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Geospatial assessment of seasonal water quality of Malad creek, Mumbai, India: An impact of sewage discharge

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Water pollution of creeks and the marine environment is a serious concern across the globe due to rapid urbanization and industrialization. Mumbai, being a densely populated industrial hub of India is facing the impact of sewage pollution in creeks and coastal belts. In this study, one of the polluted creeks of Mumbai namely Malad creek is considered a study area to assess the seasonal variation of sewage pollution with special attention to satellite image analysis and tidal characteristics. For this, *in-situ* sampling corresponding with the date and time pass of satellite images and spectral analysis are carried out to assess spatio-temporal variation in the water quality of the creek as well as establish a statistical relationship between image analysis and ground data. The purpose of this study is to avoid the limitations of monitoring point-specific data, inaccessible remote areas, labour intensiveness, higher expense, and unavailability of temporal data in the conventional method. The study provides an adequate, effective, and comprehensive way to assess sewage pollution in waterbodies and suggests future research work like the health assessment of marine organisms and threats in eco-sensitive zones of the coastal environment.

[**Keywords**: Creek, Geospatial technique, Sewage, Spectral reflectance, Water quality]

Introduction

Water is an unparalleled resource for human survival during the downtime of civilization[1]. Depletion in water quality by disposal of sewage, agricultural runoff, industrial effluent, etc. or incautious use should be a chronic threat[2] to the human society as well as hydrosphere[3]. Due to rapid urbanization[4] and industrialization, the ocean, estuaries, river, lakes, ponds and other waterbodies receive a massive load of sewage, and industrial effluent every day across the globe[5]. In India, eighty percent of the surface waterbodies are polluted as reported by Central Pollution Control Board (CPCB)[6].

In this context, there is a need for an advanced and efficient technique to frequently monitor, measure, and for real-time data analysis about those huge water resources. Remote sensing offers an efficient way to assess the water quality and creates a database/signature library of water quality[7]. The geospatial technique has huge potential to monitor and estimate the inland water quality[8-9] as well as coastal waterbodies[10]. The disposal of sewage in waterbodies produces a significant signature on satellite images[11-12] that helps to identify the presence of different pollutants in the water body. There are several methods namely thermal analysis for Sea Surface Temperature (SST), a spectral analysis or band ratio for Normalized Difference Turbidity Index (NDTI), Total Suspended Matter (TSM), bio-optical estimation for Coloured Dissolved Organic Matters (CDOM), etc. to understand the coastal environment. Although remote sensing has flourished for the evaluation of water quality, non-optically active parameters like pH, Dissolved Oxygen (DO), Bio-chemical Oxygen Demand (BOD), Chemical Oxygen Demand (COD), etc. are still unexplored or difficult to analyse through remote sensing because of their insufficient spectral response[13]. In this context, an attempt has been made to assess the seasonal dynamics of sewage pollution, considering selected water quality parameters (SST, NDTI, TSM, and CDOM) that are optically active using geospatial techniques.

Materials and Methods

Study area

The eco-sensitive zone, Malad creek is situated on the west coast of Mumbai, which is the financial capital of India with a 12.4 billion population. Malad creek, one of the polluted creeks in the vicinity of Mumbai[14-15], considered a study area to carry out this research work. The creek receives a massive quantity of untreated sewage from several adjoining drains which are coming from the city area. As per Maharashtra Pollution Control Board (MPCB) report, untreated sewage from slums and inadequately treated waste from other sources are leading to the deterioration of water quality in the coastal region of Mumbai[16]. Malad creek receives partially treated sewage from several sources like Versova Sewage Treatment Plant (STP), Mald STP, and numbers of adjoining drains as 90 Million Litter per Day (MLD), 100 MLD and, 300 MLD, respectively[17-18]. The study area along with sampling locations is represented in Figure 1.

Methodology

Ground-truthing and laboratory analysis

To carry out this study sampling was done for two different seasons namely summer and winter. For the collection of water samples from Malad creek, a boat was hired and floated around 10:30 h on 8th May 2019 and 8th February 2020, as satellite passes around 11:00 h over the region covering Malad creek. According to the tidal calendar sampling was done close to the high tide condition. Eleven different locations were identified to collect the samples with the help of a Global Positioning System (GPS) and satellite images. The samples were collected in sampling bottles as per the standard procedure prescribed by the American Public Health Association (APHA)[19]. Sampling locations S1 – S9 were categorised as creek water and S10 – S11 were considered as the creeklets/drain. The water quality parameters like temperature, turbidity, Suspended Solids (SS), and Total Organic Carbon (TOC), and a few supportive/interrelated parameters namely BOD, ammonical nitrogen (NH_3-N), and phosphate (PO_4) were analysed to establish the relationship with the targeted remote sensing parameters.

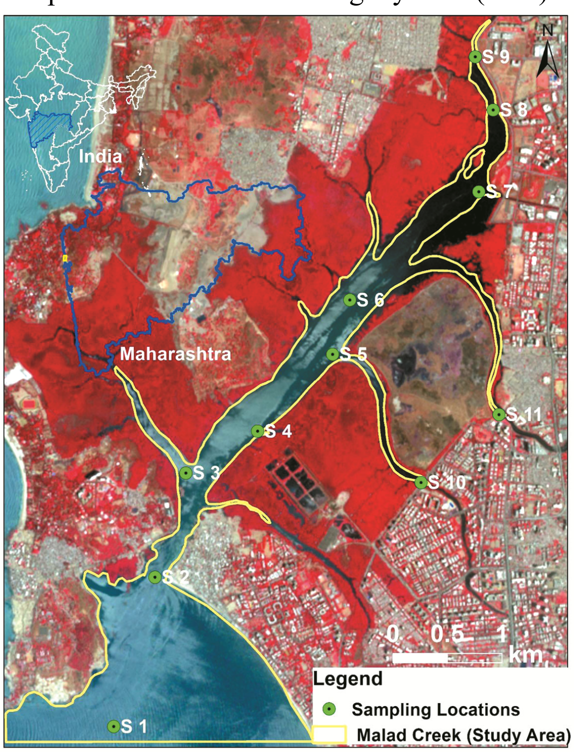

Fig. 1 — Location map

Temperature

Measurement of temperature was done with a good manual mercury-filled Celsius thermometer. The thermometer was immersed in the water to record the thermal status of the waterbody. For the accuracy of the thermal condition, three readings were taken for a specific point and the average value was taken as the final reading.

Turbidity

Turbidity was measured with a high accuracy portable Hanna USA turbidity meter (HI98703). This handheld meter works on measuring scattered light from the sample[20]. When a beam of light passes through a water sample, some part of the light scatter at an angle of 90°; the intensity of scattering reveals the concentration of turbidity. In this study, turbidity was measured by the Nephelometric Turbidity Unit (NTU) method, which is prescribed as a suitable method for turbidity assessment by the APHA[19].

Suspended Solids (SS)

Estimation of SS was done in the laboratory by gravimetric method. In analytical chemistry, this method is known as the set of procedures used for quantitative measurement of the analyte. To assess the concentration of the SS, a certain amount of well-mixed samples was taken to filter through a weighted standard glass filter. After filtration, the filter paper containing residues was dried at the temperature range of 103 to 105 °C (APHA[19]). The increasing weight of the filter paper is a representation of SS for a certain amount of water column.

Total Organic Carbon (TOC)

TOC represents total organic and inorganic carbon in the water column. As TOC is strongly correlated with CDOM, it is measured for both seasons by applying the TOC analyser to understand the presence of organic and inorganic matters in the creek water quality.

Table 1 — Details of satellite data, tidal conditions and application of satellite

Satellite	Sensor	Resolution	Date of pass	Time of Pass (GMT)**	Tidal condition* (IST)#	Application
Sentinel 2	MSI	10 m	8th May 2019	05:38	Low tide 07:37 High tide 14:33	Spectral and bio-optical analysis
Sentinel 2		10 m	8th February 2020	05:38	Low tide 05:38 High tide 11:11	
Landsat 8	OLI	30 m	12th May 2019	05:34	Low tide 04:47 High tide 11:11	Thermal analysis
Landsat 8		30 m	8th February 2020	05:34	Low tide 05:38 High tide 11:11	

* https://tides4fishing.com/as/india/bombay, #Indian Standard Time, ** Greenwich Mean Time

Other parameters

BOD is one of the significant water quality parameters that has been analysed based on the Azide-Winkler method as prescribed by APHA[19] for both seasons (May 2019 and February 2020). The Kjeldahl method or Kjeldahl digestion was applied to estimate the NH_3-N from the collected samples. This is the procedure to measure the presence of ammonia in a certain amount of toxic samples. Phosphate (PO_4) is another common component present in wastewater and it is responsible for the growth of plankton/algae in the waterbody. In this study, laboratory analysis was carried out to estimate the concentration of PO_4 in water. The calorimetric stannous chloride method was applied to determine the orthophosphate of water samples. The UV-spectro-photometer has been used to estimate the concentration of PO_4 (mg/l) by measuring the intensity of the blue-coloured complex.

Collection of satellite data and atmospheric correction

Multispectral satellite data like Landsat-8 Operational Land Imager (OLI) and Sentinel-2 Multispectral Instrument (MSI) were downloaded from the website of United States Geological Survey (USGS) earth explorer. Before starting the image analysis, the atmospheric correction including extraction of water pixels, filtration to enhance the data quality, and conversion of Digital Number (DN) to radiance were performed using the methods proposed by Setiawan[21]. This was followed for both the imageries. Details of the satellite data and its utilities in image analysis are summarised in Table 1 and False Colour Composites (FCCs) are represented in Figure 2.

Digital Number (DN) values to Top of the Atmosphere (TOA) reflectance for Landsat OLI

DN to reflectance calculation was carried out using a formula given by several researchers[22-23]:

$$\rho\lambda' = M\rho Qcal + A\rho \qquad \text{... (1)}$$

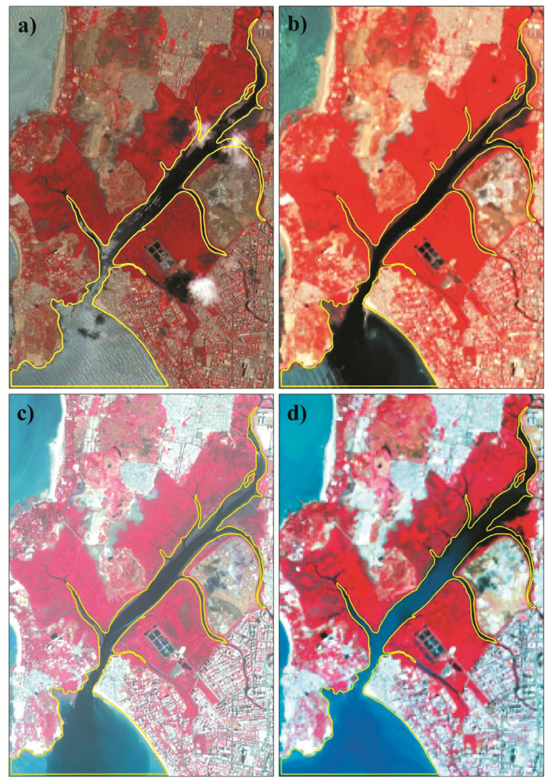

Fig. 2 — FCCs of the study area: a) Sentinel 2, 8th May 2019; b) Landsat8, 12th May 2019; c) Sentinel 2, 8th February 2020; and d) Landsat 8, 8th February 2020

Where, $\rho_{\lambda'}$ = TOA planetary reflectance, without correction for the solar angle. Note that $\rho\lambda'$ does not contain a correction for the sun angle. M_ρ = Band-specific multiplicative rescaling factor from the metadata (REFLECTANCE_MULT_BAND_x, where, 'x' is the band number); A_ρ = Band-specific additive rescaling factor from the metadata (REFLECTANCE_ADD_BAND_x, where, 'x' is the band number); and Q_{cal} = Quantized and calibrated standard product pixel values[24].

Sun angle correction

$$\rho\lambda = \rho\lambda\ '/\sin \theta SE$$

where, ρλ = TOA planetary reflectance ; θSE = Local sun elevation angle. The scene centre sun elevation angle in degrees is provided in the metadata[24].

DN values to TOA reflectance for Sentinel 2 MSI

Similarly, a correction technique has been applied for Sentinel images also. Here, a plugin with QGIS namely semi-automatic classification[25] was used for the atmospheric correction of Sentinel 2 images.

Image analysis

Landsat images are used for thermal analysis and Sentinel images are used for spectral and bio-optical analysis.

Thermal analysis for SST

In the field of ocean meteorology, SST has a significant role as it influence the ocean currents, eddies, sea-level rise, cyclone prediction, salinity, fishing zone, etc.[26]. SST has been retrieved, applying a four steps procedure using thermal bands (band 10 and 11) of Landsat 8. The steps are atmospheric correction, conversion of temperature, and estimation of SST using the split-window method. After atmospheric correction or converting DN values to at-sensor spectral radiance, the Thermal Infrared Sensor (TIRS) data was converted to brightness temperature using the following equation (Planck's law):

$$T = \frac{K_2}{\ln[(\frac{K_1}{L\lambda})+1]} - 273.15 \qquad \ldots (2)$$

Where, T = Brightness temperature/effective temperature, Lλ = Spectral radian value (watts/m²×sr×μm), K2 = Temperature constant (°K), and K1 = Temperature constant (°K).

At the third step, a split window method has been developed to automatically obtain SST from satellite brightness. The split window algorithm has been applied as given below:

$$\mathrm{TS} = \mathrm{BT10} + \big(2.946 \times (\mathrm{BT10} - \mathrm{BT11})\big) - 0.038 \quad \ldots (3)$$

Where, TS = Brightness temperature (SST) (°C), BT10 = Brightness temperature value in °C (band 10), and BT 11 = Brightness temperature value in °C (band 11)

Spectral indices

Spectral indices or band rationing is a semi-empirical method that is useful for assessing the different water quality[27]. In the spectral indices method, different bands were used to create an equation that can estimate a particular parameter regarding water pollution. The whole image pixels having spectral similarity can be treated as an object and can be masked out using a band ration algorithm. The turbidity and TSM were analysed through the spectral indices method. NDTI is a band ratio/spectral indices method that is used to assess the water turbidity[28-30]. Here, the red and green wavelengths of Sentinel 2 were considered for the creation of the NDTI algorithm[30] that is expressed as:

$$\mathrm{NDTI} = (\mathrm{Red} - \mathrm{Green})/(\mathrm{Red} + \mathrm{Green}) \qquad \ldots (4)$$

Due to the presence of suspended materials in the water column, it may appear brown to black in colour, which is a sign of turbidity. The measurement of turbidity is correlated with the estimation of SS[(ref. 31)]. Geospatial technology is now worldwide used to map the turbidity and SS concentration[32-36]. SS are those components that are present in the water column in suspension. These are mostly settleable particles like clay, sediments, silt, and algae. In this research, TSM[(refs. 11,37)] is measured using the spectral analysis algorithm as expressed as:

$$TSM = Red/Green \qquad \ldots (5)$$

Bio-optical analysis

Bio-optical analysis has been developed by researchers to overcome the spectral complexity of marine water. In this process, analysis has been carried out based on the radiative transmission from the water column. Estimation of CDOM depends on the bio-optical properties of the water and such factors as water-leaving radiance, Remote Sensing reflectance (R_{rs}), and diffuse attenuation coefficient is also called apparent optical properties. For identification and quantification of CDOM in the creek, the R_{rs} power value was developed using apparent optical properties namely absorption coefficient and band ratio of R_{rs} of certain spectral bands. The absorption coefficient has been calculated using absorbance values in spectral bands and the band ratio has been calculated using R_{rs} values of green and red bands as suggested by several researchers.

$$aCDOM(440) = A(\lambda)x\text{–}\,Power\ Value \qquad \ldots (6)$$

Where, A(λ) is the spectral absorbance of the water column in the specific wavelength λ (nm), and 'x' is the R_{rs}

Statistical analysis

To establish a relationship between water quality parameters, the Pearson correlation matrix has been derived for both seasons. Further, to understand the water quality of creek using remote sensing analysis a statistical approach has been carried out to establish a relation between spectral response and targeted water quality parameters. The analysis helped to make a strong decision about the applicability of satellite-based applications for sewage pollution assessment. This also helped to reach the conclusion that describes how water quality variables are interrelated and the adequacy of image analysis to assess the sewage pollution in waterbodies.

Results and Discussion

The dynamics of water quality have been assessed for different seasons considering various methods.

Water quality analysis

Temperature

The temperature of the creek water measured for both seasons May 2019 and February 2020 ranged from 30.7 to 36.4 °C and 30 to 36 °C, respectively. The seasonal dynamics in the temperature is represented in Figure 3(a). Seasonal variation can be seen in creek samples (S1 – S9) except in drain water (S10 & S11).

Turbidity

The laboratory analysis for turbidity represents that the turbidity is more in the middle and upper portions of the creek and adjoining drains in comparison to the creek's mouth. Turbidity is observed more in February 2020 as compared to May 2019. The higher range of turbidity in drains is strong evidence of the release of sewage into the creeks responsible for the degradation of the creek and marine water quality. Locations and season-wise turbidity concentrations are represented in Figure 3(b).

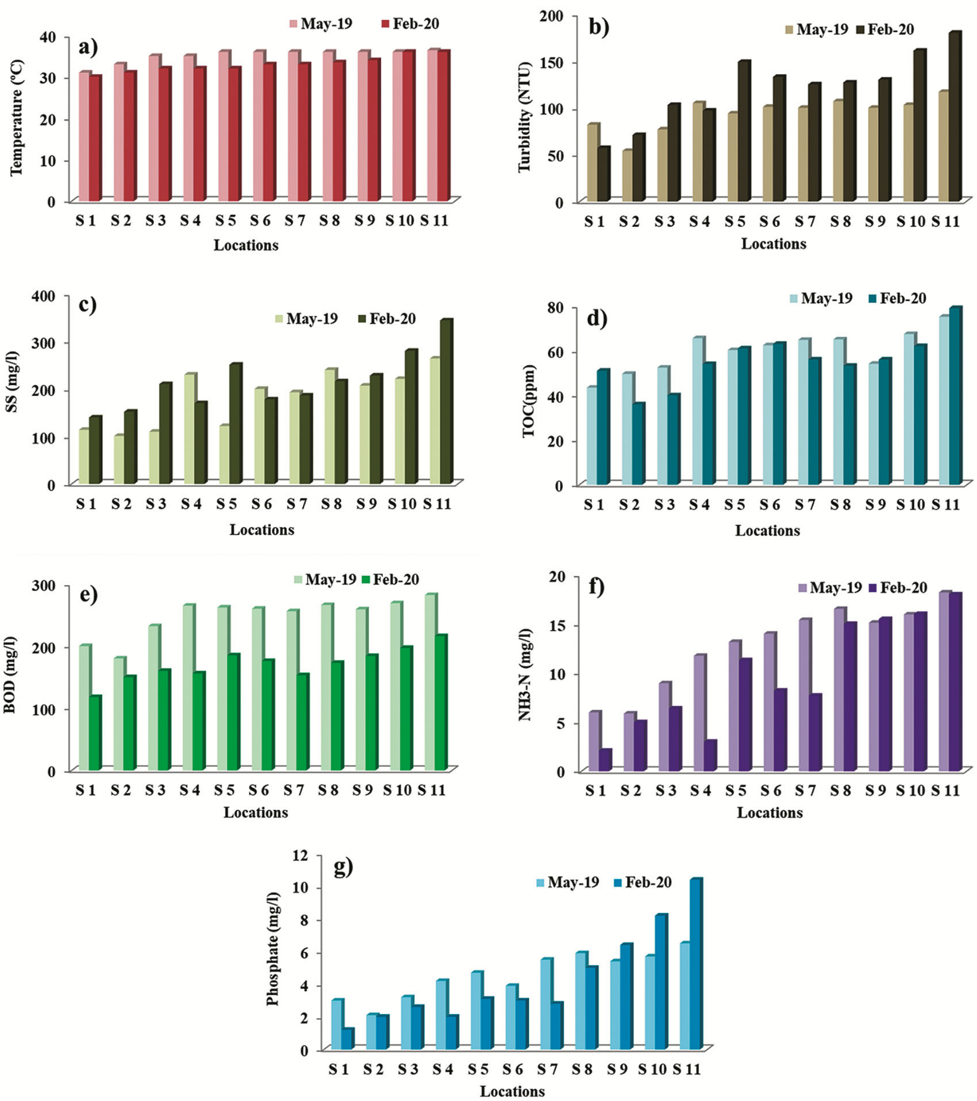

Fig. 3 — Water quality parameters in Malad creek for May 2019 and February 2020: a) Temperature, b) Turbidity, c) SS, d) TOC, e) BOD, f) NH_3-N, and g) PO_4

Table 2 — Correlation matrix amongst water quality parameters in Malad creek (May 2019 and February 2020)

May 2019							
Parameters	*Temperature*	*Turbidity*	*SS*	*BOD*	*TOC*	*NH3-N*	*PO4*
Temperature	1						
Turbidity	0.688	1					
SS	0.649	0.885	1				
BOD	0.874	0.937	0.812	1			
TOC	0.798	0.807	0.835	0.858	1		
NH3-N	0.884	0.886	0.852	0.924	0.864	1	
PO4	0.759	0.883	0.824	0.873	0.800	0.956	1
February 2020							
Parameters	*Temperature*	*Turbidity*	*SS*	*BOD*	*TOC*	*NH3-N*	*PO4*
Temperature	1						
Turbidity	0.887	1					
SS	0.850	0.896	1				
BOD	0.884	0.942	0.912	1			
TOC	0.708	0.812	0.731	0.713	1		
NH3-N	0.882	0.862	0.864	0.885	0.634	1	
PO4	0.937	0.816	0.911	0.869	0.709	0.910	1

Temperature in ºC and other parameters in mg/l

Suspended Solids (SS)

According to laboratory analysis of creek samples, the mouth of the creek has less amount of suspended particle load compared to the upper portion of the creek as well as in the drains. A comparison analysis of SS in May 2019 and February 2020 at different locations is depicted in Figure 3(c).

Total Organic Carbon (TOC)

TOC has also been analysed and mapped for May 2019 and February 2020 (Fig. 3d). The range of TOC is observed as 43 – 75 ppm and 36 – 79 ppm for May 2019 and February 2020, respectively. The presence of TOC confirms the impact of organic pollution in terms of sewage discharge in the creek.

Other parameters

The BOD range at Malad creek is measured as 186 – 282 mg/l in May 2019 and 118 – 216 mg/l in February 2020. Similarly, the concentration of NH_3-N is higher in drains and when the distance is increasing from the mouth of the creek but it is reduced towards the ocean. The NH_3-N concentration is measured as 6 – 18.2 mg/l and 2.1 – 18 mg/l for May 2019 and February 2020, respectively. Further, the PO_4 observed in May 2019 and February 2020 also revealed the same trend as of NH_3-N. The PO_4 ranged between 2.8 – 6.5 mg/l and 1.2 – 10.4 mg/l for May 2019 and February 2020, respectively. The presence of high values of BOD, NH_3-N and PO_4 in the creek water highlighted the sewage discharge from various sources. The dynamics of BOD, NH_3-N, and PO_4 are represented in Figure 3(e, f & g), respectively. A correlation study in terms of Pearson matrix is prepared to establish the relationship among water quality parameters (Table 2). A strong correlation is observed in water quality parameters that confirm the presence of sewage pollution in creeks.

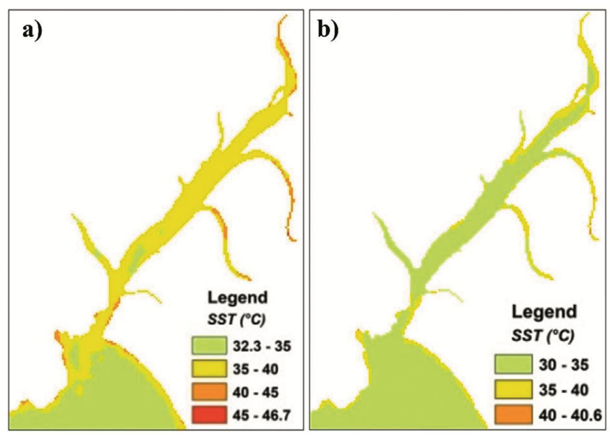

Fig. 4 — SST: a) May 2019, and b) Feb 2020

Remote sensing analysis

Sea Surface Temperature (SST)

The SST has been calculated in the creek water for May and February. There is a significant variation in temperature dynamics ranging from 32.3 – 45 °C and 30 – 40.6 °C for May 2019 and February 2020, respectively (Fig. 4). The SST is less in the inner portion of the creek during February 2020 might be possible because of seasonal change (winter) and high tide conditions (inflow of huge amounts of fresh water in the inner area of the creek). At the same time, higher temperatures in drains may indicate the presence of sewage over there. As far as areal coverage under different temperature zone is concerned to understand the temperature pattern, a statistical analysis has been carried out that reveals that 20 % of the area (creek's mouth) comes under 32.3 – 35 °C, 79 % area (major area of the creek) comes under 35 – 40 °C and only 1 % of the area (drains, coast) comes under 40 – 45 °C temperature zone for the summer season. Due to the moderate resolution of thermal bands of Landsat data, it contains mixed reflectance in marginal pixels of any objects that might be the probable reason for unreal values about an output. Here, the high reflectance from beaches, mudflats, etc. may increase the temperature range. Similarly, Temperature zonation was also carried out for winter which reveals 76 % of the area comes under 30 – 35 °C, 13.5 % comes under 35 – 40 °C and 0.05 % of the area comes under the 40 – 40.6 °C temperature zone.

Normalized Difference Turbidity Index (NDTI)

NDTI is applied for the satellite images (Sentinel 2) of May 2019 and February 2020, and the results showed that the NDTI range is varying as 0.1 – 0.14 and 0.1 – 0.12, respectively. Satellite images of both seasons also represent the high range of NDTI at drains and the upper portion of the creek, while the NDTI range is decreasing towards the mouth of the creek. A notable change is found for NDTI that in February highest range is shifted from the lower portion to the central portion of the creek, which might be possible because of high tide conditions. The upper limit of NDTI is higher during summer compared to winter, which might be possible due to the presence of less volume of water, discharge of sewage, tidal conditions, etc. The NDTI for May 2019 and February 2020 are represented in Figure 5.

Total Suspended Matter (TSM)

The satellite image analysis has also been applied to assess the concentration of TSM in creek water using a spectral analysis algorithm. It is observed that the higher range of TSM is 1.3 for both seasons (May 2019 and February 2020), and there is slight variation in the lowest range, it is measured as 1.0 for May 2019 and 0.9 for February 2020. It is also observed that in February 2020 lower value of TSM coverage is greater compared with May 2019 (Fig. 6) and the inner portion of the creek (February) is also covered by a lower range of TSM.

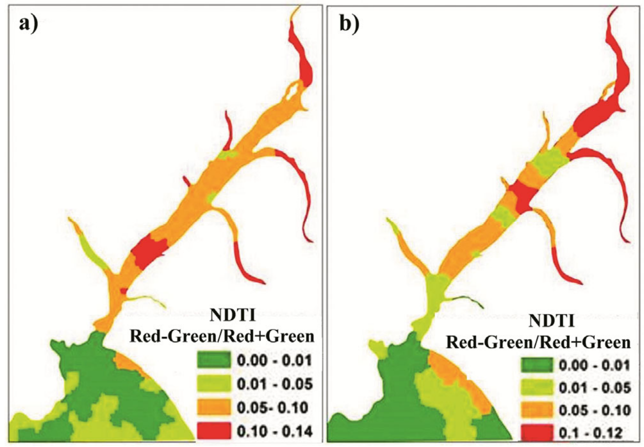

Fig. 5 — NDTI: a) May 2019, and b) Feb 2020

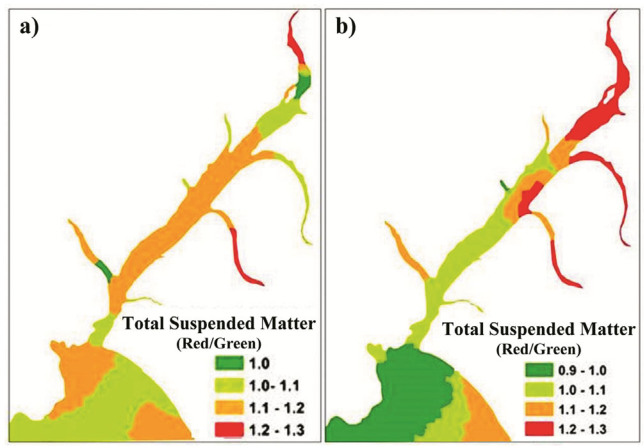

Fig. 6 — TSM: a) May 2019, and b) Feb 2020

Coloured Dissolved Organic Matter (CDOM)

Like other parameters, CDOM has also been derived for May 2019 and February 2020. The results showed seasonal variations in the range of CDOM concentration *i.e.* between 3.3 – 5.8 m^{-1} and 2.8 – 6.7 m^{-1} for May 2019 and February 2020, respectively. In May 2019, the majority of the creek comes under the CDOM concentration of 5.0 – 5.5 m^{-1} while in February 2020 significant variations are there as 56 % of the area is belon g to the CDOM range of - 6.5 m^{-1}, 30 % area is under 5.5 – 6 m^{-1}, 11 % are covered by 5 – 5.5 m^{-1} and 3 % is under the remaining categories of CDOM range. It is observed that both seasons confirmed the high CDOM in the creek due to the discharge of organic pollution loads from drains also partially treated sewage from the wastewater treatment facility. The satellite derived CDOM is represented in Figure 7.

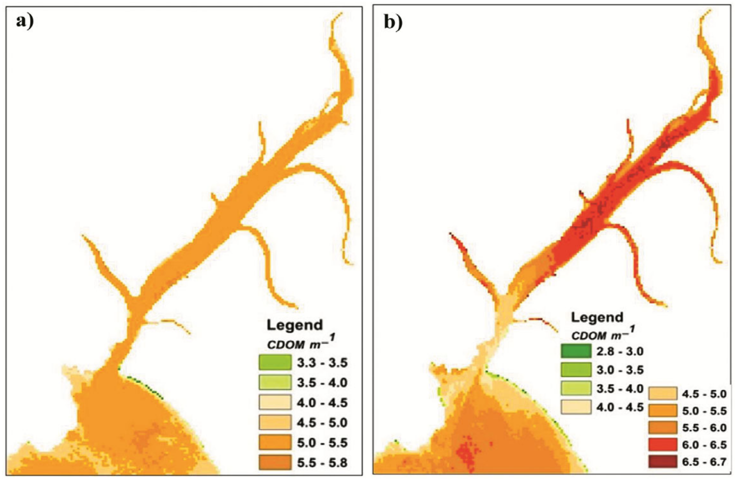

Fig. 7 — CDOM: a) May 2019, and b) Feb 2020

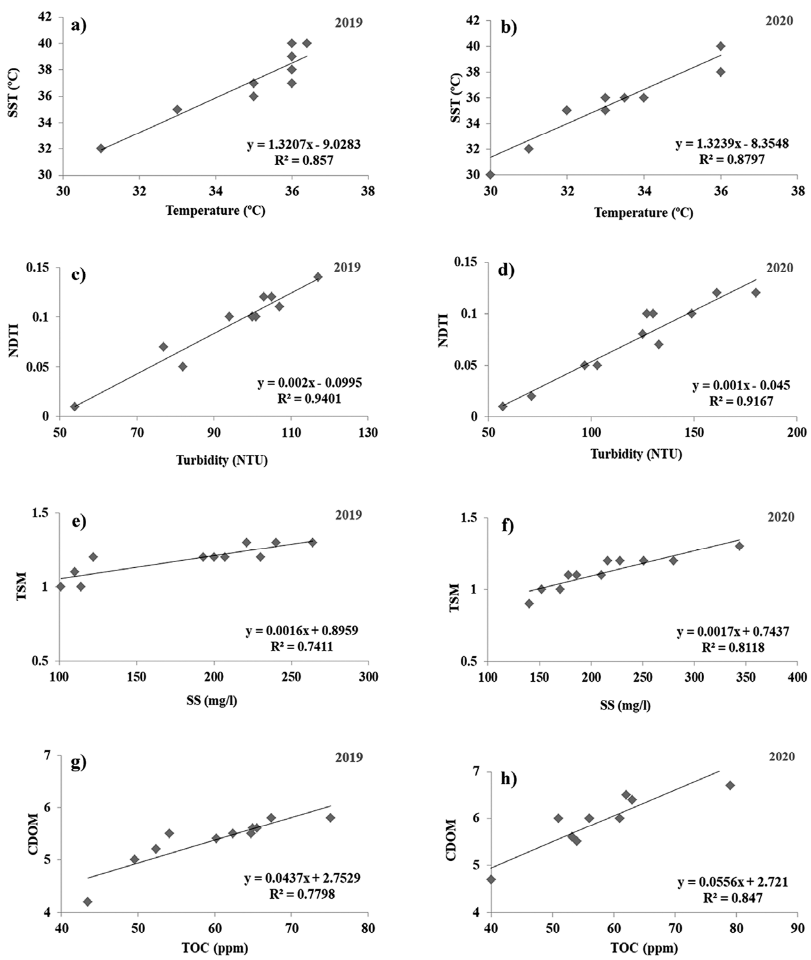

Fig. 8 — Relationship among remotely sensed parameters and observed water quality

Relationship between spectral analysis and water quality parameters

For comparison of the remote sensing results with water quality parameters, a statistical approach has been considered to validate the analysis of both. The SST was compared to temperature with a strong correlation (Fig. 8a & b). Similarly, NDTI was compared with laboratory-based turbidity analysis and

Table 3 — Correlation matrix between optical and non-optical water quality parameters in Malad creek (May 2019 and February 2020)

				2019			
parameters	*SST*	*NDTI*	*TSM*	*CDOM*	*BOD*	*NH3-N*	*PO4*
SST	1						
NDTI	0.791	1					
TSM	0.925	0.925	1				
CDOM	0.955	0.780	0.887	1			
BOD	0.846	0.981	0.946	0.840	1		
NH3-N	0.932	0.893	0.961	0.853	0.924	1	
PO4	0.846	0.876	0.920	0.738	0.873	0.956	1
				2020			
Parameters	*SST*	*NDTI*	*TSM*	*CDOM*	*BOD*	*NH3-N*	*PO4*
SST	1						
NDTI	0.899	1					
TSM	0.887	0.947	1				
CDOM	0.624	0.656	0.687	1			
BOD	0.901	0.899	0.937	0.688	1		
NH3-N	0.816	0.926	0.946	0.543	0.886	1	
PO4	0.852	0.823	0.837	0.594	0.869	0.911	1

SST in ºC; CDOM in m^{-1}; BOD, NH3-N and PO_4 in mg/l

observed a strong correlation for both the seasons (Fig. 8c & d). The TSM has been correlated with measured SS data and a significant correlation was observed at all the sampling locations except for S1, S2, S7 and S8 (Fig. 8e & f). Further, the CDOM and TOC also showed a strong correlation (Fig. 8g & h). To confirm the sewage pollution in the creek, optically active parameters such as SST, NDTI, TSM and CDOM are compared with non-optical parameters like BOD, NH_3-N. The correlation matrix (Table 3) based on optical and non-optical parameters showed a strong correlation and confirmed organic pollution in the creek.

Conclusions

An attempt has been made to assess the sewage pollution dynamics in creek water quality considering image analysis and tidal characteristics. The study reveals that seasonal and tidal conditions play a crucial role in the water quality of the creeks as well as the marine environment. The presence of different pollutants in creek and drains confirms the impact of sewage discharge and the relationship among water quality parameters. The spectral image analysis in terms of SST, NDTI, TSM, and CDOM provides spatial and temporal variation in the creek. The statistical analysis showed a strong relationship between spectral analysis of optically active parameters such as SST, NDTI, TSM and CDOM and routine method analysis of temperature, turbidity, SS and TOC, respectively. The study reflects the effectiveness of remote sensing image analysis with ground truth for the assessment of sewage pollution in the waterbody and to minimize the limitations of monitoring of point-specific data, inaccessibility of waterbodies, labour cost, and unavailability of temporal data in the conventional method. Thus, this study offers an efficient way to monitor and assess sewage pollution in similar creeks and coastal environments using geospatial techniques. The study also suggests future research in terms of marine pollution and ecosystem health, loss of navigability and biodiversity due to sedimentation and siltation in creeks, etc.

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Conflict of Interest

Authors have been declared that there is no conflict of interest.

Author Contributions

JD: Data collection, analysis, and manuscript writing; RV: Conceptualization and review of the manuscript.

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