its water was found poor for drinking & aquatic life but fair for irrigation [20]. Similarly, with the help of 11 parameters from the selected five-station that distributed along the river during 2015, the WQI for Al-Gharraf River was calculated and the CBOD annual values for the first three stations located between Kut and Hay City were found within the standard but such values for the last seven stations were not according to criteria whereas DO values, PO4 & NO3 values were within the accepted limits of Iraqi standards for river health [21].

[22], investigated water quality of Al- Gharraf River in Wasit province by studying a reach of length 50 km having five stations with a distance interval equal to 10 km during 2016 and the water quality samples were collected on monthly basis and determined its poor water quality. [23] researched about Al- Gharraf River Water's ability for different purposes by selecting seven stations for collection of samples along the river near the important cities for both the wet and dry seasons of 2017 and ascertained the availability of high concentrations of hardness due to the sewage discharge into Al-Gharraf River in these seven stations.

Geometric data was inputted to create the reach cross sections and required input during the concerned setup was a Manning's "n" value. Such value was based on the channel conditions according to field observance and corresponds to the channel's roughness coefficient. Also a typical roughness coefficient for an earth lined canal with sluggish flowing water, grass on the banks, & aquatic vegetation present is 0.030. HEC-RAS has been gaining popularity day by day for water quality analysis due to its compatibility and versatility. HEC-RAS model was employed to decide water quality in a river basin and to display the impact of bridge blockage and over bank flow on water stage variation [24]. It is quite difficult even for regulators and managers to determine water quality visually so, [25] employed HEC-RAS model to show the hydraulic behavior of Kirmir basin. For this purpose, 10 sampling stations have been designed for water quality monitoring in the Kirmir basin and the sampling procedure has been completed for a year between June 2012 and May 2013. For the collection of water samples under surface water that were stored in cooler box and transferred to DSI, air tight plastic bottles were employed. The aforesaid analytical findings were then evaluated to examine whether or not the parameters of water quality were allowed to lay in the limitations. Three variables are included in WQI, which vary between 0 and 100. Together these elements provide a single figure from 0 to 100 that reflect water quality from bad to high.

HEC-RAS model was chosen, aligned and approved utilizing two arrangements of noticed discharges, gate openings and water levels. Factual and graphical procedures were utilized for model assessment to build up its performance. [26] directed investigations on plan of river water quality monitoring networks, environmental modeling and created water quality management model for Karun. This model is a two-dimensional and performs calculations identified with steering water saltiness and quality and the balance of dissolved oxygen, ammonium, nitrates and different materials. Suspended load incorporates dregs moving above bed layer and their particular weight is conveyed by flow of water and are suspended in water for quite a while. The suspended burden and bed burden or bed material release and washed-load release together are called total sediment. All out dregs load is characterized as a total of bed load and suspended burden as bed material burden and alluvial burden when stream silt are low. In less profound rivers, total sediment load nearly equivalents to bed load while in profound streams, bed load is on recognitions simply 10 to 20% of total sediment.

The present research aims at assessing the water quality in Taunsa-Panjnad canal by calculating different parameters during different periods, which occurs by comparing these values with measured values for the accuracy of the implemented framework of HEC-RAS. The findings of the study will be useful to policymakers in developing their policies and local communities of the river delta for efficient utilization and management of water resources.

3 Methodology

3.1 Study Area:

Taunsa-Panjnad Link is an irrigation canal (class H - Hydrographic) in Punjab, Pakistan (Asia) with the region font code of Asia/Pacific and was completed in 1959. It is located at an elevation of 134 meters above sea level and links Indus River to Chenab River. Taunsa-Panjnad Link is also known as Taunsa-Panjnad Link Canal. Its coordinates are 30°36'0" N and 70°48'0" E in DMS (Degrees Minutes Seconds) or 30.6 and 70.8 (in decimal degrees) and its off-taking location is left bank canal of Taunsa Barrage. UTM position of this canal is XU78 and its Joint Operation Graphics reference is NH42-08. The length of TP link canal is 62 km having culturable command area (CCA) equal to 126000 acres and was designed for 14000 cusecs discharge. It was designed to ensure irrigation of the cultivated lands in the area of the Muzaffargarh & Dera Ghazi Khan Tehsil and is mainly responsible for supplying water to Panjnad headwork’s canals. The length of the study reach is taken equal to 1.5 km and the total length of selected reach is divided into seven stations and Fig. 1 below shows the layout of the link canal.

3.2 Water Quality Model:

Geometry data, hydraulic data, and water quality data are required for the development of water quality model (WQM). In this study, the WQM was simulated with the implementation of HEC-RAS software version 5.0.6. This section will describe the material data and used methods to develop WQM. While the most helpful are 3-dimensional models, they require vast data collection for the procedures of calibration and verification alone, leading to quite complicated models. In addition to complexity, unreliable outcomes of simulation might be encountered, since certain WQMs may contain parameters which have never been mentioned earlier in the literature, therefore one-dimensional or two-dimensional WQMs are the right alternatives. HEC-RAS was selected in this research after examination of several WQMs published in the literature. The model is used as a one-dimensional standard and resolves the dispersion equations using the numeric technique (explicit method). The HEC-RAS model has been selected to undertake modeling work for the same field scenario after an exhaustive examination of channel modeling research. These findings are compared with on-site data concerning the quality of water in order to measure the correctness of the simulation results of the model indicated above and to choose the ideal model for this field situation. The selected model is implemented in order to simulate numerous design scenarios and to anticipate the corresponding changes in water quality.

3.2.1 Geometry Data:

Geometric data within the study area of Taunsa Panjnad Link Canal is required for the simulation of the one-dimensional hydraulic model and it includes the coordinate data of the concerned canal and the survey data of available cross-sections.

3.2.2 The Steady Flow Data:

The type of flow regime and the suitable value of Manning's coefficient for the TP link canal decide the generation of flow profile, also it requires the hydrological data which includes the information of discharge and water levels. The flow regime type in TP link canal is subcritical flow and the Manning coefficient value for steady-state is equal to 0.015.

3.2.3 Water Quality Data:

The WQM requires the time-series of the temperature data of the TP link canal, chemical nutrient concentration such as CBOD, DO, NO_3, NO_2, organic phosphorous, organic nitrogen, orthophosphate, algae, ammonium nitrogen and also meteorological data such as (atmospheric pressure, air temperature, humidity, cloudiness, and wind speed). In the present study, seven stations were selected and separated along the TP link canal and the water quality data of the chemical nutrient concentration and temperature of the river at these were collected from previous studies. The meteorology datasets were taken from Pakistan Meteorological Department. Each meteorological dataset contains a time series of weather variations in the area of waterbody under study which includes air temperature, atmospheric pressure, solar radiation, cloudiness, wind speed and humidity.

3.3 HEC-RAS Model

The HEC-RAS model is often employed for the water quality assessment of the rivers or streams. As it is user friendly and does calculation in a very short interval of time, so, it is preferred over other softwares to determine water quality. For water quality modeling it utilizes nutrient modeling, temperature modeling and arbitrary constituents. The hydraulic flow is simulated before the water quality assessment in HEC-

RAS. The water surface profiles are calculated from one cross section to the next with the help of the following energy equation (i):

$Z_2 + Y_2 + (a_2V^2{}_2)/2g = Z_1 + Y_1 + (a_1V^2{}_1)/2g + h_e$ (i)
Where,

Z_1&Z_2 = elevation of the main channel inverts;

Y_1&Y_2 = depth of water at cross sections;

V_1&V_2 = average velocities;

a_1&a_2 = velocity weighting coefficients;

g = gravitational acceleration

h_e = energy head loss

The velocity weighting coefficients a_1&a_2 can be calculated based on the conveyance in the three flow elements: left overbank, right over bank, and channel. In addition, it can also be observed in terms of conveyance and area. For the water quality analysis, the transport and fate of contaminants are computed in HEC-RAS with the aid of the following advection- dispersion equation (ii):

$(\partial/\partial t)V\phi = (-\partial/\partial x)(Q\phi.\Delta x) + (\partial/\partial x)(\Gamma A (\partial\phi/\partial x)\Delta \pm S$ (ii)
Where,

V = volume of the water quality cell (m^3);

ϕ = water temperature (C) or concentration (kg/m^3);

Q = flow (m^3/s); Γ = user defined dispersion coefficient (m^2/s);

A = cross sectional area (m^2) and S = sources and sinks (kg/s).

The equation of water temperature (Heat) transport in source and sinks terms (HEC-RAS 2016) is shown as equation (iii);

Heat*(source/sink) = $(q_{net} \times As)/(\rho_{w*} c \rho_w \times V)$ (iii)
Where,

q net = the net heat flux located in the air-water interface (W/m^2),

ρ_w = water density (kg/m^3),

cp_w = Specific heat of water (J/kg℃),

As = surface area of cell (m^2),

V = The cell volume (m^3).

Also HEC-RAS has two assumptions in which the first one states that energy bed remains constant across the cross section while the other one states that velocity vector is at right angle to cross section.

3.4 Modeling – HEC-RAS

3.4.1 Channel Geometry:

HEC-RAS modeling utilized user inputs to specify the channel geometry and field measurements taken during the summer months decides the geometric data such as cross-sectional geometry, elevations, channel length, stream bank stations, and channel slope. The channel slope is calculated as 1/5000 $\frac{m}{m}$ for the selected reach. A total of seven locations are used in the initial formation of the steady flow model. The headwater was located at the station no 7, and the ending boundary was located at station no1. The additional locations used in the model corresponds with the sampling locations. The second step is to add an inline structure, a sluice gate, at the headwaters and its dimensions as well as the height of water are obtained in the field. A cross section interpolation is carried out in HEC-RAS to ignore instability and reduce errors which can be occurred because of large changes in velocity head or conveyance ratio. The reach is divided uniformly into 250 m intervals, creating a total of seven cross sections. The dispersion coefficient is set to a single value and is the final input to the channel geometry. The value is calculated in m^2/s, through the multiplication of a dimensionless coefficient, shear velocity, and mean channel depth together. Figures 2 & 3 show the one-dimensional river scheme in the geometry window of HEC-RAS software.

3.4.2 Steady Flow Inputs and Boundary Conditions:

To define a problem boundary conditions are practically required and, at the same time, of vital importance in computational fluid dynamics as the implementation of numerical methods and the resultant quality of measurements can critically be based on how those are numerically treated. The reach is simulated as steady flow to realistically model flow conditions. The obtained flow measurements are employed in the model and adjust the flow rate for the cross section which gives high measurement error. Using mass flow rate and specific conductivity concentrations is considered as a simplified additive procedure. The groundwater inputs may assess into the model right after the calibration of the steady channel hydraulic simulation which is the satisfaction of the observed water surface elevations with the simulated ones. Based on the elevation of the channel bottom at each location, the water surface elevation measurements are adjusted.

3.4.3 Surface Water Temperature Parameters:

Length of water quality cells, initial conditions, boundary conditions dispersion coefficient, and meteorological data are the five required user inputs. The length of water quality cells is set to 15 m and surface water temperatures are noted and entered, in degrees Celsius, as initial conditions for all of the sampling locations. The boundary conditions for the reach are used using observed data from only the most upstream and downstream locations as shown in the Table 1. For the entire under study reach, a fixed dispersion coefficient is employed. Phenomenon of heat transport from sources to sinks is employed by water temperature parameter in the model and its general equation is the same as equation (iii) and is written as;

$$\text{Heat*(source/sink)} = (q_{net} \times As)/(\rho_{w*} c\, \rho_w \times V) \quad \text{(iiv)}$$

Table 1 Boundary Conditions

	TP Link Canal ab 7 (Upstream)	**TP Link Canal ab 1 (Downstream)**
Water Temperature	24–32.5°C	24.5–33°C
Algae	4–5 mg/L	1.5–3 mg/L
Dissolved Oxygen	6–7 mg/L	4.5–5.5 mg/L
Carbonaceous BOD	14–16 mg/L	16–17 mg/L
Organic Nitrogen	0.2–0.35 mg/L	0.35–0.45 mg/L
Ammonium Nitrogen	0.05–0.065 mg/L	0.066–0.085 mg/L
Nitrite Nitrogen(NO_2)	0.075–0.23 mg/L	0.475–0.615 mg/L
Nitrate Nitrogen(NO_3)	0.4–0.6 mg/L	0.6–0.7 mg/L
Organic Phosphorus	0.1–0.2 mg/L	0.2–0.3 mg/L
Orthophosphate	0.045–0.055 mg/L	0.035–0.042 mg/L

3.4.4 Meteorological Datasets:

Hourly meteorological data was obtained from the Pakistan Meteorological Department, Multan, Punjab, Pakistan. Atmospheric pressure, air temperature, humidity, short wave radiation, cloudiness, & wind speed are all input parameters to the model and the final phase in the calibration process started right after the proper functioning of surface water temperature component of the model. The meteorological dataset that we used in this assessment is shown in the Table 2.

Table 2
Meteorological Datasets

Date	Atmospheric Pressure (mb)	Air Temp. (°C)	Humidity (0-100%)	Shortwave Radiation	Cloudiness (0–1)	Wind Speed (mph)
01-04-21 14:00	1001	34.7	24	7	0.11	7.3
01-05-21 14:00	998	36.2	19	8	0.1	9
02-06-21 14:00	997	41.6	26	9	0.11	9.1
02-07-21 14:00	999	43.4	33	9	0.16	9.8
03-08-21 14:00	998	40	38	8	0.16	9.8

3.4.5 Nutrient Modeling:

With the help of the Nutrient Modeling (NSM), the water quality analysis is simulated in HEC-RAS. In order to get the better understanding of the nutrient impacts, the calibrated hydraulic model was coupled with the water quality simulation. Water temperature, algae concentration, dissolved oxygen, carbonaceous BOD, organic nitrogen, ammonium, nitrite, nitrate, organic phosphorus, and orthophosphate are the input state variables required for the nutrient simulation. Water temperature, dissolved oxygen, ammonium, and nitrate are the values entered from field measurements. Based on multiple literature sources compiled, the remaining variables are estimated and summarized as user inputs. Boundary and initial conditions are both required for all ten variables and to simulate a conservative event or an extreme event two scenarios are produced. The conservative scenario, algae concentration of 2 mg/L, signifies availability of aquatic vegetation, and its possibility to exist at low concentrations. The extreme scenario, algae concentration of 8 mg/L, indicates not only aquatic vegetation but also high concentrations of algae availability as well.

Typical value of water temperature should not exceed from the typical range for water temperature in cold water stream should not be more than 20°C whereas for warm water stream it should not exceed 27°C. Non-compound and free oxygen concentration available in water or other liquids is known as dissolved oxygen. It is one of the most crucial metric in water quality assessment because of its impact on the living beings present in any waterbody. Suitable DO values lies between 0 & 16mg/L. As due to biological reasons the concentration of CBOD in canal water is greater than the concentration available in sample, so, the sample must be diluted before the incubation period for CBOD calculations. It is done by adding some quantity of water and also H_2SO_4 or NaOH is used to neutralize samples which have $pH < 6.5$ or > 8.5.

Observed concentrations of water quality parameters on the upstream and downstream stations can be shown in Table 3 & Table 4.

Table 3
Observed Concentrations of Water Quality Parameters on the Upstream Station

Date	Water Temp. (˚C)	Algae mg/L	DO mg/L	CBOD mg/L	Organic N mg/L	NH_4-N mg/L	NO_2-N mg/L	NO_3-N mg/L	Organic N mg/L	ortho-PO_4^{3-} mg/L
03-05-21 14:00	24.2	4.8	6.9	14.2	0.22	0.055	0.081	0.45	0.11	0.055
10-05-21 13:00	24.5	4.8	6.9	14.5	0.23	0.057	0.162	0.48	0.11	0.055
17-05-21 13:00	25	4.8	6.8	14.5	0.25	0.058	0.162	0.51	0.13	0.055
24-05-21 13:00	26.3	4.7	6.9	14.7	0.25	0.058	0.165	0.51	0.13	0.054
31-05-21 14:00	26.8	4.6	6.8	14.8	0.28	0.059	0.178	0.5	0.14	0.054
07-06-21 14:00	28.4	4.6	6.8	14.8	0.29	0.061	0.172	0.52	0.15	0.055
14-06-21 14:00	29.8	4.6	6.7	14.8	0.31	0.061	0.186	0.53	0.15	0.054
21-06-21 14:00	31.2	4.5	6.6	14.9	0.32	0.063	0.205	0.52	0.16	0.053
28-06-21 14:00	31.6	4.3	6.6	15.1	0.32	0.064	0.208	0.54	0.16	0.054
05-07-21 14:00	31.7	4.3	6.7	15.2	0.33	0.064	0.204	0.53	0.15	0.053
12-07-21 14:00	32	4.2	6.5	15.2	0.34	0.064	0.211	0.53	0.15	0.053
19-07-21 14:00	32.1	4.2	6.3	15.4	0.34	0.064	0.223	0.54	0.16	0.053

Table 4
Observed Concentrations of Water Quality Parameters on the Downstream Station

Date	Water Temp. (˚C)	Algae mg/L	DO mg/L	CBOD mg/L	Organic N mg/L	NH_4-N mg/L	NO_2-N mg/L	NO_3-N mg/L	Organic N mg/L	ortho-PO_4^{3-} mg/L
03-05-21 14:00	24.8	2.8	5.3	16.3	0.39	0.073	0.486	0.61	0.23	0.04
10-05-21 13:00	25.1	2.5	5.4	16.3	0.38	0.066	0.575	0.62	0.23	0.039
17-05-21 13:00	25.6	2.5	5.4	16.4	0.38	0.067	0.575	0.63	0.23	0.039
24-05-21 13:00	26.9	2.4	5.3	16.3	0.37	0.068	0.583	0.65	0.25	0.039
31-05-21 14:00	27.4	2.3	5.3	16.5	0.37	0.067	0.591	0.65	0.25	0.04
07-06-21 14:00	29	2.3	5.3	16.5	0.38	0.069	0.585	0.66	0.24	0.04
14-06-21 14:00	30.4	2.3	5.4	16.7	0.39	0.07	0.599	0.66	0.25	0.038
21-06-21 14:00	31.8	2	5.2	16.7	0.40	0.072	0.608	0.67	0.26	0.038
28-06-21 14:00	32.2	1.9	5.2	16.7	0.40	0.075	0.611	0.66	0.26	0.038
05-07-21 14:00	32.3	1.9	5.2	16.5	0.41	0.075	0.607	0.66	0.26	0.039
12-07-21 14:00	32.6	1.9	4.9	16.5	0.42	0.078	0.614	0.67	0.25	0.037
19-07-21 14:00	32.7	1.7	4.7	16.9	0.44	0.08	0.577	0.67	0.27	0.037

3.5 Model Calibration:

During the field work and data analysis, it is observed that storm events impacts the model profoundly. Such events not only cause large errors in the water surface elevation but also negatively impacts the calibration of model and to assure that simulation only includes low flow conditions, such events can be excluded with the aid of a common practice of waiting a minimum of three days after a storm event. In our case, simulation time frame is 1 week. The duration is opted since it is not impacted by precipitation events, and discrete flow measurements can be taken. And through the prediction of low flow water surface elevations in the reach, above measure advances the research towards the completion of the model calibration. So, we compared the observed data values of water quality parameters with simulated ones from the results during the same simulation period for calibration of our water quality model. And for this purpose root mean square value (RMSE) has been computed as it tells us about the performance and accuracy of the model and it is calculated with the help of following formula;

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n} (Pi - Oi)^2}{n}}$$

Here;

O_i = Observed values

P_i = Predicted or simulated values

n = number of measurements

Table 5
RMSE Results

Parameter	RMSE	Parameter	RMSE
Water Temperature	0.070711	Ammonium Nitrogen	0.001678
Algae	0.304138	Nitrite Nitrogen	0.059161
Dissolve Oxygen	0.158114	Nitrate Nitrogen	0.1
CBOD	0.257391	Organic Phosphorous	0.048
Organic Nitrogen	0.02	Orthophosphate	0.001275

3.5.1 Comparison of computed RMSE with international study

According to [27] & [28], a good calibrated model is the one which have RMSE value less than 0.5 mg/L and as in our case RMSE values for all water quality parameters, as shown in Table 5, are less than 0.5 mg/L, so, our WQM validation is good and we can proceed with it to assess of quality of water in the under-study reach of the TP link canal.

4 Results And Discussion

With the aid of collected data of nutrients (Algae, DO, CBOD, Organic nitrogen, Ammonium nitrogen, Nitrite nitrogen, Nitrate nitrogen, Organic phosphorous, Orthophosphate) from previous studies in the selected seven stations distributed along the Taunsa-Panjnad link canal, the WQM was calibrated. According to the final computed profile, the highest channel depth at the upstream station of reach was 3.34 m and the lowest channel depth at the downstream station of reach was 3.16m. In addition to this, the highest velocity and velocity head were observed at the downstream station of reach having values equal to 1.50 m/s and 0.11 m whereas at the upstream station of reach velocity was 1.41 m/s and velocity head was 0.10 m. Table 6 is showing the comparison of observed and computed concentrations of water quality parameters at the upstream and downstream stations of under-study reach.

Table 6
Observed and Computed concentrations at the U/S & D/S stations

Parameters	**Observed Value**		**Computed Value**	
	Upstream	**Downstream**	**Upstream**	**Downstream**
Water temperature	24.2	24.8	24.3	24.8
Algae	4.8	2.8	4.55	3.15
Dissolved Oxygen (DO)	6.9	5.3	6.75	5.4
CBOD	14.2	16.3	14.55	16.2
Organic Nitrogen	0.22	0.39	0.24	0.37
Ammonium Nitrogen	0.055	0.073	0.055	0.0705
Nitrite Nitrogen NO_2	0.081	0.486	0.090	0.470
Nitrate Nitrogen NO_3	0.45	0.61	0.455	0.585
Organic Phosphorus	0.11	0.23	0.115	0.220
Orthophosphate	0.055	0.04	0.0540	0.0415

As a result of simulation, two different types of plots have been observed;

- Water quality spatial plots
- Water quality time series plots

4.1 Water Quality Spatial Plots

From water quality spatial plots we can compare the concentrations of algae, DO, CBOD, organic nitrogen, ammonium nitrogen, nitrite nitrogen, nitrate nitrogen, organic phosphorous and orthophosphate present on upstream station of under-study reach with the ones present on downstream station of reach and we can also compare these concentrations with their permissible range values. Actually such plots tell us about the variations along the length of the channel reach.

From Figs. 4 to 13, it can be seen that the values of water temperature, CBOD, organic nitrogen, ammonium nitrogen, nitrite nitrogen, nitrate nitrogen & organic phosphorous continue to increase towards the lower part of TP link canal while algae, DO & orthophosphate concentrations continue to decrease towards its lower part. Therefore, it can be inferred from the results that water quality is continuously getting polluted from upstream to downstream station. However, according to [29], [30] & [31] the concentrations of all the concerned water quality parameters were within the permissible ranges for both upstream and downstream locations except ammonium nitrogen.

4.2 Water Quality Time Series Plots

The process of canal assessment requires representing the canal during different possible operational flowrate for different periods. In this study, the WQM was simulated during the three months' period using the measured flowrate values for the selected reach of TP link canal. Following figures show the time series variation of concentration of water temperature, algae, DO, CBOD, organic nitrogen, ammonium nitrogen, nitrite nitrogen, nitrate nitrogen, organic phosphorous and orthophosphate respectively on the upstream station of under-study reach of TP link canal during the 12 weeks' period extended from May 03, 2021 to July 19, 2021.

The Figs. 14 to 18, show the time series variation of the water temperature, algae, DO, CBOD, organic nitrogen, ammonium nitrogen, nitrite nitrogen, nitrate nitrogen, organic phosphorous and orthophosphate concentrations on the upstream station of the under-study reach during the simulation period of 12 weeks extended from May 03, 2021 to July 19, 2021. It can be observed from the figure that water temperature, CBOD, organic nitrogen, ammonium nitrogen, nitrite nitrogen, nitrate nitrogen & organic phosphorous concentrations continue to increase as time increases while algae, DO & orthophosphate concentrations continue to decrease as time increases. So, it can be inferred that water quality is decreasing as time increases.

5 Conclusions

HEC-RAS model is employed for analyzing and projecting variations in concentrations of water quality parameters in twelve-week period extended from May 03, 2021 to July 19, 2021. In this study one dimensional steady flow analysis was carried out for under-study reach of Taunsa-Panjnad link canal. The validity of HEC-RAS model is confirmed through the stable and consistent simulated results. The modeling strategies explored in this study can be applied to a wide range of waterbodies around the globe for the purpose of water quality assessment.

Water having **4–8 mg/L** DO is considered good while in under-study reach of TP link canal it ranges between **5.4–6.85 mg/L**. Likewise, acceptable water quality demands orthophosphate concentration **less than 3 mg/L** and in our reach it varies as **0.0415–0.0540 mg/L.** So, for now DO and orthophosphate parameters for the concerned assessment lies within the satisfactory range.

In addition to this, water quality spatial and time series plot it is concluded that algae, DO & orthophosphate concentrations continue to decrease from not only upstream station to downstream station of channel reach but also during the simulation period as well. Also according to international research, water quality decreases as DO & orthophosphate concentration decreases, so, regular monitoring is essential and suitable measures must be taken to maintain DO and orthophosphate concentrations within satisfactory ranges in the future.

Water quality is considered acceptable if CBOD **< 10 mg/L**, organic nitrogen **< 15 mg/L**, ammonium nitrogen **< 0.5 mg/L**, nitrite nitrogen **< 1 mg/L**, nitrate nitrogen **< 10 mg/L** and organic phosphorous **< 0.1 mg/L**. In our case CBOD varies as **14.3–16.2 mg/L**, organic nitrogen ranges as **0.23–0.37 mg/L**, ammonium nitrogen ranges as **0.055–0.071 mg/L**, nitrite nitrogen varies as **0.09–0.47 mg/L**, nitrate nitrogen lies in the range **0.455–0.585 mg/L**, and organic phosphorous ranges between **0.115–0.228 mg/L**. Immediate actions must be taken to control CBOD and organic phosphorous concentrations in the concerned reach.

Similarly, a continuous increase in the concentrations of CBOD, organic nitrogen, ammonium nitrogen, nitrite `nitrogen, nitrate nitrogen & organic phosphorous is noted not only during the simulation period but also from upstream station to downstream station of channel reach as well. And according to previous research, increase in concentrations of above mentioned water quality parameters results in deterioration of water quality of any waterbody. To sum up, at present only CBOD and organic phosphorous parameters require suitable measures to bring their concentrations back within satisfactory range but other parameters also need regular monitoring as they are facing gradual increments towards forbidden limits.

6 Recommendations

In this research we applied water temperature modeling and NSM-I modeling in HEC-RAS for water quality assessment of Taunsa-Panjnad link canal using twelve weeks as simulation period. Our reason for opting such simulation period was limitations due to COVID-19 pandemic. Moreover, other researchers can employ the same modeling by increasing the simulation period for better results. Soil erosion, deforestation, improper waste management, overgrazing, lack of awareness in management, etc. may result in contamination of water. Various suitable techniques can be employed to further study their effects on contamination of water.

Declarations

Author's Declaration

We hereby declare that we are the soul authors of this thesis. To the best of our knowledge, this thesis contains no facts previously published by any other person except where due acknowledgment has been made.

Funding

Not applicable.

Conflicts of interest

Not applicable.

Data availability

The datasets generated during and/or analyzed during the current study are available from the corresponding author on reasonable request.

Code availability

Not applicable.

Author's Contributions

AL conceived the original idea and supervised the project. ZA, TH, MH and SK developed the theory and decided about the methodology. TH and SK gathered all the required data. AL, ZA and MH developed the model and planned & carried out the simulations. ZA and MH contributed to the interpretation of the results. All authors provided critical feedback and helped shape the research, analysis and manuscript.

References

1. M. E. Goher, A. M. Hassan, I. A. Abdel-Moniem, A. H. Fahmy, and S. M. El-Sayed, “Evaluation of surface water quality and heavy metal indices of Ismailia Canal, Nile River, Egypt,” *Egypt. J. Aquat. Res.*, vol. 40, no. 3, pp. 225–233, 2014, doi: 10.1016/j.ejar.2014.09.001.
2. A. Hayat Khan, “Water Sharing Dispute in Pakistan: Standpoint of Provinces,” *Berkeley J. Soc. Sci.*, vol. 4, p. 17, 2014, [Online]. Available: http://www.sanalist.org/kalabagh/a-19.htm.
3. A. Chinyama, G. M. Ochieng, I. Nhapi, and F. A. O. Otieno, “A simple framework for selection of water quality models,” *Rev. Environ. Sci. Biotechnol.*, vol. 13, no. 1, pp. 109–119, 2014, doi: 10.1007/s11157-013-9321-3.
4. B. Engel, D. Storm, M. White, J. Arnold, and M. Arabi, “A HYDROLOGIC ⁄ WATER QUALITY MODEL APPLICATION PROTOCOL 1,” *JAWRA-Journal-of-the-American-Water-Resources-Association-1752-1688*, vol. 43, no. 5, 2008, doi: 10.1111/j.1752-1688.2007.00105.x.

5. O.-A.-A. K, "Analyzing of Flow in Open Channels Networks Using HEC-RAS," *J. Ecol. Nat. Resour.*, vol. 2, no. 4, pp. 1–7, 2018, doi: 10.23880/jenr-16000136.
6. Z. Zhang and B. E. Johnson, "Application and Evaluation of the HEC-RAS-Nutrient Simulation Module (NSM I)," *Ecosyst. Manag. Restor. Res. Progr.*, no. June, p. 19, 2014.
7. A. K. Afeta, "Assessing Relationships between Stream Water Quality and Watershed Attributes Using the SWAT2000 Integrated Watershed ModelA Case Study in the Rönne River Basin, Sweden," p. 95, 2006.
8. S. O. F. Nutrien, F. The, C. Of, W. Durgesh, and K. Singh, "ASSESSMENT OF NUTRIENT LOADING IN LAKE RINGSJÖN FROM THE CATCHMENT OF HÖRBYÅN CREEK IN SOUTHERN SWEDEN Durgesh," 2013.
9. Q. Wang, S. Li, P. Jia, C. Qi, and F. Ding, "A review of surface water quality models," *Sci. World J.*, vol. 2013, 2013, doi: 10.1155/2013/231768.
10. H. F. Ahmad, A. Alam, M. S. Bhat, and S. Ahmad, "One Dimensional Steady Flow Analysis Using HECRAS – A case of River Jhelum, Jammu and Kashmir," *Eur. Sci. Journal, ESJ*, vol. 12, no. 32, p. 340, 2016, doi: 10.19044/esj.2016.v12n32p340.
11. B. Traore, S. Sambou, H. Sambou, and A. T. Diaw, "Steady flow simulation in Anambe river basin using Hec-RAS," *Int. J. Dev. Res.*, vol. 5, no. 7, pp. 4968–4979, 2015.
12. L. A. M. Saleh, S. A. A.-D. Majeed, and H. H. Algretawee, "Analysis of the Euphrates River's movement within Al-Hindiya, Karbala, relative to steady flow conditions using the HEC-RAS model," *IOP Conf. Ser. Mater. Sci. Eng.*, vol. 1067, no. 1, p. 012081, 2021, doi: 10.1088/1757-899x/1067/1/012081.
13. P. D. Taralgatti, R. S. Pawar, G. S. Pawar, M. H. Nomaan, and C. R. Limkar, "Water Quality Modeling of Bhima River by using HEC-RAS Software," *Int. J. Eng. Adv. Technol.*, vol. 9, no. 3, pp. 2886–2889, 2020, doi: 10.35940/ijeat.b3481.029320.
14. B. S. Abed, M. H. Daham, and H. A. Al-Thamiry, "Assessment and modelling of water quality along Al-Gharraf River (Iraq)," *J. Green Eng.*, vol. 10, no. 12, pp. 13565–13579, 2020.
15. K. H. Al-Husseini and I. M. A. Alsalman, "Quarterly variation and their impact on phytoplankton dynamics in the Gharraf River environment in southern Iraq," *Plant Arch.*, vol. 20, pp. 1354–1360, 2020.
16. S. H. Ewaid, S. A. Abed, N. Al-Ansari, and R. M. Salih, "Development and evaluation of a water quality index for the Iraqi rivers," *Hydrology*, vol. 7, no. 3, pp. 1–14, 2020, doi: 10.3390/HYDROLOGY7030067.
17. B. A. Butler and R. G. Ford, "Bewertung der Beziehungen zwischen der Gesamtsumme gelöster Feststoffe und der gesamten Schwebstoff-Fracht in einem bergbaubeeinflussten Wassereinzugsgebiet," *Mine Water Environ.*, vol. 37, no. 1, pp. 18–30, 2018, doi: 10.1007/s10230-017-0484-y.
18. A.-I. Y. Mohammed, A. N. Arrar, and A. A.-H. Abed, "Roughness Characteristics Of Kut-Hay Reach Of The Gharraf River And Its Impact On The Hay Regulator," *Assoc. Arab Univ. J. Eng. Sci.*, vol. 25, no. 5, pp. 607–622, 2018.

19. J. S. Maatooq, H. A. Omran, and H. K. Aliwe, “Empirical Formula for Estimation the Sediment Load in Shat AL-Gharaf River,” *Basrah J. Eng. Sci.*, vol. 16, no. 1, pp. 38–41, 2016, [Online]. Available: https://www.iasj.net/iasj?func=fulltext&aId=133214.
20. S. H. Ewaid and S. A. Abed, “Water quality index for Al-Gharraf River, southern Iraq,” *Egypt. J. Aquat. Res.*, vol. 43, no. 2, pp. 117–122, 2017, doi: 10.1016/j.ejar.2017.03.001.
21. S. H. Ewaid, “Water quality evaluation of Al-Gharraf river by two water quality indices,” *Appl. Water Sci.*, vol. 7, no. 7, pp. 3759–3765, 2017, doi: 10.1007/s13201-016-0523-z.
22. N. N. M. and M. R. Nashaat, “Journal of Research in Nursing,” *J. Res. Nurs.*, vol. 6, no. 2, 2018.
23. M. A. Al-dabbas, A. M. Al-shamma, and K. G. Al-mutawki, “Evaluation of Gharraf River Water for different Uses, South Iraq,” *Iraqi J. Sci.*, vol. 59, no. 3C, pp. 1697–1709, 2018, doi: 10.24996/ijs.2018.59.3c.15.
24. Y.-J. C. Kwan Tun Lee and Yao-Hsien Ho, “Bridge Blockage and Overbank Flow Simulations Using HEC – RAS in the Keelung River during the 2001 Nari Typhoon,” *Journal-of-Hydraulic-Engineering-0733-9429*, no. March, pp. 319–323, 2006, doi: http://dx.doi.org/10.1061/(ASCE)0733-9429(2006)132:3(319).
25. W. Sun, C. Xia, M. Xu, J. Guo, and G. Sun, “Application of modified water quality indices as indicators to assess the spatial and temporal trends of water quality in the Dongjiang River,” *Ecol. Indic.*, vol. 66, pp. 306–312, 2016, doi: 10.1016/j.ecolind.2016.01.054.
26. M. Delphi, M. M. Shooshtari, and H. H. Zadeh, “Sensitivity Analysis of Sediment Transport in Karun River,” vol. 1, no. 3, pp. 221–224, 2010.
27. C. Giardino, V. E. Brando, A. G. Dekker, N. Strömbeck, and G. Candiani, “Assessment of water quality in Lake Garda (Italy) using Hyperion,” *Remote Sens. Environ.*, vol. 109, no. 2, pp. 183–195, 2007, doi: 10.1016/j.rse.2006.12.017.
28. S. Kim, D. J. Seo, H. Riazi, and C. Shin, “Improving water quality forecasting via data assimilation - Application of maximum likelihood ensemble filter to HSPF,” *J. Hydrol.*, vol. 519, no. PD, pp. 2797–2809, 2014, doi: 10.1016/j.jhydrol.2014.09.051.
29. A. C. C. Bowie, G., W. Mills, D. Porcella, C. Campbell, “Rates, Constants, and Kinetics Formulations In Surface Water Quality Modeling (Second Edition).” .
30. A. E. Edet and O. E. Offiong, “Evaluation of water quality pollution indices for heavy metal contamination monitoring. A study case from Akpabuyo-Odukpani area, Lower Cross River Basin (southeastern Nigeria),” *GeoJournal*, vol. 57, no. 4, pp. 295–304, 2002, doi: 10.1023/B:GEJO.0000007250.92458.de.
31. A. H. M. J. Alobaidy, H. S. Abid, and B. K. Maulood, “Application of Water Quality Index for Assessment of Dokan Lake Ecosystem, Kurdistan Region, Iraq,” *J. Water Resour. Prot.*, vol. 02, no. 09, pp. 792–798, 2010, doi: 10.4236/jwarp.2010.29093.

Figures

Figure 1

Under-study reach of TP link canal

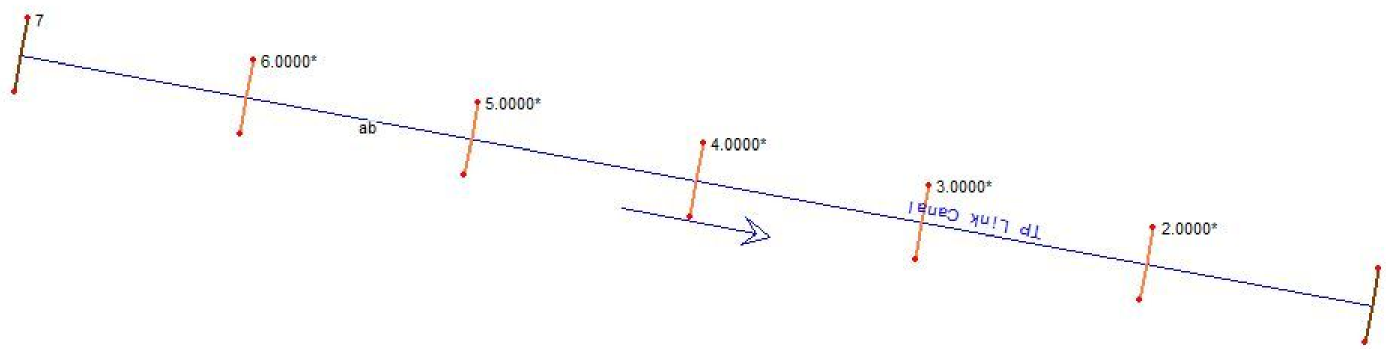


Figure 2

Channel Reach Schematic Diagram

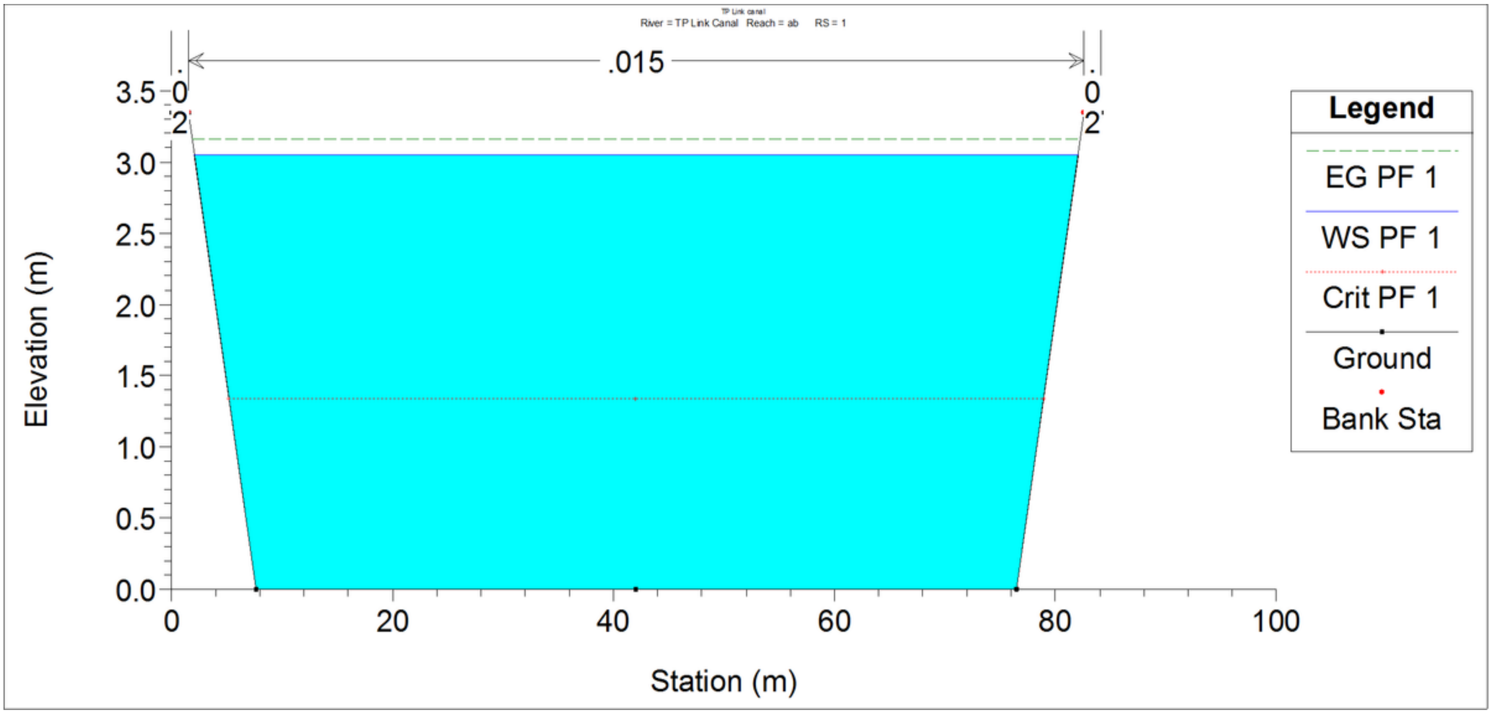


Figure 3

Downstream Station Cross-section

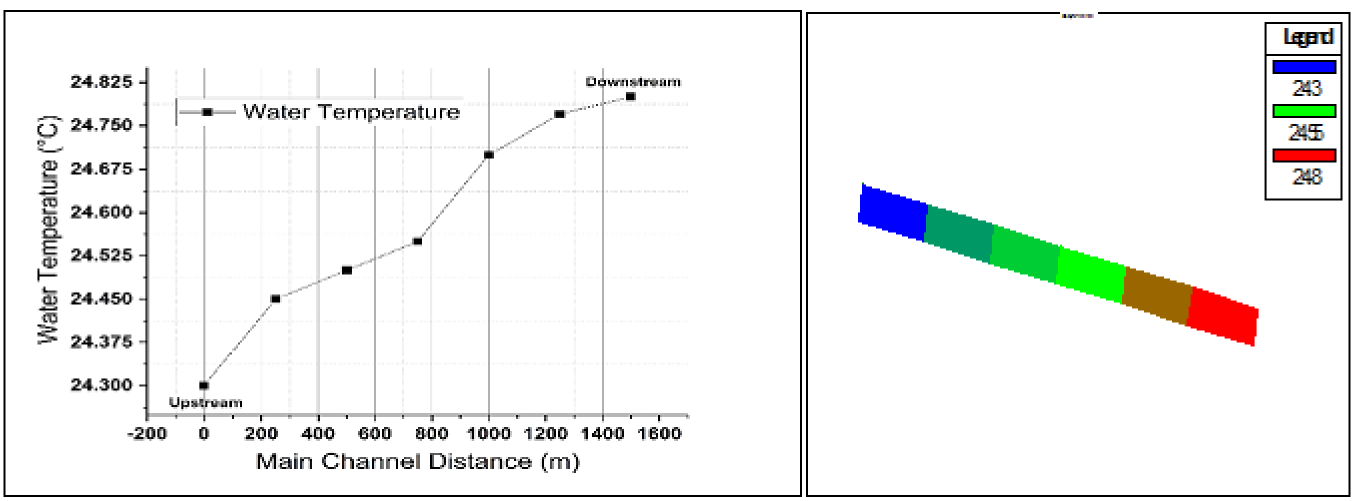
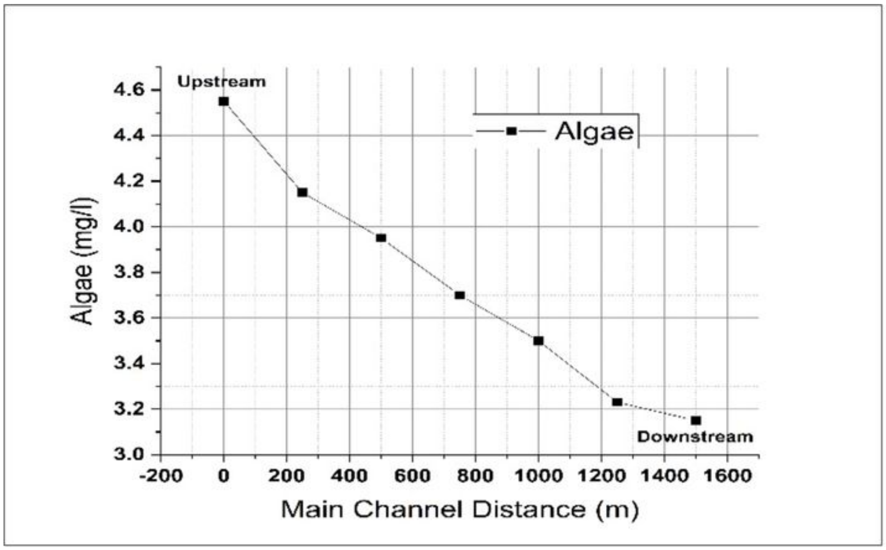


Figure 4

Water Temperature (a) Spatial Plot & (b) Schematic Plot



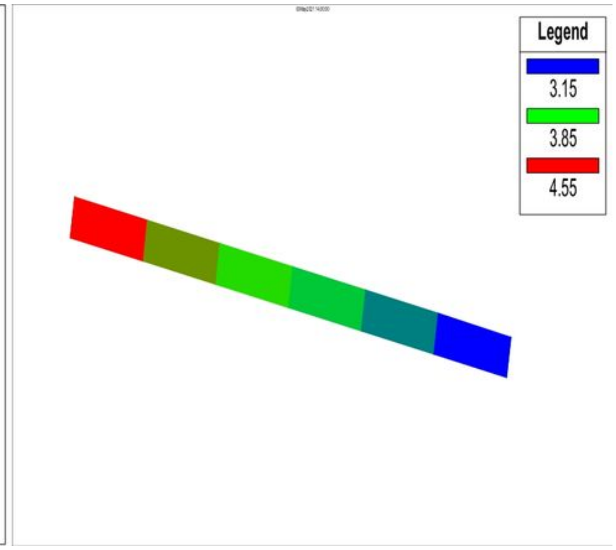
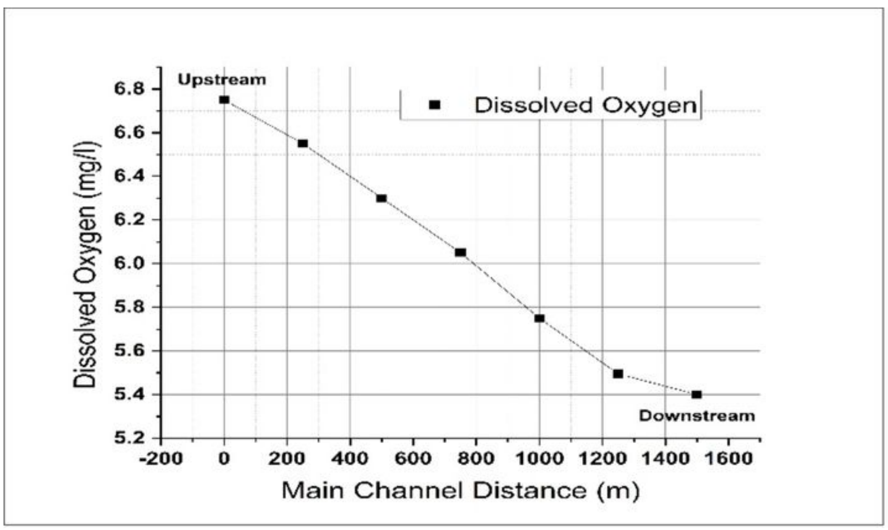


Figure 5

Algae (a) Spatial Plot & (b) Schematic Plot



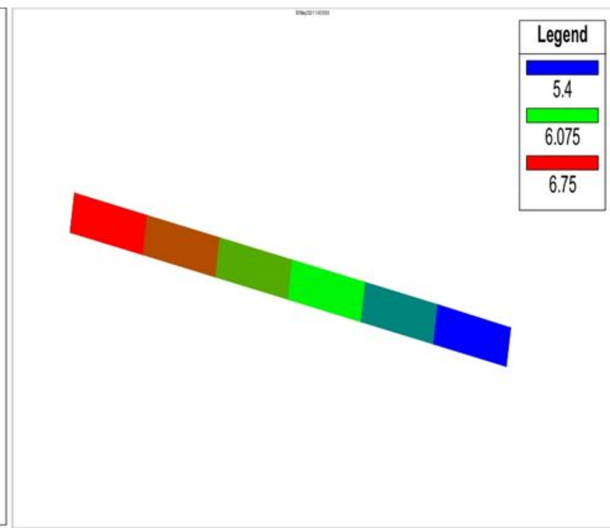


Figure 6

DO (a) Spatial Plot & (b) Schematic Plot

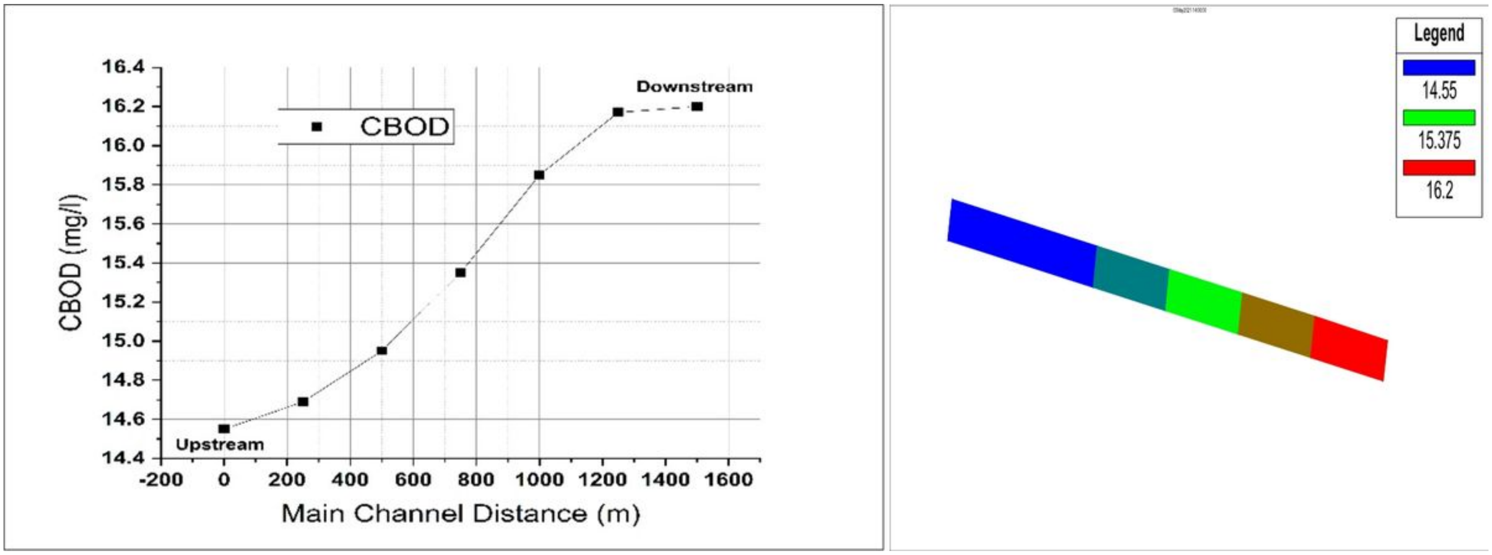


Figure 7

CBOD (a) Spatial Plot & (b) Schematic Plot

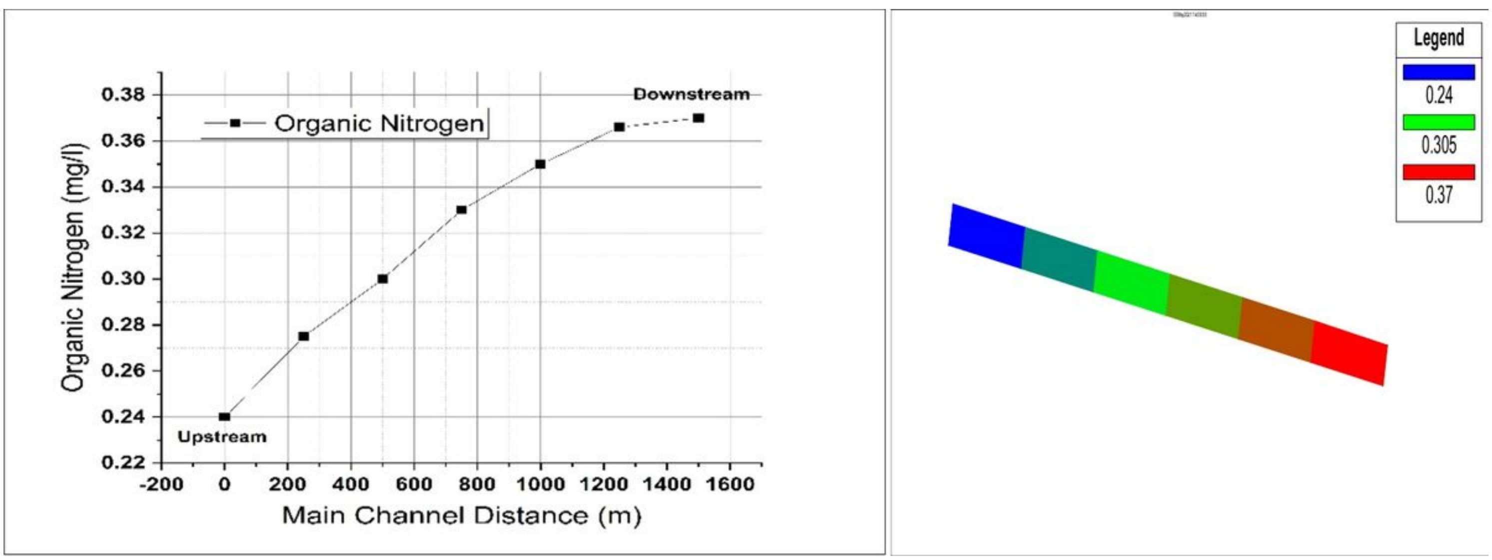


Figure 8

Organic Nitrogen (a) Spatial Plot & (b) Schematic Plot

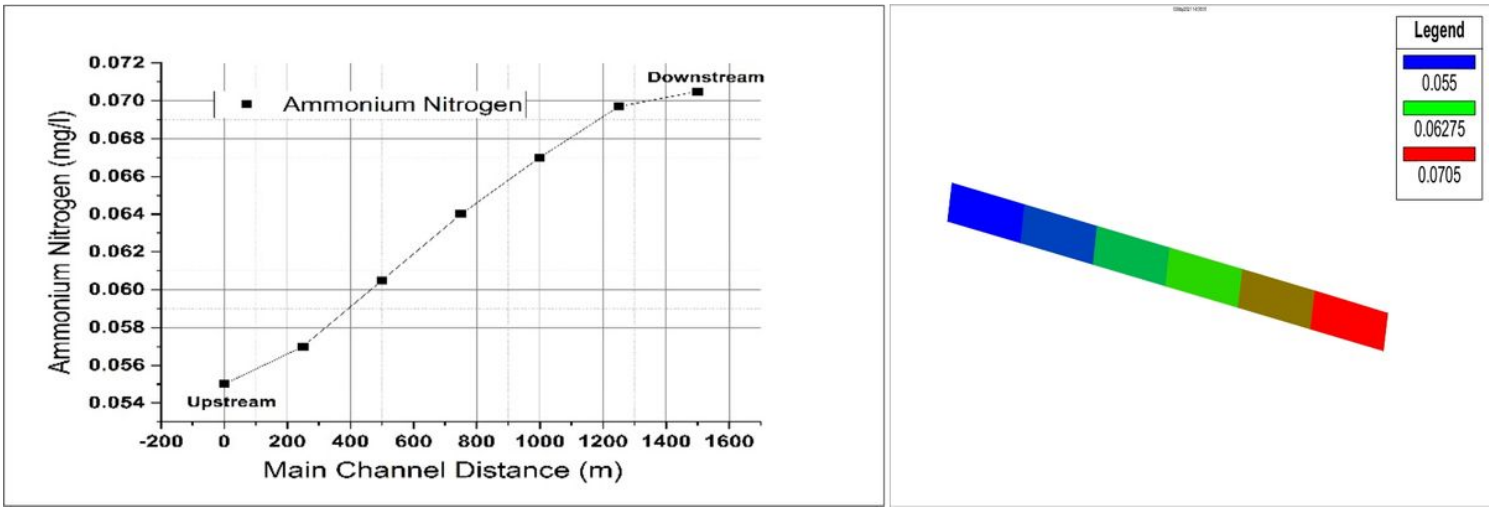


Figure 9

Ammonium Nitrogen (a) Spatial Plot & (b) Schematic Plot

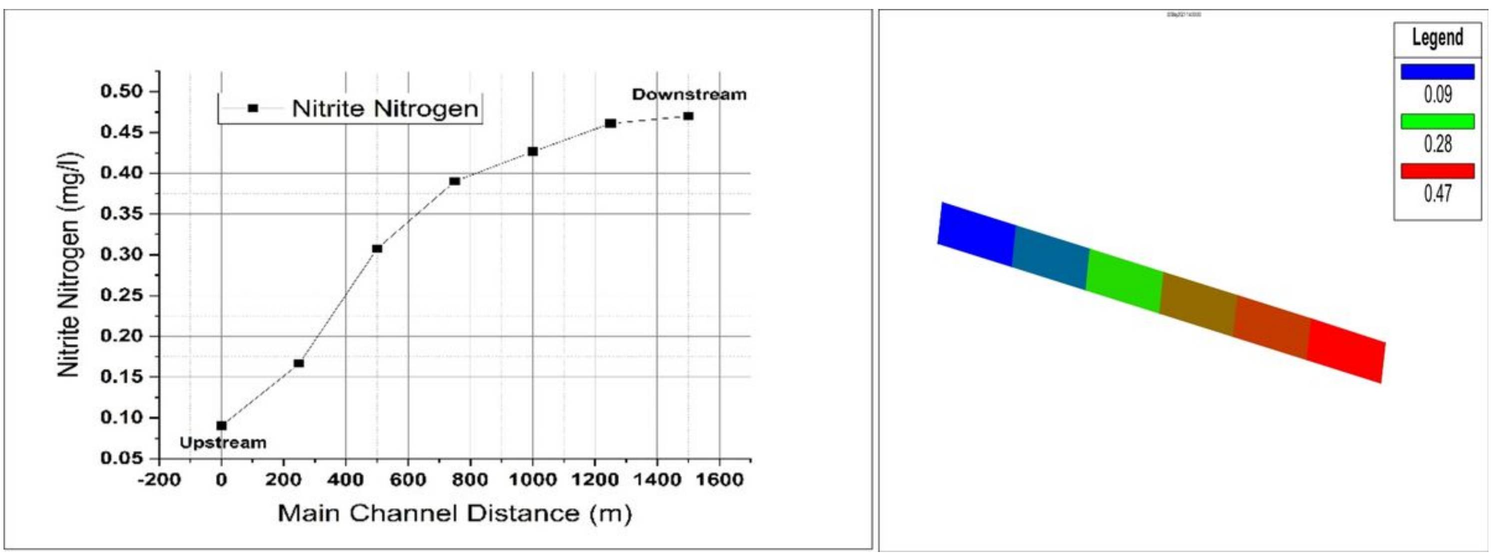


Figure 10

Nitrite Nitrogen (a) Spatial Plot & (b) Schematic Plot

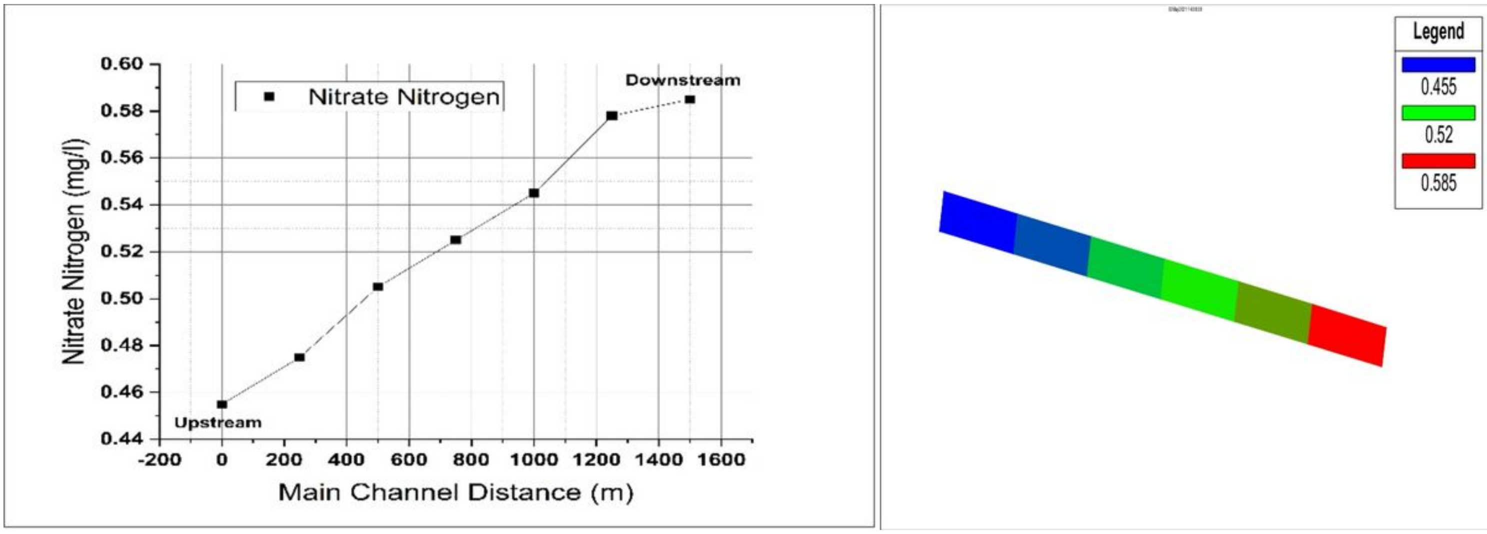


Figure 11

Nitrate Nitrogen (a) Spatial Plot & (b) Schematic Plot

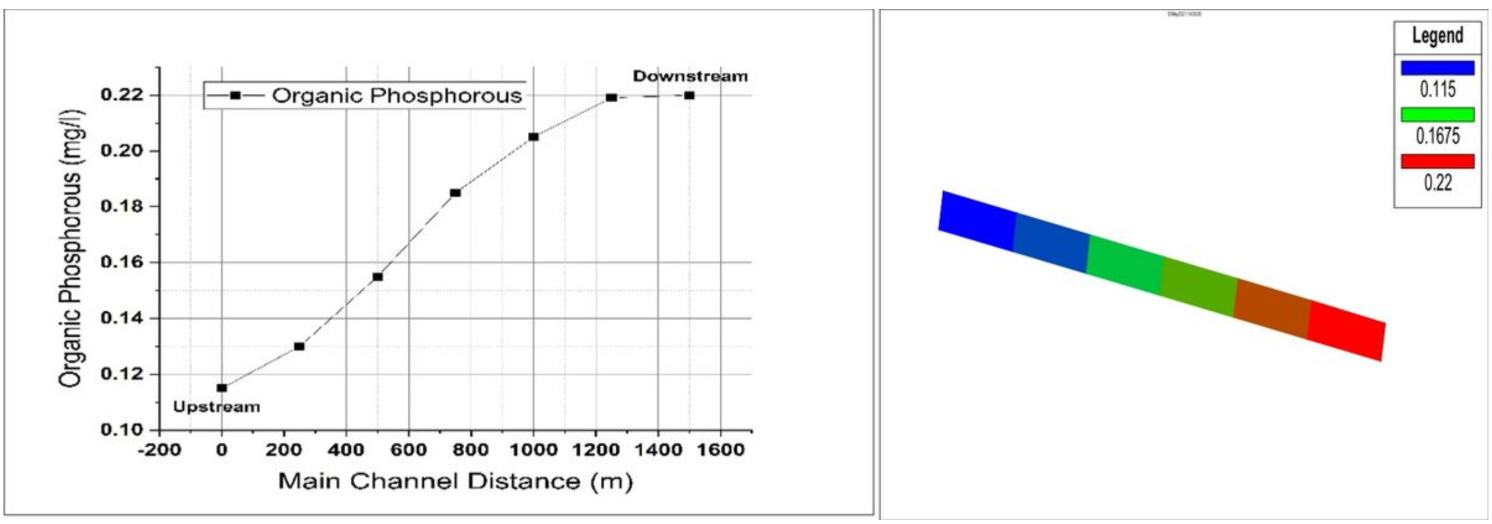


Figure 12

Organic Phosphorous (a) Spatial Plot & (b) Schematic Plot

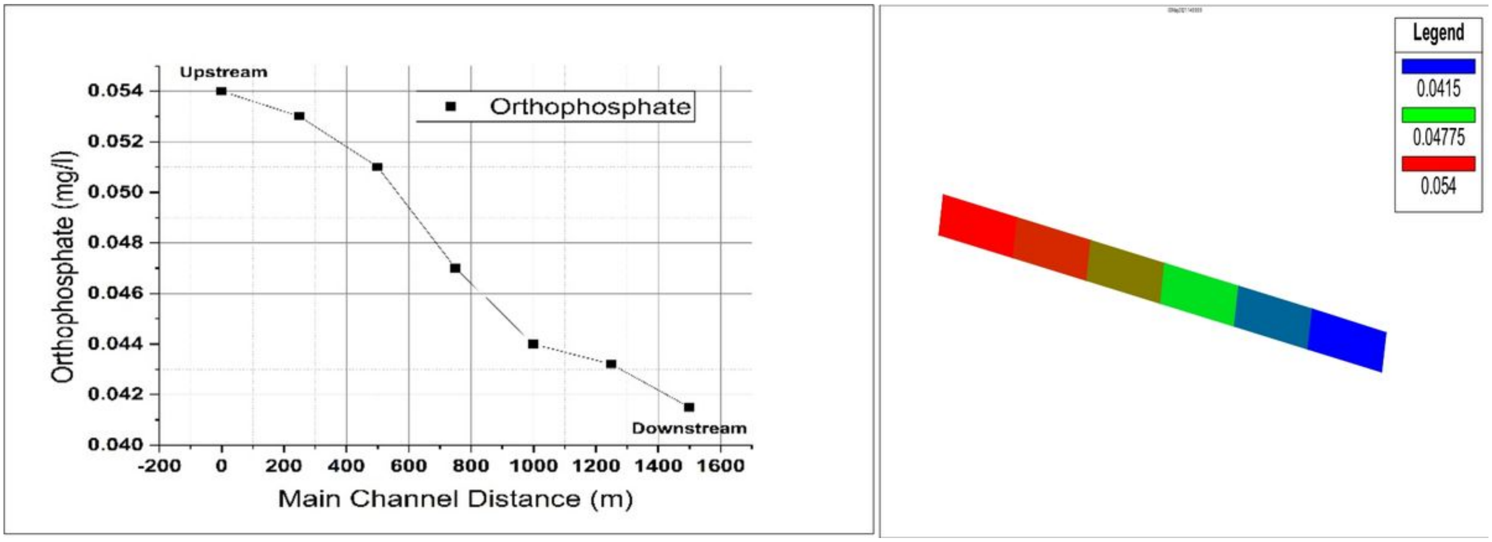


Figure 13

Orthophosphate (a) Spatial Plot & (b) Schematic Plot

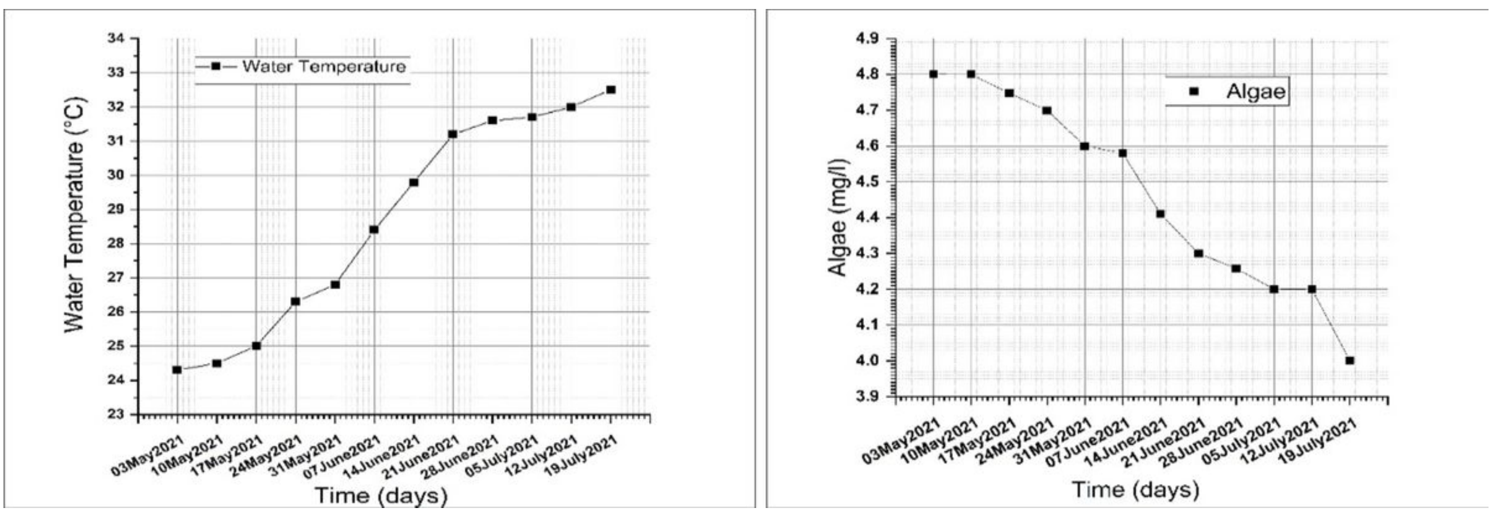


Figure 14

Water Temperature & Algae Time Series Plot

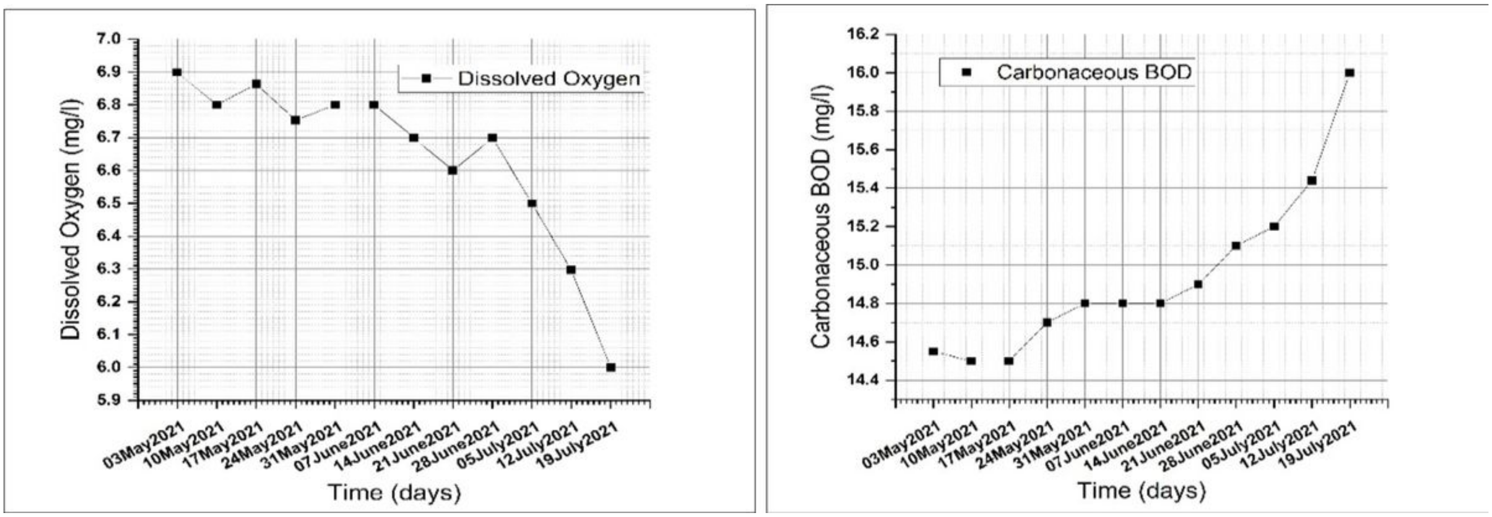


Figure 15

DO & CBOD Time Series Plot

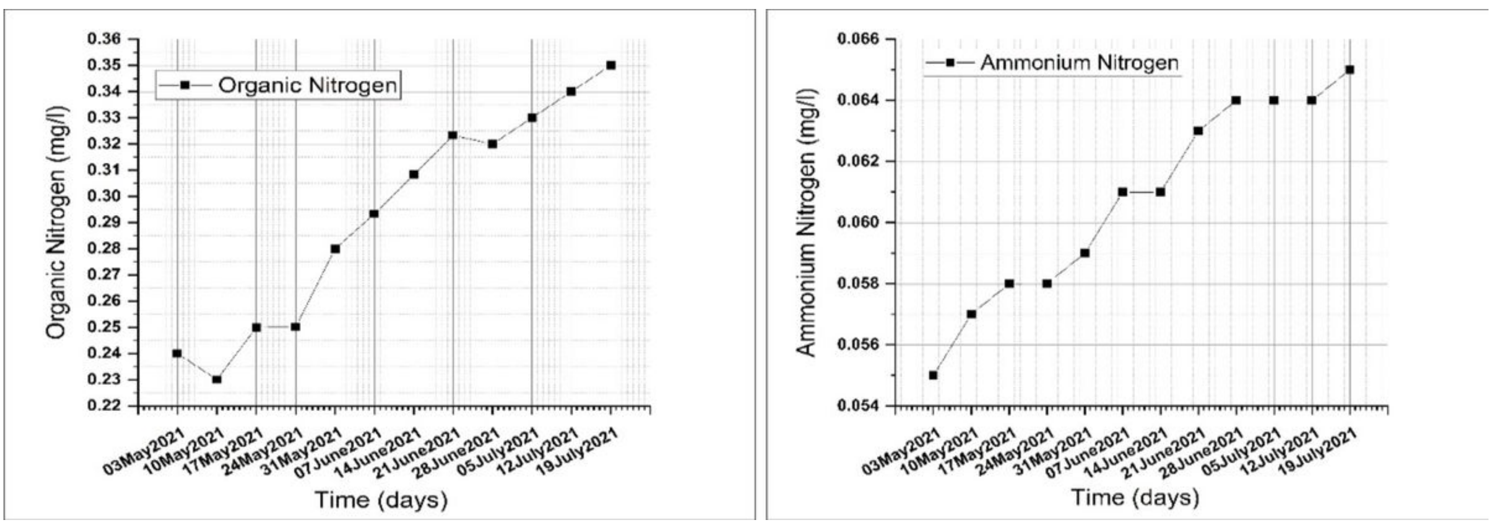


Figure 16

Organic Nitrogen & Ammonium Nitrogen Time Series Plot

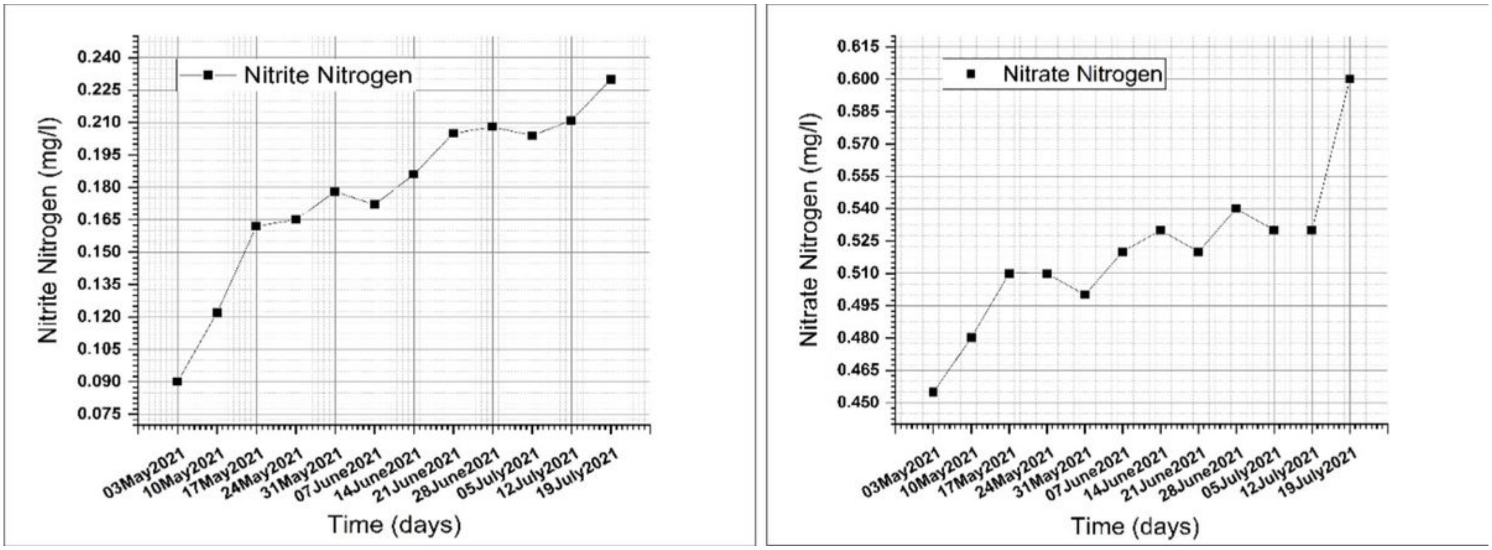


Figure 17

Nitrite Nitrogen & Nitrate Nitrogen Time Series Plot

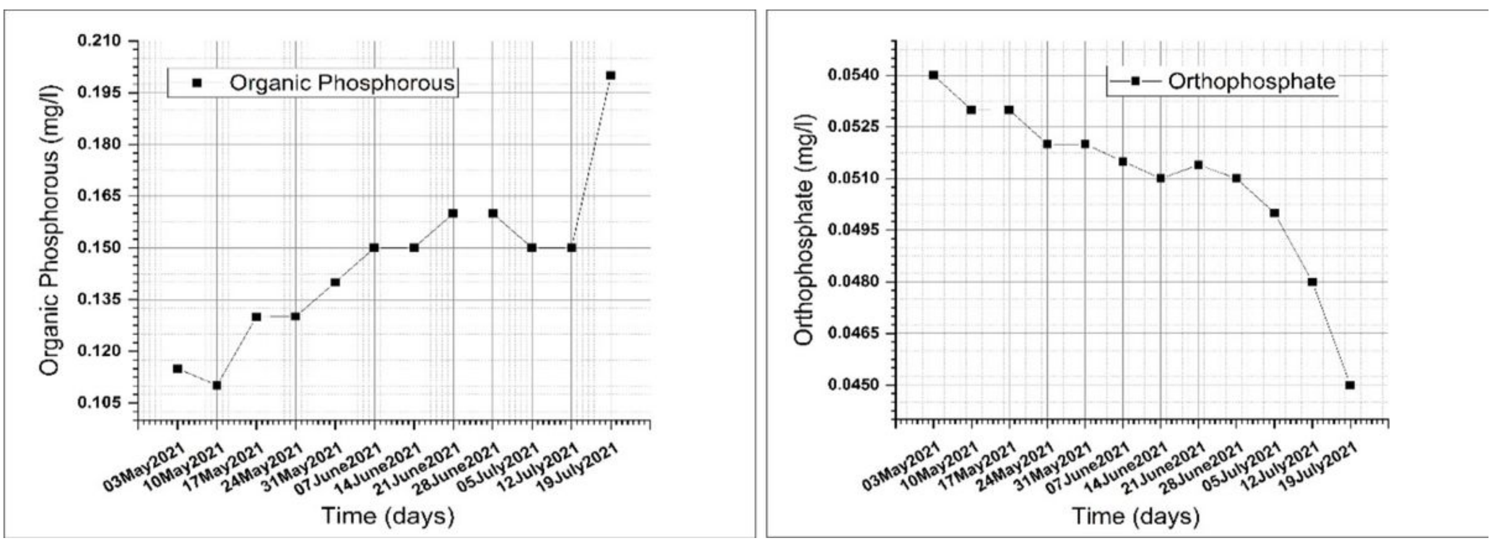


Figure 18

Organic Phosphorous & Orthophosphate Time Series Plot