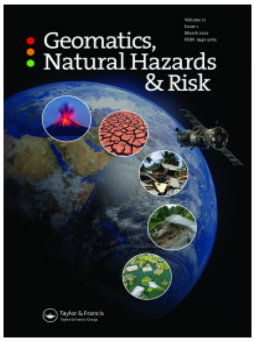

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Changes in turbidity along Ganga River using Sentinel-2 satellite data during lockdown associated with COVID-19

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ABSTRACT

India had announced the longest ever lockdown from 25 March 2020 to 14 April 2020 amid COVID-19 pandemic. It was reported that the water quality of the Ganga River has improved as compared to regular during this country-wide lockdown. In the present study, an attempt has been made to study the change in water quality of the river in terms of turbidity purely through remote sensing data, in the absence of ground observations, especially during this time period. The change in spectral reflectance of water along the river in the visible region has been analyzed using the Sentinel-2 multispectral remote sensing data at Haridwar, Kanpur, Prayagraj, and Varanasi stretches of the river. In the present study, it was found that the red and NIR bands are most sensitive, and can be used to estimate the turbidity. Further, the temporal variation in turbidity was also analyzed through normalized difference turbidity index at each location. It was observed that the turbidity in the river has reduced drastically at each stretch of the river. The study elicited that the remote sensing approach can be used to make qualitative estimates on turbidity, even in the absence of field observations.

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Water quality; turbidity; remote sensing; reflectance; Ganga River; lockdown; NDTI; COVID-19

1. Introduction

Mapping of water quality of inland waters using remote sensing is being carried out since 1970s, with the launch of Landsat series of satellites (Klemas et al. 1971; Kritikos et al. 1974; Johnson 1975; Ritchie et al. 1976). Every feature on the surface of the earth behaves differently on interacting with electromagnetic radiation (EMR). Based on their spectral response these features are identified in a satellite image. The slight change in their composition, changes the spectral properties of the feature. Similarly, many factors affect the spectral response of the water such as time of the year, sun-elevation angle, the concentration of atmospheric constituents, roughness of the water, suspended matter, turbidity, depth of water, and submerged or emergent

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vegetation (Moore 1980). On simultaneously analyzing the change in composition and changes in the reflectance properties of the water, the abundance or concentration of a particular component can qualitatively or sometimes quantitatively be estimated using remote sensing data. It is to be noted that the water quality parameters that affect its optical properties are generally being studied through remote sensing. Therefore, the studies are mainly constrained to the estimation of turbidity and chlorophyll, colored dissolved organic matter (CDOM) concentration (Lim and Choi 2015; Gholizadeh et al. 2016; Trinh et al. 2017; Chander et al. 2019; Luis et al. 2019).

Among all the water quality parameters suspended sediments are the most common problem in inland waters such as rivers, lakes, and estuaries (Ritchie et al. 1974) . These suspended particles attenuate the light required for aquatic life (Ritchie et al. 1974; Doxaran et al. 2002; Garg et al. 2017). It is also considered as an indicator of eutrophication (Güttler et al. 2013; Sebastiá-Frasquet et al. 2019). Traditionally, the concentration of these sediments is assessed optically or through gravimetric methods or laboratory analysis (Pavelsky and Smith 2009). Nowadays, it is measured visually through Secchi disk depth or directly using the light turbidimeters in the field (Pavelsky and Smith 2009; Quang et al. 2017). The field measurements are considered to be more accurate, but, they are both labor-intensive and time-consuming (Pavelsky and Smith 2009; Quang et al. 2017). However, these measurements are limited to point information, and the concentration of total suspended particles varies both temporally and spatially (Gholizadeh et al. 2016; Garg et al. 2017). It is reported in the literature that the three variables turbidity, suspended particulate matter and Secchi disk depth are closely related (Sebastiá-Frasquet et al. 2019).

Turbidity is an important optical property of water, where suspended sediments scatter the light rather than transmit it along the water column (Sebastiá-Frasquet et al. 2019). The turbidity increases with an increase in the concentration of suspended solids or sediments in water (Ritchie et al. 1976; Garg et al. 2017). Turbidity enhances the opacity of water, which hampers the aquatic life (Güttler et al. 2013; Quang et al. 2017; Sebastiá-Frasquet et al. 2019). It is also mentioned in the literature that there can be temporal variation in turbidity concentration due to fluctuation in weather, climate pattern and human activities along the banks (Luis et al. 2019). This property of water is being mapped for long using remote sensing data as it provides synoptic coverage of earth at regular temporal time domain. It has been done by analyzing how suspended sediment concentration change alters the optical properties of the water column. It has been reported in the literature that the reflectance in visible region specifically red region increases with increase in sediments in the water or turbidity (Ritchie et al. 1976; Moore 1980; Doxaran et al. 2002; Pavelsky and Smith 2009; Gholizadeh et al. 2016; Garg et al. 2017). It has also been noticed that the reflectance peak shifts from green to red region of the spectrum (Gholizadeh et al. 2016). It has been mentioned that the concentration of suspended sediments or turbidity shows good relation with the visible region of the spectrum whereas red and NIR regions are more sensitive towards turbidity (IOCCG 2000; Toming et al. 2016; Caballero et al. 2019; Sebastiá-Frasquet et al. 2019).

Novel Corona Virus (COVID-19) has emerged as a deadliest disease across the globe (Chauhan and Singh 2020; Paital et al. 2020), which has affected around 210 countries. Considering, its nature and spread, World Health Organization declared it as a pandemic (Saadat et al. 2020). To safeguard their countrymen from the pandemic, each country declared lockdown time to time in phased manner (Chauhan and Singh 2020). India had also called the longest ever lockdown in the entire country in view of the pandemic. Studies reported that the environmental condition over major cities has improved in terms of reduction in pollution either water or air across globe due to the lockdown (Braga et al. 2020; Chauhan and Singh 2020; Collivignarelli et al. 2020; Dantas et al. 2020; Lal et al. 2020; Li et al. 2020; Muhammad et al. 2020; Otmani et al. 2020). In India also, it has been reported that the air quality in the major cities and the water quality of the rivers/water body improved with the lockdown period (Chauhan and Singh 2020; CPCB 2020; Paital et al. 2020; Saadat et al. 2020; Yunus et al. 2020). It was also stated that the water of the rivers such as Ganga and Yumuna passing through major cities is much clear and their turbidity has reduced. In the present study, an attempt has been made to verify it using remote sensing data for different stretches of the Ganga River. The temporal changes in reflectance in visible region bands of the Sentinel-2 data and normalized difference turbidity index (NDTI) have been analyzed for pre and post-nationwide lockdown dates. Further, as no field data were available for this time period, the results are presented in qualitative terms.

2. Study area and data used

Ganga River is the most sacred river and has mythological importance in India. It originates in Himalaya as Bhagirathi and Alakhnanda rivers, after the confluence of these tributaries at Deoprayag, the river is then called as Ganga River. Its basin area falls in four adjacent countries India, Nepal, Tibet (China), and Bangladesh. The Ganga River basin in India covers nearly one-third of its total geographical area. The river runs a total length of 2525 km before draining into the Bay of Bengal (Jain et al. 2007). From mountainous Himalaya, the river flows mostly in the south direction and enters in plains near Haridwar, one of the most pilgrimage towns in the country. Then it turns in south-east direction and flows through the industrial city of Kanpur. The most important tributary of the river, Yamuna, joins it at Prayagraj (formerly known as Allahabad). The confluence of Yamuna and Ganga at Prayagraj is called *Sangam* (means confluence only). From here the river flows in east-ward direction through eternal cities of Varanasi (also known as Banaras or Kashi) and Patna. Then it enters the state of West Bengal, gets split into two Bhagirathi and Padma. The first branch directly drains into the Bay of Bengal and the other enters Bangladesh and then ends in the Bay of Bengal. The river feeds billions of people along its course. As mentioned earlier, the river is most worshipped and holy in nature for Indians, millions of people take a holy dip in it almost every day. The government of India keeps on trying to maintain its water quality through various national-level plans and programs (NMCG 2020). Still, the water quality in many places is not fit for direct drinking.

In the present study, the stretches of the river at Haridwar, Kanpur, Prayagraj, and Varanasi have been studied for change in turbidity during the Phase-I (25 March–14 April 2020) of the lockdown through remote sensing data. The location of these cities/stretches is provided in Figure 1. Haridwar lies in Uttarakhand and the other 03 are major cities of Uttar Pradesh State of India. Haridwar is the city where the Ganga River enters the plains. It has mythological importance in India, therefore, a very large number of pilgrims visit this place every day throughout the year and take a holy dip in Ganga water. The place people take holy bath '*Har-ki-Pauri*', is the diverted water from Bhimgoda Barrage in its right bank canal (see Figure 1). Further, the upstream region of the river, from its origin, has several places for pilgrims, therefore, many developmental activities going on in the vicinity to cater to the huge population of the visitors. Due to these types of activities along the river upstream, the water in the river remains turbid, most of the time. Kanpur is a city famous for its leather and textile industries. It is generally said that the water quality of the river deteriorates after the city. It can be seen from Figure 1 that there is Ganga Barrage on the river just before it enters Kanpur city. Therefore, the turbidity remains low to moderate along the river across the city. The city at the confluence of Yamuna and Ganga called Prayagraj is again a pilgrimage city. Large devotees take a holy bath at the *Sangam*, every day. Last year, the city conducted the major bath festival (bath in Ganga River) '*Kumbh*'. Then the next important city is Varanasi , another sacred city. It is also regarded as the spiritual capital of India. The city is known for its silk fabric industry along with perfumes, ivory, sculpture, etc.

To map the turbidity in these stretches of Ganga River, the Sentinel-2A/B dataset has been used. The Sentinel-2A and Sentinel-2B satellites were launched on 23 June 2015 and 07 March 2017, respectively. Its Multi-spectral Instrument (MSI) provides data in 13 spectral bands ranging from visible and near-infrared to short wave infrared (443–2190 nm) regions, with a swath width of 290 km and a spatial resolution of 10 m (four visible and near-infrared bands), 20 m (six red edge and shortwave infrared bands) and 60 m (three atmospheric correction bands). The details of each band and wavelength regions are given in Table 1.

The details of stretch wise satellite data used are given in Table 2. The cloud-free data of respective dates were downloaded from the Sentinel Scientific Data Hub (https://scihub.copernicus.eu/). In the present study, the Level-1C, that is, radiometrically and geometrically corrected top of atmosphere reflectance product of Sentinel-2A/B were used to maintain the uniformity in terms of atmospheric correction.

The intermittent rainfall, during the study period, has also changed the turbidity pattern at each of the stretches under consideration. Therefore, the daily rainfall (in mm) data available for Haridwar, Kanpur, Prayagraj, and Varanasi stations at India - Water Resources Information System (India-WRIS) for the period from 15 March–15 April 2020 was analyzed.

3. Methodology

Due to the COVID-19 outbreak, India has declared country-wide lockdown in two phases from 25 March – 14 April 2020, and 15 April – 03 May 2020 (MHA 2020). Because of this, all the industrial activities other than essential were closed, and people asked to confine themselves in their houses. The lockdown resulted in minimum disturbance to the nature, especially, the Ganga River (Yunus et al. 2020). There was

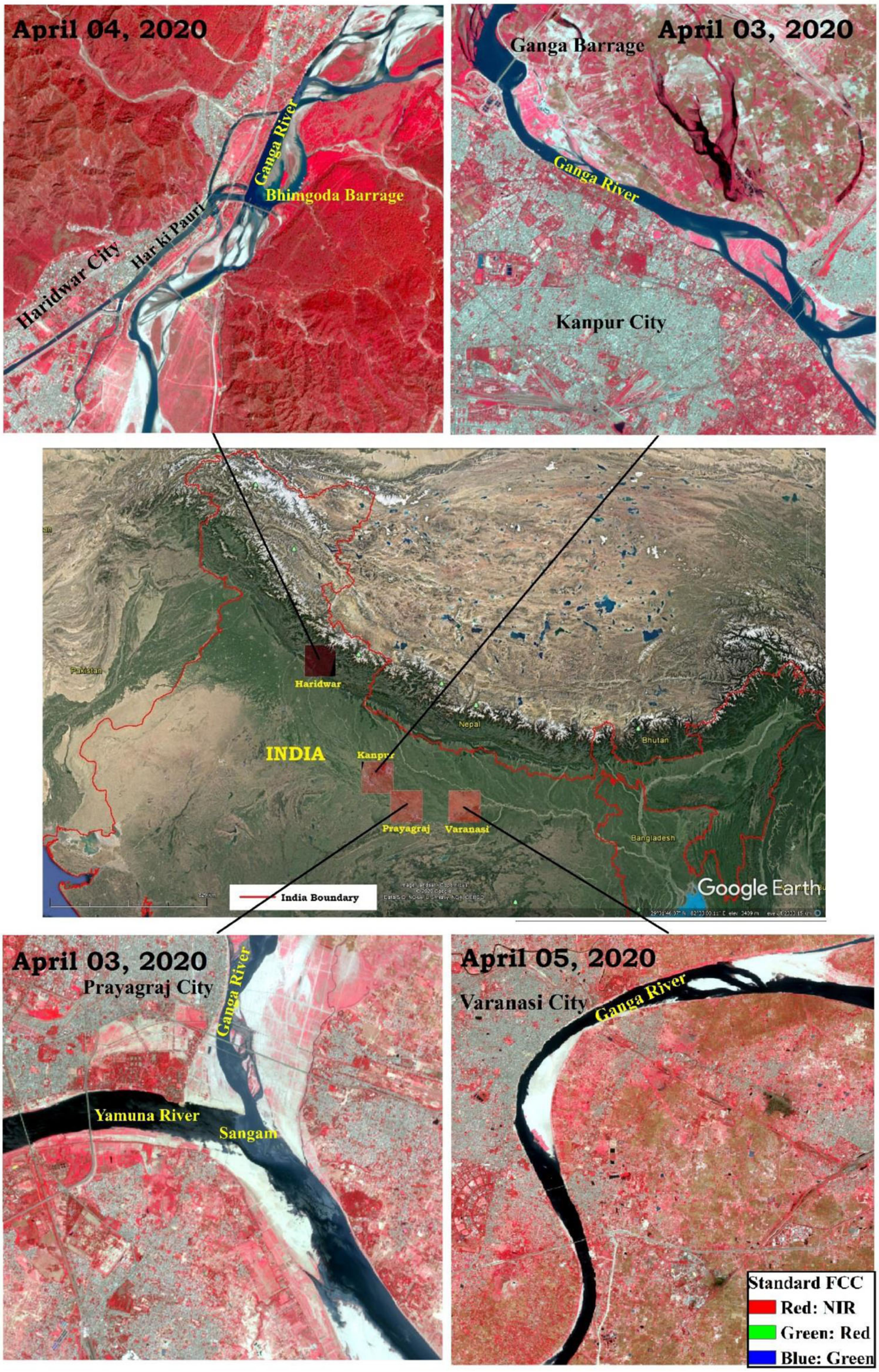


Figure 1. Location of Ganga River stretches under consideration on Google Earth Image.

Table 1. Sentinel-2 Multispectral Imager bands and their details.

Band (wavelength region)	Central wavelength (nm)	Resolution (m)
Band – 1 (Coastal aerosol)	443	60
Band – 2 (Blue)	490	10
Band – 3 (Green)	560	10
Band – 4 (Red)	665	10
Band – 5 (Vegetation red edge)	705	20
Band – 6 (Vegetation red edge)	740	20
Band – 7 (Vegetation red edge)	783	20
Band – 8 (NIR)	842	10
Band – 8A (Vegetation red edge)	865	20
Band – 9 (Water Vapor)	945	60
Band – 10 (SWIR - Cirrus)	1375	60
Band – 11 (SWIR)	1610	20
Band – 12 (SWIR)	2190	20

less industrial waste effluent in the water, minimum anthropogenic activities along its banks due to restricted pilgrim visits, and other activities along its course (CPCB 2020). It was reported that the water quality, in terms of clarity or turbidity, of the river has improved at many places along its course during this short time period (CPCB 2020; Yunus et al. 2020). In the present study, an effort has been made to study it using remote sensing data, as there was no scientific investigation supporting it. For the analysis, the major cities or cities associated with major pilgrim activities namely Haridwar, Kanpur, Prayagraj, and Varanasi were identified as study stretches of the river. The overall methodology adopted to map the changes in turbidity is provided in Figure 2.

3.1. Identification of water pixels

To study the water quality of the river, in terms of change in turbidity, the optical remote sensing data from Sentinel-2 data (as given in Table 2) of pre- and post-lockdown were analyzed for change in reflectance and hence change in turbidity. The MSI sensor provides data from visible to SWIR wavelength region in reasonably high spatial resolution. Initially, the water pixels on each date were estimated using the normalized difference water index (NDWI) given by McFeeters (1996) as provided in Eq. (1).

$$NDWI = \frac{R_G - R_{NIR}}{R_G + R_{NIR}} \quad (1)$$

Where R_G and R_{NIR} are reflectance in green and NIR bands, respectively. The reason for considering green and NIR wavelength regions was that water reflects the highest in the visible region and absorbs all energy in the NIR region of EMR. The value of NDWI varies from -1 to $+1$. The value of more than 0 is theoretically being considered as water in the NDWI image. However, it is recommended that one should follow a trial and error approach and decide the threshold for water pixels. After identifying the water pixels, the visible to VNIR bands were masked only for water

Table 2. The list of data used in the present study.

City	Sensor	Date
Haridwar	Sentinel-2B	20 March 2020
	Sentinel-2A	25 March 2020
	Sentinel-2B	30 March 2020
	Sentinel-2A	04 April 2020
	Sentinel-2A	14 April 2020
Kanpur	Sentinel-2A	19 March 2020
	Sentinel-2A	29 March 2020
	Sentinel-2B	03 April 2020
	Sentinel-2B	13 April 2020
Prayagraj	Sentinel-2A	09 March 2020
	Sentinel-2B	24 March 2020
	Sentinel-2A	29 March 2020
	Sentinel-2B	03 April 2020
	Sentinel-2B	13 April 2020
Varanasi	Sentinel-2A	16 March 2020
	Sentinel-2A	26 March 2020
	Sentinel-2B	31 March 2020
	Sentinel-2A	05 April 2020
	Sentinel-2B	10 April 2020

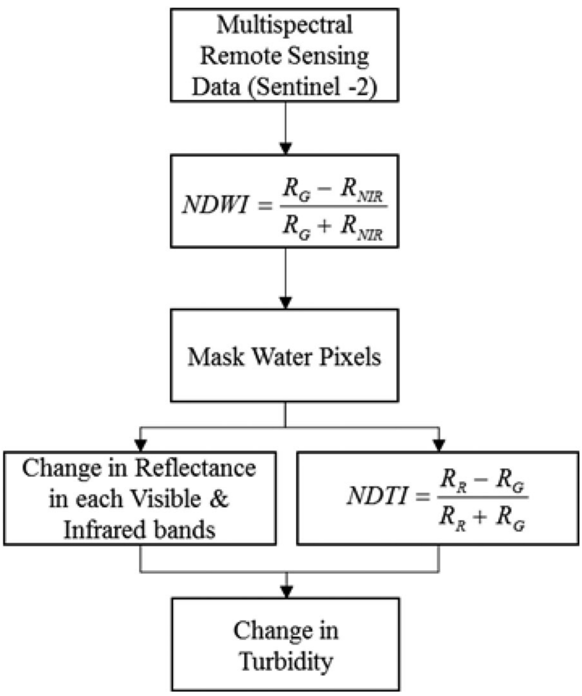


Figure 2. A broad framework of the methodology used.

pixels on the respective dates. It has been reported in the literature that the red and NIR region of EMR is most sensitive to turbidity. Therefore, initially, the change in reflectance in each visible to NIR wavelength bands was studied.

3.2. Change in reflectance in each visible to NIR band of sentinel-2

It is to be noted that the suspended sediment concentration and the turbidity are frequently being treated as similar or same in the remote sensing technology field (Ritchie et al. 2003). Therefore, in the present study, the turbidity term has been used throughout, as a proxy for suspended sediment concentration. It has been reported in the literature and proved that, due to the change in turbidity of the water, the changes in spectral reflectance in visible regions of the spectrum are significant (Ritchie et al. 1976; Liedeke et al. 1995; Brezonik et al. 2005). Literature suggests that even a single band, if chosen appropriately, can provide a robust estimate of turbidity (Pavelsky and Smith 2009; Nechad et al. 2010; Gholizadeh et al. 2016). It was suggested that a single red wavelength region can be used to estimate the water turbidity (Miller and McKee 2004; Hellweger et al. 2007; Shi and Wang 2009). However, it was reported that the NIR region is also equally sensitive to turbidity and less influenced by bottom reflectance in shallow waters (Caballero et al. 2019; Sebastiá-Frasquet et al. 2019). Studies also mentioned the use of red and NIR together for better turbidity assessment (IOCCG 2000; Doxaran et al. 2002; Toming et al. 2016). These single band approaches were used where the reflectance increases with increment in turbidity. There are a large number of studies, where all the bands of the entire visible wavelength region are analyzed either individually or in combination for turbidity estimation (Sebastiá-Frasquet et al. 2019). In the present study also, the bands through blue to NIR were analyzed for change in their spectral response due to a change in turbidity concentrations in view of the longest ever lockdown in India. The simple approach of density slicing has been adopted over each visible region band of each day image. The reflectance on each water pixel of each day was sliced or classified into a number of groups. It was considered that as the sediment concentration increases, the reflectance in visible region increases or vice-versa. Therefore, the pixels with high reflectance in each band are regarded as high turbid regions, whereas low reflectance as low turbid. In this way, all the bands of Sentinel-2A/B are classified as very low, low, moderate, high, very high turbid. However, these results couldn't be validated as field data was not available due to lockdown in the country.

3.3. Qualitative estimate of turbidity through NDTI

It has also been reported in the literature that relying on a single band or algorithm sometimes results in overestimation or underestimation of suspended sediment concentration (Kuhn et al. 2019; Pahlevan et al. 2019). It was suggested, either use combination of sensitive bands or different algorithms to reach the final conclusion. Therefore, an attempt has been made to qualitatively estimate the temporal turbidity in each stretch using the NDTI developed by Lacaux et al. (2007).

$$NDTI = \frac{R_R - R_G}{R_R + R_G} \tag{2}$$

Where R_R is the reflectance in the red band. Generally, the reflectance of pure water is more in green than the red wavelength region. However, it has been reported that the red region reflectance increases with an increase in turbidity. Therefore, the red and green bands were used to enhance the image for turbidity. Initially, the water pixels were identified as mentioned above, then Eq. (2) was applied using these two bands to map NDTI. The higher value of turbidity yields a high value of NDTI and vice versa.

4. Results and discussion

The water quality, in terms of turbidity, has been analyzed to verify the change in the quality of Ganga River water due to the longest ever country-wide lockdown. In the present study, the Sentinel-2 multispectral data of the first phase of lockdown, that is, from 25 March–14 April 2020, was analyzed. Ganga River is considered as most sacred river and people have associated sentiments or rituals with it in India. Further, a million people reside at the bank of the river along its course. However, in many places, the quality of water in the river is not fit for drinking. The change in turbidity at the most popular and crowded stretches of the river, that is, Haridwar, Kanpur, Prayagraj, and Varanasi has been analyzed purely based on remote sensing data adopting the methodology discussed in the previous section. The results are discussed in the subsequent section.

4.1. Change in reflectance in each visible to NIR band of sentinel-2

It has been reported in the media that the water of the Ganga River has improved a lot in terms of its clarity during the lockdown. In this study, it has been investigated simply through the remote sensing data and techniques. The data of Sentinel-2 satellites (both A & B) as mentioned in Table 2 were analyzed. Initially, the change in reflectance in each visible to NIR band was accessed, as the minute change in turbidity, changes the reflectance in these wavelength regions. In the case of river stretch at Haridwar (Figure 3a), the depth of water is mostly shallow downstream Bhimgoda Barrage, therefore, there is not much change in the water reflectance in the blue band with a central wavelength of 490 nm. However, there was a decrease in reflectance in the water upstream of the barrage from 25 March – 04 April 2020; which may be due to a reduction in sediments causing less scattering of blue light. Similar changes, reduction in blue band reflectance, were found near the '*Har ki Pauri*' region, which might be attributed to less disturbance by pilgrimage activities near this place. The same kind of results was found in the green band (560 nm), that is, reduction of reflectance of water due to reduction in human activities in and around Ganga River near Haridwar leading to a reduction in turbidity. Major changes in reflectance were noticed in red and NIR regions of the spectrum, as these bands have relatively less interference from the bottom and return backscattered energy from suspended particles mainly.

The decrease and increase in reflectance of water due to turbidity have also been affected by intermittent rainfall during the period of analysis, in this regard, the rainfall data of this time period was also analyzed as shown in Figure 4a. It can be seen that after 15 March 2020, there was no heavy rainfall in the region till 20 March

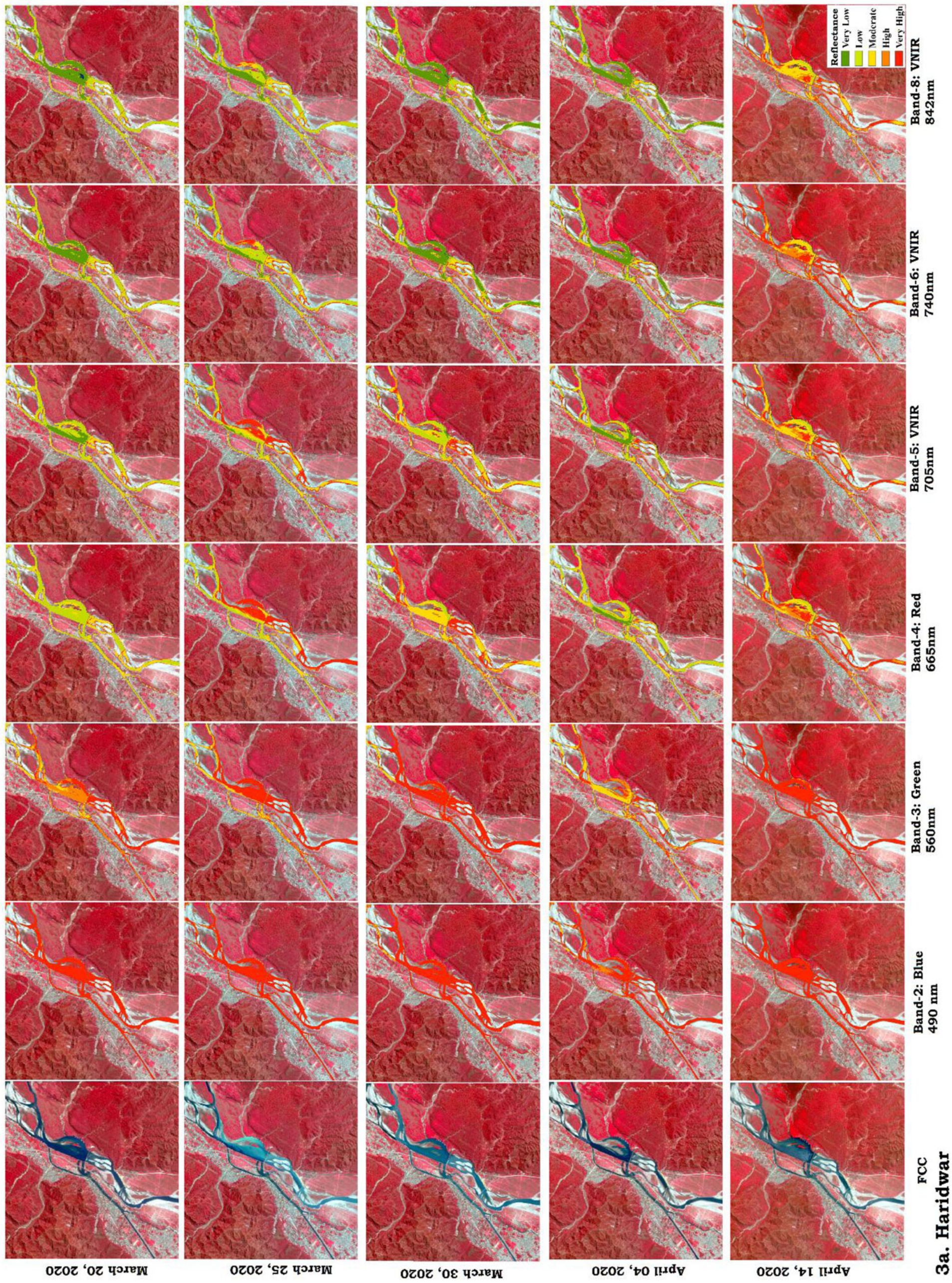
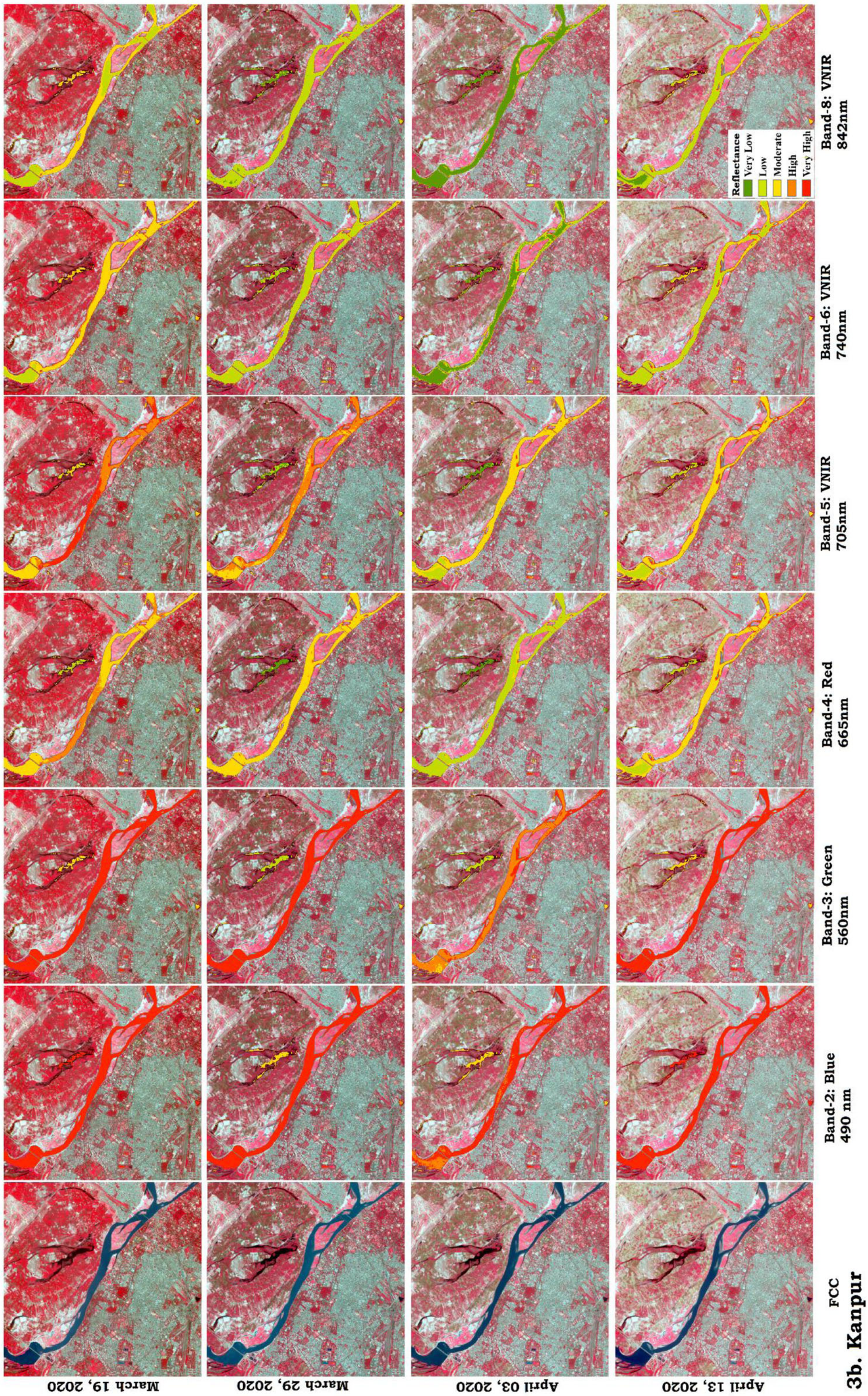


Figure 3. Change reflectance in Visible to NIR bands of Sentinel – 2 due change in turbidity concentration on respective dates; (a) Haridwar, (b) Kanpur, (c) Prayagraj, (d) Varanasi.

2020, therefore, the water was relatively clear on 20 March 2020. However, there was rainfall from 21 to 24 March 2020 of around 2.5 mm in Haridwar, leading to more turbidity in the water of the Ganga River. That is why, all the bands were showing high reflectance due to more sediments in the river on 25 March 2020. On the other hand, there was not much precipitation after 25 March 2020, therefore, the



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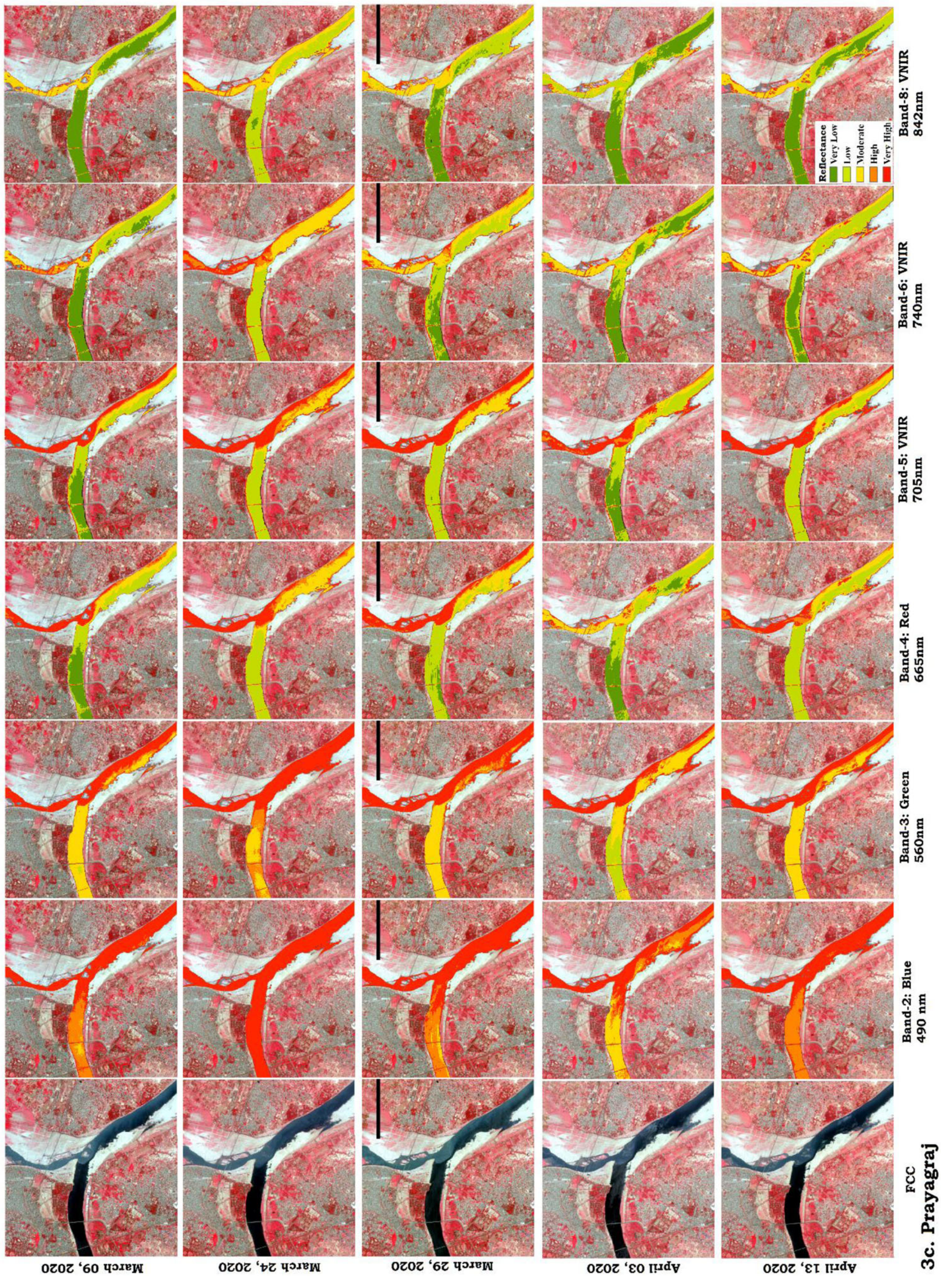

Figure 3. Continued.

reflectance of water reduced throughout in the visible region spectrum bands. Based on visual interpretation, it can be said that water is less turbid. Again, the pattern of reflectance or turbidity has changed on 14 April 2020, which might be attributed to rainfall occurred during 10–11 April 2020. It is inferred that the water quality of the river water has improved, however, it is affected by the contribution from intermittent rainfall occurred during the lockdown period at Haridwar.

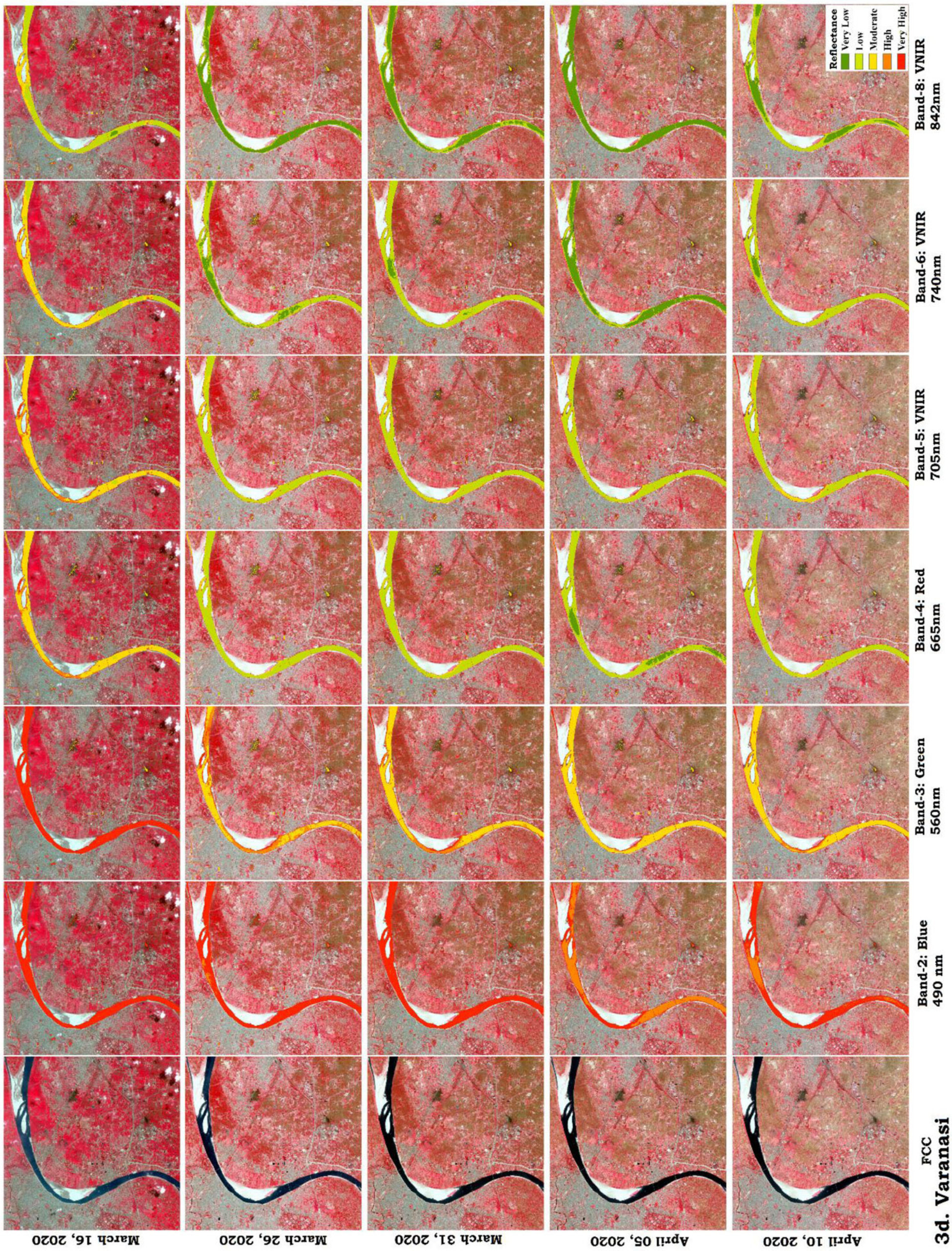

Figure 3. Continued.

Kanpur is again an important city, known for the textile and leather industry. Being on the bank of the river, the effluent from these industries reach Ganga River and pollute its water. A similar approach of monitoring change in reflectance in each visible to NIR band, as mentioned in the previous section was used. The results of the analysis are provided in Figure 3b. In the case of the Ganga River stretch at Kanpur, it can be observed that the water quality of the water has improved continuously till 08 April 2020. It has to be noted that the water in this particular stretch is deeper than the depth at Haridwar stretch considered in the study. Therefore, there was less interference from bottom surface reflectance. However, the rainfall on 08 April 2020 (Figure 4b), has altered the turbidity on 14 April 2020. There was very little change in reflectance in the blue band, whereas, it has slightly reduced in the green band. That might be attributed to reduced turbidity during the period of analysis. Again, it can be noticed that the red and NIR regions are more sensitive towards turbidity.

The river stretch at *Sangam*, Prayagraj, showed major changes in turbidity. At this location, Ganga is shallow as compared to the Yamuna and brings more sediments along with it. Further, heavy pilgrimage activity at this location keeps water turbid. As Kanpur and Prayagraj are not very far away from each other, the rainfall pattern is almost similar. There was no rainfall from 24 March–08 April 2020, in the region. Therefore, the reduction in reflectance or in other terms 'turbidity' was very well analyzed. Yamuna River, as it is deep at this location, some changes, that is, reduction in reflectance, even in the blue region were observed (Figure 3c). This might have occurred due to less suspended sediments yielding less scattering or reflectance. Further, there was less effect of bottom reflectance in the analysis. Even after the confluence, where the river is deeper, it showed a reduction in reflectance in this particular band. Similar results were found in the green band. Again, with the help of red and NIR most sensitive bands, one can easily make out the concentration of turbidity qualitatively. It was noticed that the turbidity at *Sangam* was continuously low as compared to the condition before lockdown. However, the rainfall of 08 April 2020 (Figure 4c), has changed the turbidity condition.

The analysis at river stretch near Varanasi, again showed continuous lowering of turbidity, as reflectance throughout the visible and NIR region has reduced till 08 April 2020 (Figure 3d). It must be noted that the depth of water at this stretch is also deep as compared to Haridwar. Figure 3d depicted that there was a significant reduction in reflectance of the blue band, after the start of the lockdown. However, pixel-wise better spatial variation of turbidity can be studied in longer wavelengths, that is, red and NIR. Again the rainfall on 08 April 2020 (Figure 4d), in the city has altered the turbidity variation.

The study elicited that the red and NIR regions of the spectrum are more sensitive towards suspended sediments or the turbidity, and are in the line of findings reported in the literature. Moreover, these bands have less interference from the bottom. The results of Haridwar upstream Bhimgoda Barrage, Kanpur, the Yamuna at Prayagraj, and Varanasi support this statement. However, for shallow water (2–5 m depth), it is suggested to use the NIR band for inferring about turbidity concentration. Further, the most appropriate band for turbidity mapping using Sentinel-2 is 'red edge' with 705 nm wavelength (Liu et al. 2017; Caballero et al. 2019; Sebastiá-Frasquet et al. 2019). Further, the turbidity concentration is affected by the precipitation in the region, therefore, it is recommended to analyze precipitation data before reaching a conclusion on change in turbidity.

4.2. Analysis of spatio-temporal change in NDTI

There may be some extent of radiometric inconsistency in temporal remote sensing data, even with the same sensor, therefore, sometimes relying on single-band

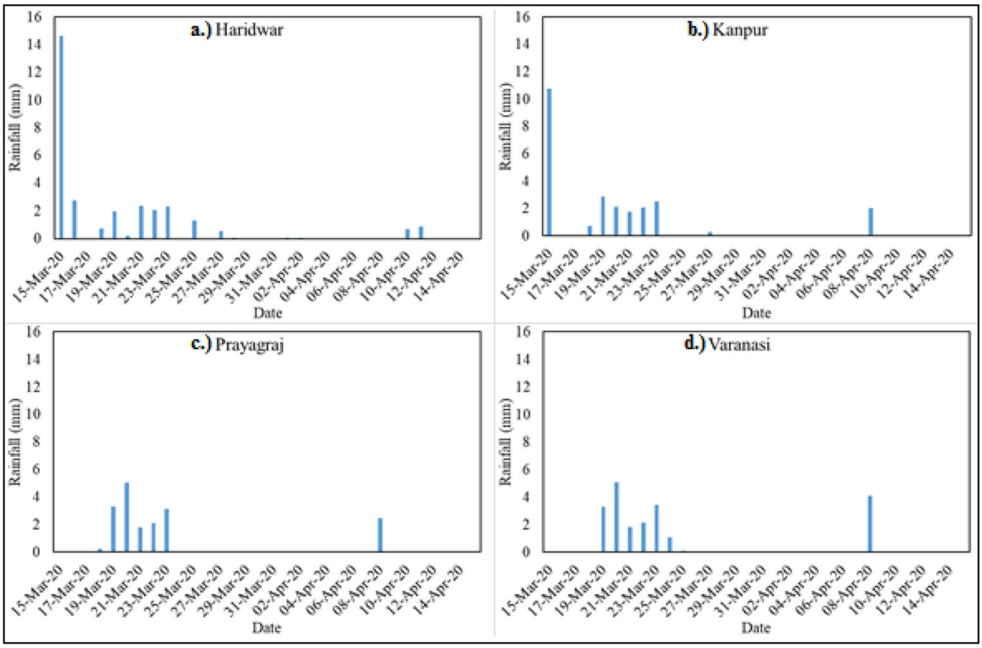

Figure 4. Rainfall at each location during 15 March–15 April 2020 (Source: India - Water Resources Information System, India-WRIS: http://indiawris.gov.in/wris/#/ … accessed on 23 April 2020).

information for turbidity estimation is not always advisable (Kuhn et al. 2019; Pahlevan et al. 2019). It is suggested to blend approaches that use different algorithms at different reflectance ranges to map water quality parameters using remote sensing data such as turbidity (Hu et al. 2012). Tassan (1997) suggested the use of green and red band reflectance to estimate variable suspended sediment concentration in the stratified water column. Therefore, later the results were validated through mapping of NDTI, which is a normalized ratio of red and green band reflectance as given in Eq. (2), of each date at each location as shown in Figure 5. At Haridwar, it is perceivable that the turbidity was low almost every day after the lockdown started. However, intermittent rainfall has changed the turbidity pattern in-between. It was observed that the flow has also increased due to rainfall in the region. The results of Kanpur are much better than Haridwar, as rainfall was less in this stretch. At Kanpur, it was noticed that the turbidity has reduced continuously during the lockdown period. The Yamuna River at *Sangam*, Prayagraj was showing uniform low turbidity, however, the impact of lockdown are evident on Ganga River water. Even after the intermittent rainfall, the water in the Ganga River stretch at *Sangam* is less turbid then ever before. At this location also the flow has increased after the rainfall. It should be noted that the Ganga River water is shallow here than the Yamuna River. The results of NDTI are much better than the single-band approach in shallow water stretches due to the normalization of band reflectance.

Varanasi is another stretch where the water is comparatively deeper. The NDTI analysis at this location showed a consistent reduction in turbidity with the lockdown time period. The analysis depicted that the NDTI value is consistently low in the deep water during this period. It signifies that the turbidity has reduced during the

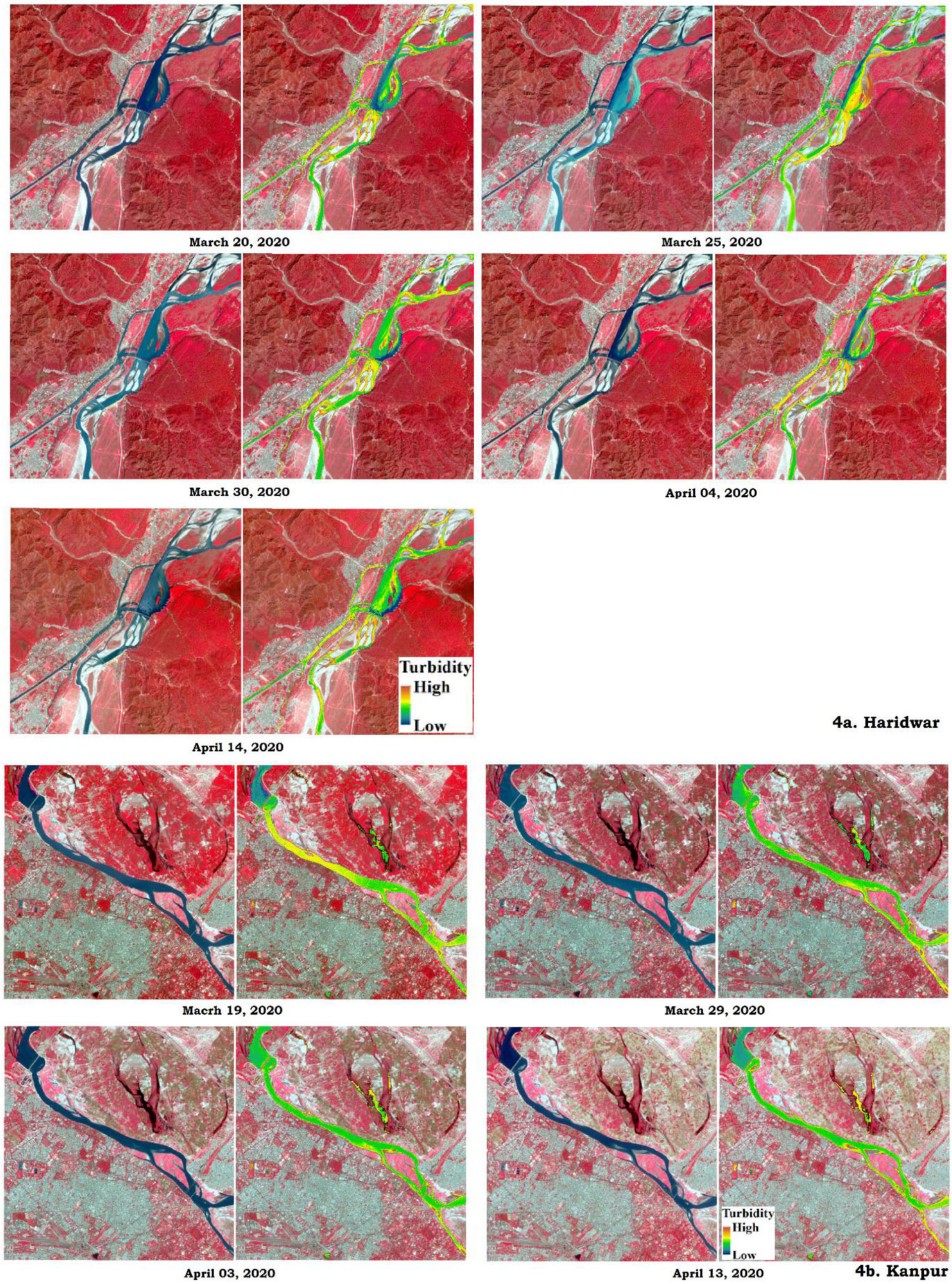

Figure 5. The temporal NDTI maps of Ganga River water at each location along with their FCC; (a) Haridwar, (b) Kanpur, (c) Prayagraj, (d) Varanasi.

period of analysis. Based on the finding, it can be deduced that in the absence of ground observed data, remote sensing approach can be used for preliminary estimates on water quality. The present study focused on turbidity concentration, however, the other optical properties of water can also be analyzed.

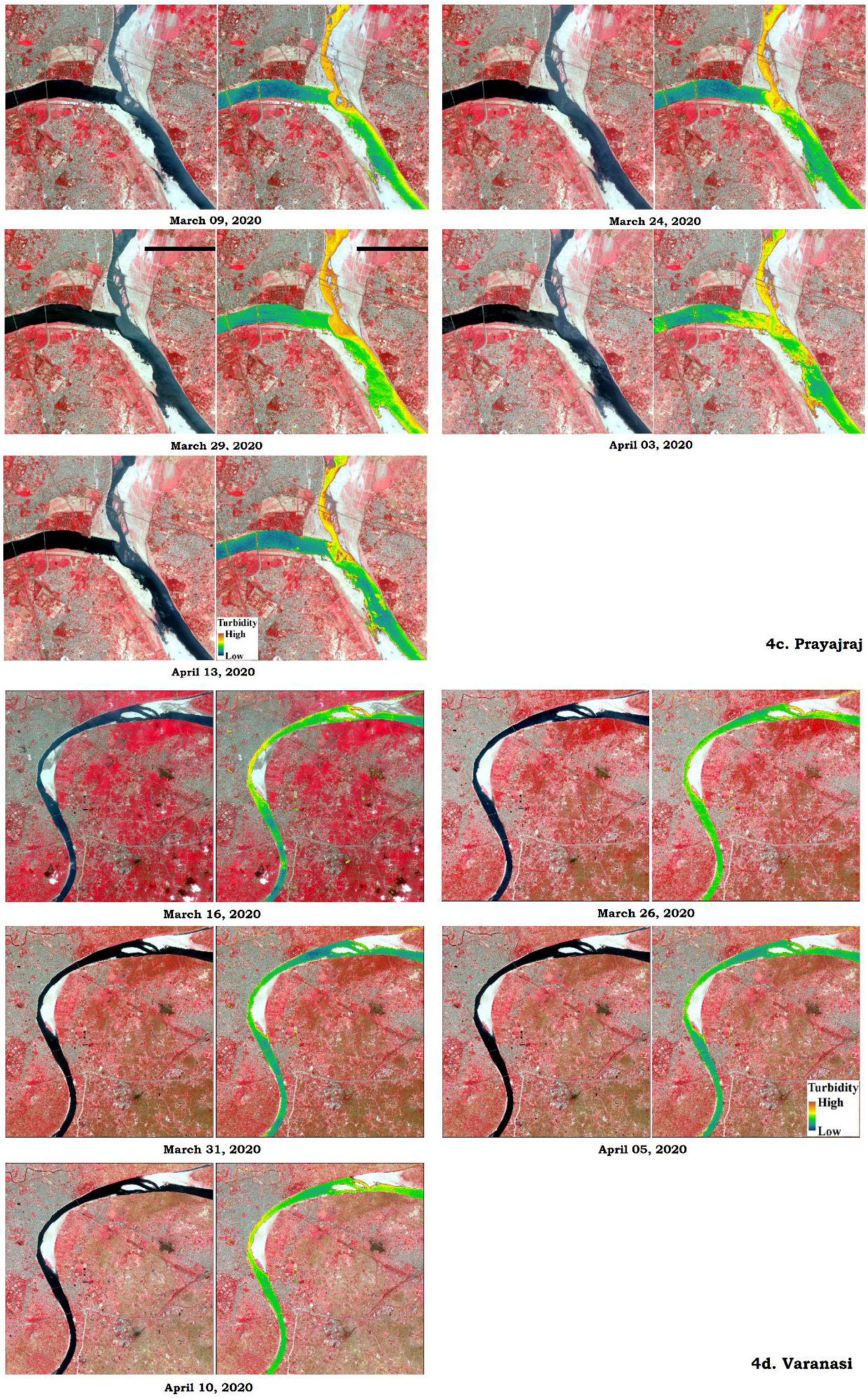

Figure 5. Continued.

5. Conclusions

Turbidity is an important optical property of water that reduces the energy required for aquatic growth. It has been reported that the water quality of Ganga River has improved in terms of clarity due to recent Nationwide lockdown from 25 March–14 April 2020 (Phase-I) in India due to COVID-19. In the present study, the spatial and temporal change in turbidity have been analyzed along the Ganga River during the said period purely through remote sensing. The most attractive pilgrimage stretches of Ganga River i.e., Haridwar, Kanpur, Prayagraj, and Varanasi were selected in this study. Initially, the change in turbidity has been analyzed in terms of change in reflectance in the visible and NIR region of Sentinel-2A/B data. It has been reported in the literature that with the increase in turbidity the reflectance in visible region increases and vice versa. Similar results were found in the present study, the temporal change study showed that reflectance in each visible to NIR region has reduced, which might be attributed to a reduction in turbidity in the water of the river. The blue and green bands could not map the spatial heterogeneity in the turbidity variation due to interference from the bottom. However, a slight reduction in reflectance or turbidity, even in these bands, could be seen in the deep water. It was noticed that red and NIR bands are more sensitive towards turbidity estimation. The deep water absorbs almost all the energy incident upon it, however, due to the presence of suspended matters some energy reflects in these regions of the spectrum. These bands are very useful to quantitatively estimate the turbidity in the absence of field observed data for optically deep water. However, it was also observed that the small amount of precipitation can bring large sediments in the river and change in turbidity immediately. Further, the results were verified through the NDTI band ratio technique. The analysis also confirmed that the turbidity has reduced during the lockdown period. The main reason for the reduction in turbidity in the river, might be less effluent generation and discharge into the river. Further, the activities of pilgrimage along the river were below the minimum during this period of lockdown. It was realized that the spatial water quality information can be generated using the remote sensing approach, which is much better than field-based point information. It is well proven that remote sensing can provide preliminary qualitative estimates of turbidity, however, it is always recommended to verify the results through observed turbidity values. Therefore, the retrieved turbidity through remote sensing approach required verification, which may be conducted once the lockdown will be over. Further, the accuracy of the remote sensing approach for water quality studies may be improved with very high spatial, spectral, and temporal resolution datasets, especially for river water.

Disclosure statement

The authors declare no conflicts of interest.

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