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Some respite for India's dirtiest river? Examining the Yamuna's water quality at Delhi during the COVID-19 lockdown period

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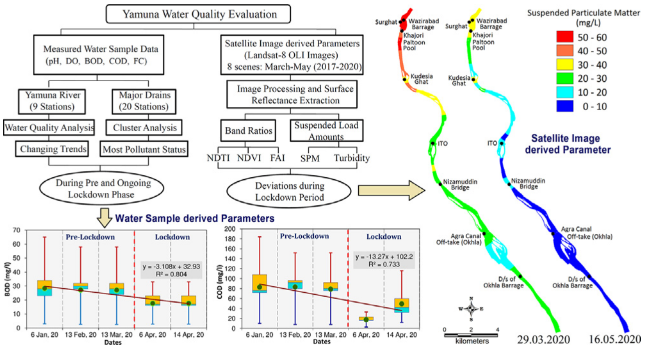
HIGHLIGHTS

- Examines the lockdown's effects on the Yamuna's water quality parameters at Delhi.
- Uses multi-temporal water sample measurements and satellite image derived indices.
- Reductions in turbidity and suspended particulate matter observed in some reaches.
- Extent of improvement dependent on flow conditions and point-pollution sources.
- Domestic sewage increases pollution load markedly despite no industrial effluents.

GRAPHICAL ABSTRACT



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ABSTRACT

The Yamuna's stretch within Delhi is considered as the dirtiest river reach in India and despite numerous restoration plans, pollution levels have risen unabated. However, the enforcement of a nationwide lockdown due to the ongoing COVID-19 pandemic can possibly provide a ray of hope. We analyze the lockdown's impact on the water quality status of this stretch using a combination of measured parameters and satellite image derived indices. Class C Water Quality Index estimates of nine stations indicate an improvement of 37% during the lockdown period. The Biological Oxygen Demand and Chemical Oxygen Demand values reduced by 42.83% and 39.25%, respectively, compared to the pre-lockdown phase, while Faecal Coliform declined by over 40%. Similar analysis of 20 major drains that meet the Yamuna revealed declining effluent loads and discernable improvements in drain contaminant status were ascertained via a hierarchical cluster analysis. Reach-wise suspended particulate matter content, turbidity and algal signatures were derived from multi-temporal Landsat-8 images of prior and ongoing lockdown periods for 117 channel segment zones. These parameters also declined notably within most stretches, although their extents were spatially varied. While the partial/non-operational status of most industries during the lockdown enabled significant reduction in effluent loads and a consequent betterment in the river water quality, its spatial variations and even deterioration in some locations resulted from the largely undiminished inflow of domestic sewage through multiple drains. This study provides an estimate of possible river recovery extents and degree of improvement if deleterious polluting activities and contaminants are regulated properly.

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1. Introduction

The COVID-19 global pandemic, caused by the Novel Coronavirus, is considered to be one of the most virulent diseases to have afflicted humankind. SARS-CoV-2 virus cases were first detected in December 2019, in China's Hubei province (WHO, 2020a), being subsequently declared as a Public Health Emergency of International Concern by the World Health Organization (WHO, 2020b). Till 2nd July 2020, over 10.5 million positive cases have been reported worldwide, with 512,842 deaths (WHO, 2020c), which includes 627,168 detected cases and 18,225 deaths from India alone (https://www.covid19india.org/). With infections rising swiftly and no vaccine/treatment yet formulated, most nations had called for immediate and widespread lockdowns to curb the virus' transmission. The Indian Government had similarly implemented a complete lockdown since the midnight of 24 March 2020 (The Lancet, 2020), to restrict the contagion's spread. With work halting in factories/ industries, closing of commercial establishments and transportation systems almost at a standstill, an obvious result of the lockdown was the improvement in air quality across India's megacities (e.g. Kambalagere, 2020; Mahato et al., 2020; Sharma et al., 2020). The other most obvious consequence pertains to a possible cleansing of the nation's rivers (Mani, 2020; Shukla and Srivastava, 2020), particularly those flowing through large urban areas. However, there is a dearth of any detailed study on this aspect so far.

In 2018, the Central Pollution Control Board (CPCB), India's nodal pollution monitoring agency, had identified over 351 polluted river stretches across India (https://www.downtoearth.org.in/news/governance/as-told-to-parliament-july-15-2019-351-polluted-river-stretches-on-323-rivers-identified-during-2018-65647), with most of these situated along large urban/industrial areas (Basu Roy, 2013). To rehabilitate such reaches, several river clean-up and management programmes like the Ganga Action Plan (GAP Phase-I, 1985), Yamuna and Gomti Action Plans under GAP Phase-II (1993), the National River Conservation Plan (1995) and the Namami Gange (2015) endeavours have been implemented (http://moef.gov.in/wp-content/uploads/report/0203/chap-06.htm). However, such attempts have seldom borne sustained success (Misra, 2018, 2020; Parmar and Singh, 2015), or little recent improvement (Sharma and Kansal, 2011a; Misra, 2014) and pollution levels have risen unabated (Jaiswal, 2007; Luthra and Yadav, 2019).

The River Yamuna, the largest tributary of the River Ganga, flows through the National Capital Territory (NCT) of Delhi and is considered to be the most polluted river in the world (Mishra, 2010). The river enters into the Delhi NCT about 23 km upstream of the Wazirabad Barrage near Palla and departs about 6.9 km downstream of the Okhla Barrage near Jaitpur (Fig. 1a). In this stretch of about 48 km within the Delhi NCT, which comprises only 2% of the Yamuna's total length, it receives almost 79% of its total pollutant load (CPCB, 2006, 2013). Multiple drains connected to major industrial estates contribute such exorbitant amounts (almost 3296 MLD of domestic sewage- CPCB, 2004; Paliwal et al., 2007; Upadhyay et al., 2011; Gautam et al., 2017). The total Biological Oxygen Demand (BOD) content in the Yamuna is about 93 mg/L as against the CPCB standard of 3 mg/L while the Dissolved Oxygen (DO) concentration ranges around 4 mg/L, with it dropping to 0 mg/L in some stretches just downstream of major urban/industrial locales (Mishra, 2010; Kumar et al., 2018). These industrial effluents also foster high levels of heavy metal pollution in this reach (Yadav and Khandegar, 2019). With water abstraction increasing after the construction of the Wazirabad Barrage (for drinking water supply) and the Okhla Barrage (for irrigation), limited freshwater is available during the non-monsoon months, thus diminishing the river's regenerative capacity by retarding contaminant dilution (CWC, 2017). As a result, there have been rising concerns over the deterioration in the Yamuna's water quality (Babu and Seth, 2007).

Upadhyay et al. (2011) and Kumar et al. (2018) have revealed that the Yamuna's water quality in its Himalayan segment up to Palla, before it enters Delhi NCT, is of moderate quality, complying with CPCB standards, whereas the Delhi segment is the worst affected stretch of the entire river. This is substantiated by a number of studies, all based on point sampling of the river at select locations within the above two Barrages, which have ascertained the Water Quality Index (WQI) (e.g. Sharma and Kansal, 2011a; Saini and Sonkar, 2015; Sharma et al., 2017a, 2017b; Roy and Ghosh, 2019). Industrial effluents and the discharge of domestic sewage through drains (Bhardwaj et al., 2017; Parihar et al., 2019), improper location of Sewage Treatment Plants (STPs) and inconsistencies between their operating capacities (of the 41 STPs installed some are at times non-operational due to power cuts and technical/ maintenance issues) and the actual sewage amounts generated are the usual primary causes for such heightened pollution levels (Jain, 2009; Upadhyay et al., 2011; Kumar et al., 2018), with periodic spikes being recorded in the aftermath of idol immersions post religious festivals (Kaur et al., 2013). Some studies have used statistical measures to link the different pollutant loads (e.g. Singh and Singh, 2015; Singh et al., 2018), while models like QUAL2E/QUAL2Kw and STREAM-II have been used to simulate different pollution scenarios to determine the maximum permissible pollutant discharge (Paliwal et al., 2007; Sharma and Singh, 2009; Walling et al., 2014; Sharma et al., 2017a, 2017b). Only one study has linked satellite image derived parameters with measured pollution loads in this stretch of the Yamuna (e.g. Said and Hussain, 2019), with this method presenting possibilities for continuous monitoring of the entire stretch (for further information on the Yamuna's water quality degradation, see Supplementary Section 1). The effectiveness of the Yamuna Action Plan (YAP I and II) was examined by Sharma and Kansal (2011b), with their results suggesting that all attempts so far have been unsuccessful and that the river fails to maintain the minimum ecological flow necessary to sustain aquatic life (as was also reported by Upadhyay et al., 2011, Rani et al., 2013 and Sharma and Bhadauriya, 2019).

An otherwise difficult to achieve condition, the nationwide lockdown enforced in India from 25th March 2020, to curb the spread of COVID-19, may have possibly resulted in improving the water quality of the Yamuna. The ensuing partial operational status of most industries within Delhi would likely reduce the amount of untreated industrial effluents and sewage being discharged into the river and the BOD and other pollutant loads might possibly diminish as a result. However, to what extent the above surmise actually holds true and which stretches of the river are precisely affected in what manner, needs more in-depth investigation. To achieve this, a combination of measured parameters and geospatial techniques has been employed. The baseline information presented herein provides insights into the extent of water quality enhancement obtainable by periodic suspension of polluting industrial activities and identifies river reaches that benefit the most from this.

2. Materials and methods

2.1. Conceptual framework of the Water Quality Index (WQI)

Water quality assessments gauge whether or not the available water is suitable for a specific use (bathing, industrial or domestic purposes) or if the environment is adversely affected by any pollutants within it (Bagchi and Bussa, 2011). A water sample's quality is thus defined in terms of its physical, chemical and biological parameters (Abbasi and Abbasi, 2012; Kachroud et al., 2019). First devised by Horton, 1965, for the U.S., it has emerged as one of the simplest and most efficient means of depicting the overall water quality (Tyagi et al., 2013). The different measured variables are standardised and converted into a composite number that best denotes the suitability of use of a particular water sample (Kumar and Dua, 2009). Different agencies like the European Community, World Health Organization, CPCB and the Indian Standard Specifications for drinking water, have formulated their own standards regarding the permissible limits of measured

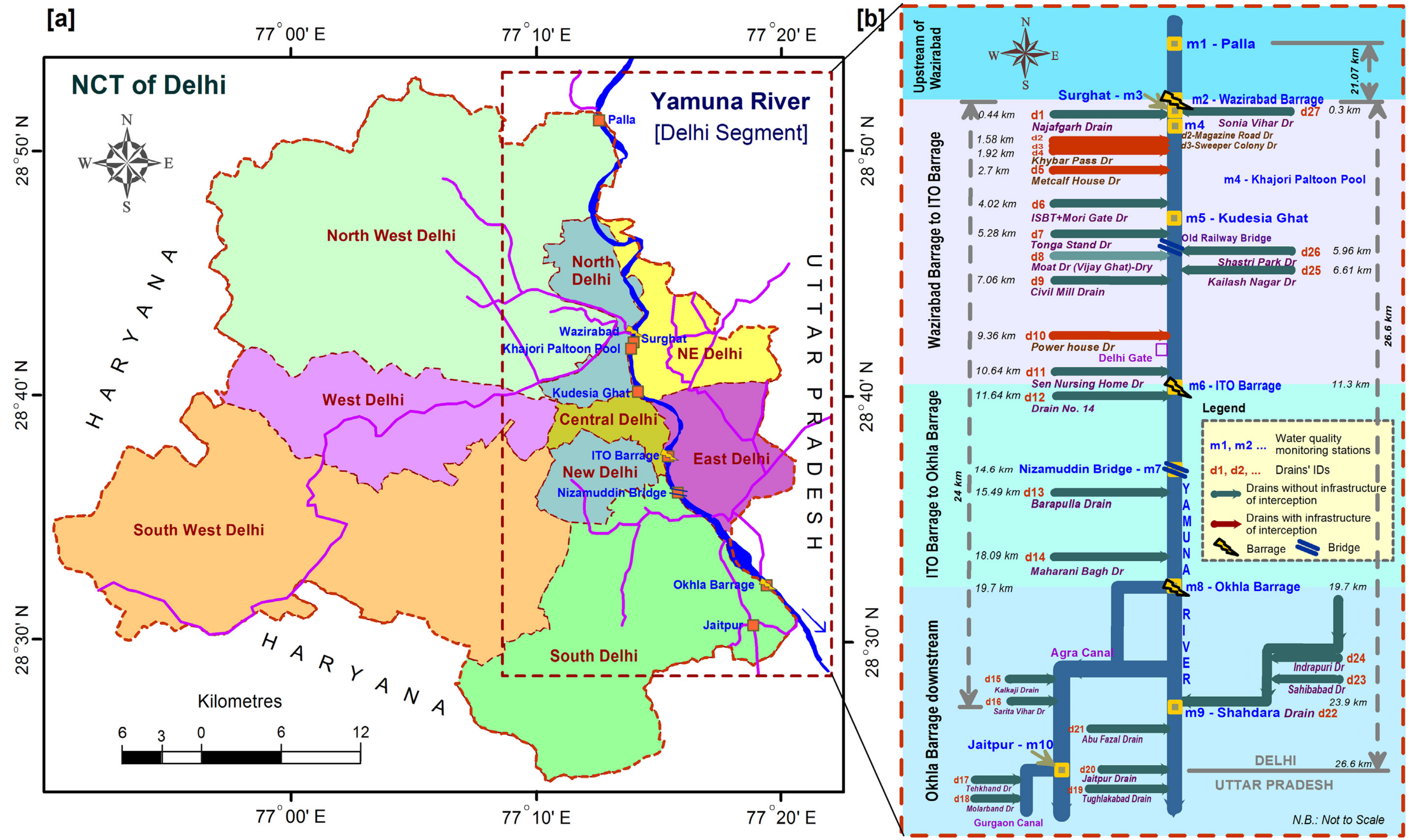

Fig. 1. Reference map, showing **(a)** The study area, and **(b)** Schematic diagram of the Yamuna's stretch within the Delhi NCT, with water quality monitoring stations (m1-m9) and major drains (d1-d27) (based on CPCB, 2020; Paliwal et al., 2007).

parameters for rating a sample as good/suitable for a specific use (Sargaonkar and Deshpande, 2003; Bharti and Katyal, 2011; Rout, 2017).

Five water quality parameters- pH, BOD, DO, Chemical Oxygen Demand (COD) and FC, were used for the WQI assessment (for further information about the individual parameters and the commonly used WQI formula, see Supplementary Section 2). The considered parameters here are those that are most commonly used for water quality analysis (Abbasi and Abbasi, 2012) and these are also employed by the CPCB for deriving the water use suitability as per the different designated water quality classes (CPCB, 2006). However, the DO is excluded during the detailed analysis (see Section 3.2) as it was not available within the examined period for all stations. The derived WQI results were compared against the designated CPCB water quality standards (see Table S1 in the Supplementary Information file), based on the parameters used.

2.2. Water quality data source and analysis

Water quality data was obtained from the Delhi Pollution Control Committee (DPCC) for nine monitoring stations (m1-m2) (Fig. 1b- for individual station details see Table S2 in the Supplementary Information file). Of these, the first 8 are located on the Yamuna itself while the last station at Jaitpur is located on the Agra Canal, that off-takes from the Yamuna at Okhla. As this canal carries a portion of the Yamuna's flow and is also linked to it through a smaller channel at Jaitpur, we have considered it to be representative of the Yamuna's water quality characteristics in its lower reaches within the Delhi NCT.

The time period primarily examined is from January to April of 2020. The data obtained for 6 January, 13 February and 13 March 2020, was taken to represent the pre-lockdown state while that of 6 April and 14 April 2020, as indicative of the water quality status during the lockdown phase. For comparisons between the previous year's non-lockdown state with the present year's lockdown period, water quality data for 14 January, 19 February, 16 March and 23 April of 2019 was also considered. Thus each of the four examined months in 2019 and 2020 had one representative value for each water quality parameter (where available), with only April 2020, having two representative values (i.e. on 6th and 14th April), which were taken to respectively denote conditions in the early and latter phases of the imposed first lockdown phase (25 March to 14 April 2020) that was operative in the country. The water quality status of the 20 drains flowing into the Yamuna at Delhi was also obtained from the DPCC for the same time period as the river dataset. This was examined to discern the effluent quality meeting the river and gauge if the lockdown has had any effect on the area's drains besides its effects on the main channel.

Statistical attributes, trend analysis as well as box-whisker plots were computed and visualized using MS-Excel. Among the frequently used normalization techniques (i.e. ranking, distance to target, *Z*-score, min-max and proportionate normalization) (Nardo et al., 2009), the Decimal Point Normalization (also sometimes referred to as the Floating Point Number) technique was employed to rank the drains during the prior-lockdown and lockdown periods, based on the resulting additive aggregation (arithmetic mean) scores (Tate, 2012; Tofallis, 2014). In this normalization method, the data attributes are transformed by simply moving the decimal points of the original data (García et al., 2015) and the maximum number of decimal points to be moved is dependent on the maximum values of the attribute data (Han et al., 2011). Furthermore, Hierarchical Cluster Analysis (HCA) was carried out using the Squared Euclidean Distance and Ward's method (Bu et al., 2010), with Z-score standardization by variable, in IBM SPSS, to sort the drain sampling stations into distinct clusters and identify the most polluting ones. This clustering was visualized using dendrograms, which are widely used in water quality analysis (e.g. Vega et al., 1998; Shrestha and Kazama, 2007; Tokatli et al., 2014).

2.3. Satellite image datasets and processing

While in-situ methods (i.e. water sample testing) provide accurate data, they are often labour-intensive and thus not time/cost-effective (Adsavakulchai and Panichayapichet, 2003). Furthermore, monitoring the entire river from a one-time/single dataset is quite difficult (Gholizadeh et al., 2016). Geospatial datasets/techniques are thus valuable tools in water quality studies (Ritchie et al., 2003; Elhag et al., 2019), being widely used to measure parameters like suspended sediments, coloured dissolved organic matter, turbidity, BOD, COD, chlorophyll-a and sea surface temperature (e.g. Klemas, 2013; Bulgarelli and Zibordi, 2018; Luis et al., 2019; Vanhellemont, 2020). Such studies provide baseline datasets for temporal comparisons (Bukata, 2005) and sensor improvements have enabled the study of complex aspects like algal bloom and mineral content in water bodies (Ramadas and Samantaray, 2018; Wang and Yang, 2019).

The utilized Landsat-8 OLI images (spatial resolution 30 m, Path: 140, Row: 46) were obtained from the United States Geological Survey EarthExplorer repository, with a single scene containing the entire studied stretch. Four images were initially downloaded for early-March to mid-May of 2020 (for 13.03.2020, 29.03.2020, 30.04.2020 and 16.05.2020). These dates respectively represent the pre-lockdown stage, just after lockdown stage, more than a month into the lockdown stage and finally, the end phase of the third lockdown stage in India (a fourth phase was implemented till 31st May 2020). Suitable images could not be obtained for mid-April 2020, due to excessive cloud cover. Images for the preceding years (2017–2019) were downloaded for the days closest to the above four dates (for 2017: 05.03.2017, 21.03.2017, 22.04.2017 and 08.05.2017; for 2018: 08.03.2018, 24.03.2018, 25.04.2018 and 11.05.2018; for 2019: 11.03.2019, 27.03.2019, 28.04.2019 and 14.5.2019), and 16 scenes in all were eventually processed.

While there was a slight dissonance between the dates of the measured water quality parameters and the satellite images (since they were obtained from two different organisations), the water sampling dates were quite proximate to the image scene dates for at least a portion of the dataset and as such these parameters could then be feasibly compared (albeit partly). Furthermore, we compared the measured water quality parameters mostly within themselves while the image derived indices were examined in the same manner, and so for the greater part of the analyses these two datasets were mutually exclusive and did not skew the results. Since there are no other similar datasets for any alternate dates within the examined time period, this analysis was perforce based on whatever information was available.

Image pre-processing was done on the ACOLITE (Atmospheric Correction for OLI 'lite'- Dogliotti et al., 2018) platform, which enables quick processing of multiple scenes (Yunus et al., 2020) and the direct derivation of some studied parameters (see ACOLITE User Manual-RBINS-REMSEM, 2019). ACOLITE uses a Dark-Spectrum Fitting (DSF) algorithm (Vanhellemont, 2019) to correct for atmospheric effects and obtain band-wise surface reflectance, with it being specifically calibrated for the Landsat-8 OLI and Sentinel-2 sensors (see Vanhellemont and Ruddick, 2015, 2016, 2018 for processing details). Since the Yamuna was depicted as a dark feature in all scenes with no whitecaps from waves nor were any exceptionally bright pixels due to specular reflectance evident (Mobley et al., 2016), sun glint correction was not deemed necessary. ACOLITE also enabled extraction of the surface reflectance specifically for water pixels, the remote sensing reflectance and the Rayleigh corrected reflectance, which were used later to derive the Suspended Particulate Matter (SPM) and turbidity measures (for all definitions/formulae see RBINS-REMSEM, 2019, Vanhellemont, 2019 and Supplementary Section 3). The other parameters derived were the Normalized Difference Turbidity Index (NDTI), Normalized Difference Vegetation Index (NDVI) and the Floating Algal Index (FAI) (see Supplementary Section 3).

2.4. Delineating channel segments and reach-wise database creation

The Yamuna's outline within the Delhi NCT was obtained from the OpenStreetMap dataset, overlain on Google Earth imagery and edited manually to obtain accurate banklines. The thalweg was prepared similarly and divided along its length into 117 segments of 500 m length each. These were overlain on the NDTI, NDVI, FAI, SPM and Turbidity layers for the different time periods (as mentioned in Section 2.3 in the second paragraph), cropped accordingly and reach-averaged values for each parameter were extracted into the corresponding channel polygon segment (while doing this, a 500 m wide buffer was first created around the river to avoid any edge effects). To preclude mid-channel islands (whose spectral signatures differ markedly from that of the adjacent water pixels) from skewing the derived values, such features were digitized and masked during the database updation.

3. Results and discussion

3.1. Water Quality Index (WQI) at the different locations prior to and during the lockdown

In the lockdown phase (i.e. 6th April and 14th April 2020), six monitoring stations for Class B (about 67%) and 8 monitoring stations for Class C (about 89%), out of the nine stations overall, recorded significant improvements in their WQI (Table S3 and Fig. 2a), in comparison to the prior-lockdown phase (i.e. 6th January, 13th February and 13th March 2020). On the whole, the improvement was 10% for Class B and more prominently for Class C (37%). The difference of the WQI computed above in comparison to that recorded during the same months in the previous year (i.e. April 2019) was clearly discernable, particularly for Class B (Table S3 in the Supplementary Information file).

A >40% improvement in the WQI for both Class B and C was noticed for the monitoring stations at Nizamuddin Bridge (m6), Okhla (m7), Shahdara (m8) and Jaitpur (Agra Canal) (m9), all of which are located in South Delhi, downstream of the ITO Barrage (Fig. 2). The closure of almost all industries during the lockdown has likely resulted in minimal effluent discharge and thereby lessened the level of contamination in the Yamuna (as has been reported in leading dailies- Gandhiok, 2020; PTI, 2020). Nevertheless, even during the lockdown phase, the recorded water quality at Palla (m1), Kudesia Ghat (m4) and the ITO Barrage (m5) shows an increase in contamination. Possibly, as these locations are in north and central Delhi [areas that are either extensively cultivated (m1) or heavily built-up (m4 and m5)], even during the lockdown period, partly treated or untreated agricultural runoff and domestic wastewater continues to contaminate the river via the many drains that debouch into the Yamuna herein (zone demarcated by grey background in Fig. 1b).

While substantial precipitation can reduce the river's contaminant load by enabling greater dilution, the rainfall received at Delhi in the period following the lockdown's commencement was quite meagre [only 9.8 mm for the entirety of April 2020- Indian Agricultural Research Institute (IARI), New Delhi (https://www.iari.res.in/index.php?Itemid=1033&id=402&option=com_content&view=article)]. Despite there being substantial cloud cover in the region (as a result of which no clear satellite image could be obtained for April 2020), almost no precipitation was received during this time period. Delhi had received a lot of unseasonal rainfall during early-to-mid-March (https://weather.com/en-IN/india/news/news/2020-04-03-delhi-wettest-march-ever-records-589-rainfall-weather) due to several Western Disturbances that passed over the region. Yet despite this substantial amount of rainfall (a total of 174.6 mm of rainfall was received in March 2020, as recorded by the IARI), the pollution load in the Yamuna was still high, whereas despite rainfall being minimal in April 2020, we could still observe the reductions in the concentrations of the polluting parameters and a betterment in the WQI for the datasets of 6th April 2020 and 14th April 2020. Moreover, the examined stretch of the River Yamuna lies entirely within the National Capital Territory of Delhi, which is one of the most densely urbanized locales in India. As such, almost the entire stretch of the river here is affected almost wholly by anthropogenic factors and the influence of natural causes on water quality variation are quite minimal. This is even more so since the study was conducted during the dry season (and thereby minimal surface dilution of the contaminant load from meteoric water sources). Furthermore no tributaries, apart from sewer drains, come and meet the Yamuna River within this stretch. Thus the reductions observed in the polluting parameters for the 6th April 2020 and 14th April 2020 datasets and the corresponding betterment in the WQI may be taken to directly arise from the lockdown situation.

Despite significant improvements at most stations during the lockdown period, the Yamuna's water quality in the NCT remained far beyond permissible limits (Fig. S1). Only two stations namely Palla (m1) and Surghat (m2) recorded WQI values below 100 throughout the pre-lockdown and lockdown periods and only at Surghat could the water quality be accorded as being non-polluted, with WQI values of 31.7 and 29.9 for Class B and Class C, respectively, on the 14th of April 2020. The Yamuna's water quality within Delhi, particularly just downstream of the Wazirabad Barrage, did not meet either the criteria for bathing nor for use as drinking water after conventional treatment and disinfection, even after 3 weeks of full-fledged lockdown in spite of minimal industrial effluent discharge during this period (which otherwise generate about 35.9 MLD of waste water- CPCB, 2020) and minimal direct human interventions like waste disposal, bathing and washing. This highlights the extreme stress on the river from domestic sewage disposal (cf. Soni et al., 2014). The seven drains (d1-d6 and d27- Fig. 1b) that inflow into the Yamuna in the above 4.6 km stretch between the Wazirabad Barrage and Kudesia Ghat, engender this situation.

3.2. Changes in water quality parameters at different monitoring sites before and during the lockdown

The BOD and COD values have been considerably attenuated during the lockdown in comparison to their respective pre-lockdown amounts (Fig. 2b). Their mean concentrations (considering all monitoring stations for both parameters) have changed by much as −42.83% (net reduction of 11.82 mg/L) and −39.25% (net reduction of 32.06 mg/L), respectively (Table S5, column 7, 8, 11 and 12). When compared against the previous year's levels, their reduction amounts were 19.78% and 10.45%, respectively. For monitoring stations downstream of the ITO Barrage (m6, m7, m8 and m9), the magnitude of reduction in both these parameters was >40% during the lockdown phase. Yet, the water quality criteria in terms of both the BOD and COD parameters, from Khajori Paltoon Pool (m3) downstream, does not meet the desirable standards for Class B or Class C.

While the FC parameter showed a substantial variation (>40% reduction) between the prior and during lockdown phases in four monitoring stations (Table S5, column 14), its overall variation does not support any explicit trend (Fig. 2b), since at Palla (m1), Kudesia Ghat (m4) and ITO Barrage (m5), it got amplified by about +2223%, +202% and +70% respectively. Such substantial boosting up of the faecal contamination may result from untreated domestic waste discharging from the drains at these sites. Notably, a total of 5 (d2, d3, d4, d5 and d6) and 7 (d7, d8, d9, d10, d11, d25 and d26) drains merge in the immediate upstream reaches of Kudesia Ghat (m4) and ITO Barrage, respectively. As the COVID-19 virus has been shown to be present in wastewater and excreta (Amirian, 2020), such high faecal loads in the Yamuna are worrying, as this can form a possible transmission pathway for the virus (Lodder and de Roda Husman, 2020; Quilliam et al., 2020), away from the Delhi NCT (which has substantial numbers of COVID-19 positive cases- 89,802 confirmed cases as on 2nd July 2020- https://www.mygov.in/covid-19/) and into its southern hinterlands. The augmentation of FC at Palla (m1) is primarily due to livestock excreta in drainage

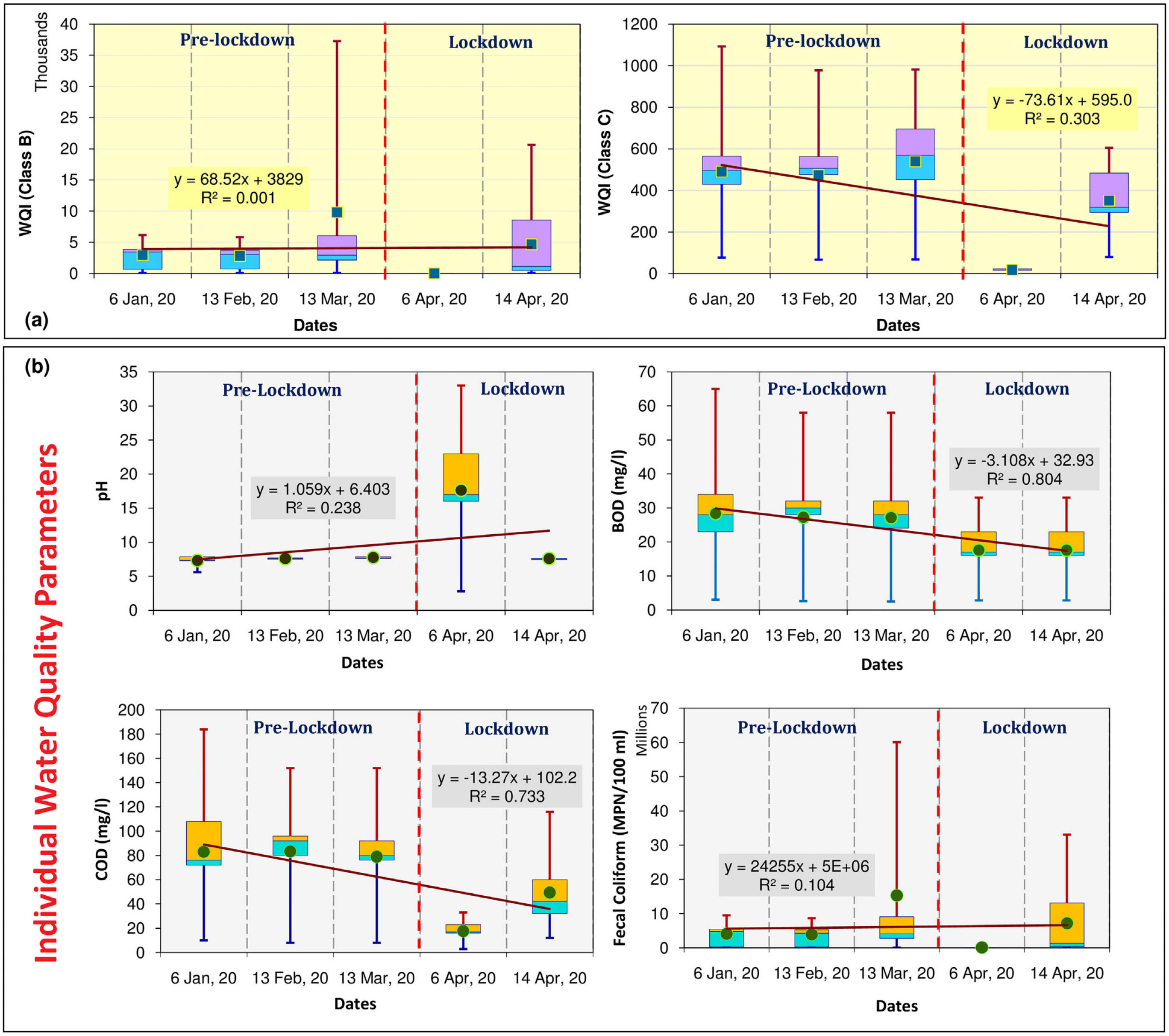

Fig. 2. The recorded changes in the Yamuna's water quality aspects within its stretch in the Delhi NCT during the months of January, February, March and April 2020, showing **(a)** Deviation in the Water Quality Index (WQI), and **(b)** Variation in individual parameters like pH, BOD, COD and Faecal Coliform Note: The lockdown began on 25th March 2020. The CPCB water quality standards are shown in Table S1; the WQI standard ranges and CPCB classification are given in Fig. S1; the deviations and associated key statistics of the WQI's Box-and-Whisker plots are given in Tables S3 and S4 in the Supplementary Information file; and the variations and associated key statistics of the individual parameters' Box-and-Whisker plots are given in Tables S5 and S6, in the Supplementary File.

ditches and a mixture of agricultural runoff flowing in from outside the Delhi NCT area (Gopal and Chauhan, 2007; Kumar et al., 2019; Sharma, 2015), with the pollutant diuron (used as a herbicide/pesticide during sugarcane production whose cultivation is widespread in the area) being especially present in this stretch (Glorian et al., 2018). Newer urban growth, upstream of the Delhi NCT, also contributes some industrial/urban area derived contaminants, presently (Parmar and Singh, 2015).

The pH value has increased slightly in the upstream section of Khajori Paltoon Pool (m3) but decreased faintly at its downstream section (from m4 onwards) in the lockdown period (Table S5, column 3 and 4). Its overall pattern demonstrates a slight rising trend (Fig. 2b) and at all stations pH values have remained >7 (basic) in both the prior-to-lockdown and during-lockdown periods. The entry of organic matter from anthropogenic sources into river systems in urban areas is again a possible cause for such an alkaline nature of the stream, as has been documented in several studies (e.g. Peters, 2009; Mocellin and Magro, 2011).

3.3. Water quality at different point sources (drains) within the Delhi stretch of the River Yamuna

Significant differences were reported (Table S7, columns 10, 11, 14 and 15) in the mean COD and BOD values between the pre-lockdown and during-lockdown dates for the 20 drains meeting the River Yamuna within its Delhi NCT stretch, for which the required data are available. Their respective overall percentage deviations were as much as −32% and −36%, with this attributable to industrial closure during the lockdown. However, such marked differences were not observed for the pH and Total Suspended Solids (TSS also referred to as SPM) concentrations (Table S7, columns 1, 2, 6 and 7) and their trends demonstrated analogous results (Fig. 3). Domestic sewage expectedly did not decline markedly during the lockdown, with estimates putting it at about 2990 MLD during the lockdown as against around 3026 MLD previously (CPCB, 2020).

Even during the lockdown, TSS, COD and BOD levels have augmented considerably in drains d2 (Magazine Road Drain), d14 (Maharani Bagh Drain), d17 (Tekhand Drain), d21 (Abu Fazal Drain) and d24 (Indrapuri Drain) (Table S7 in the Supplementary Information file). Despite the reduction in industrial effluents (of about 35.9 MLD), a BOD load of 260 TPD was still expected to be discharged from domestic sewage (CPCB, 2020). Apart from the domestic waste contribution that keeps levels up, another possible reason is that from January to April (covering our study period) pollutant concentrations are usually at their highest levels due to negligible dry season flow (even with minimal abstraction for industrial or agricultural purposes during the lockdown- Jha, 2020a, 2020b). This retards effective pollutant dilution and flushing out of contaminants. Further insights are thus desirable into the individual nature of these drains to identify those contributing the largest pollutant loads.

3.4. Hierarchical Cluster Analysis (HCA) for identifying distinct groups of polluting drains

The HCA elicited the correspondence between drains based on four parameters (pH, TSS, COD and BOD), similar to the approach of Gautam et al. (2013) for classifying Delhi's STPs. Three statistically significant clusters $[(D_{link}/D_{max})*25 < 5]$ for both the pre-lockdown and lockdown periods (Fig. 4a and 4b) were identified. Cluster 1 comprises 9 drains in both the pre-lockdown (d1, d6, d7, d9, d10, d11, d13, d14, d15) and lockdown (d3, d4, d6, d7, d9, d12, d15, d16, d19) periods. Based on the computed aggregate mean decimal point scores (Table S9 in the Supplementary Information file) that are rooted in the pollution magnitude, the drains under Cluster 1 were designated as 'moderately polluting' (thereby transferring relatively lesser contaminants than other more polluting drains) [*Note: All the drains within the Delhi NCT contribute huge pollution loads into the Yamuna that are well above acceptable standards. The use of terms like 'low/least', 'moderate/medium' and 'most/high' in this section relates to simply the internal variations among them*]. Four drains (d6, d7, d9 and d15- all moderately polluting) fall under Cluster 1 in both pre and during-lockdown stages. Seemingly, their effluents have been somewhat limited during the lockdown phase (possibly from retarded industrial and restricted daily commercial/residential activities within their catchment zones), diminishing pollution loads. Cluster 2 corresponds to 3 drains (d3, d4 and d12) in the pre-lockdown period and 7 drains (d1, d10, d11, d13, d14, d22 and d23) in the lockdown period. Interestingly, d3, d4, d7, d10 and d12 are the least polluted drains in both these time slots (Table S9). Therefore Cluster 2 indicates the 'low-polluted' group. Cluster 3 contains 8 drains for the pre-lockdown (d2, d16, d17, d19, d21, d22, d23 and d24) and 4 drains (d2, d17, d21 & d24) for the lockdown slots and the lowest water quality level was recorded in them in both phases, i.e. these comprise the 'most' polluting group (Table S9). These drains likely receive effluents from mostly domestic sources and from industries that may have perforce operated during the lockdown period. Notably, due to the imposed restrictions, the number of drains in this cluster reduces by 50% from its pre-lockdown membership. The drains under Cluster 3 are of the highest priority for regulation and treatment, especially

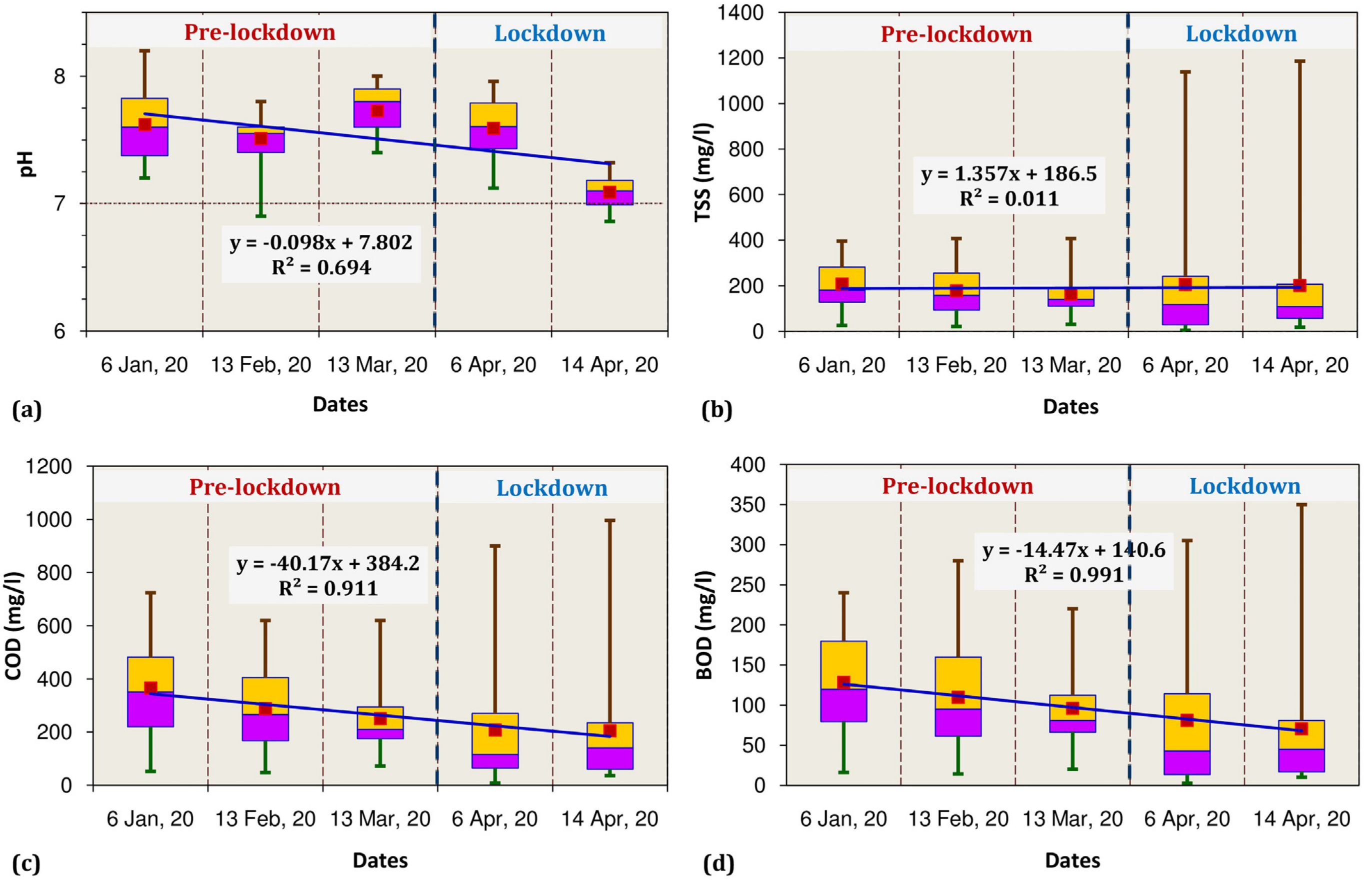

Fig. 3. Overall trend in the concentration of **(a)** pH, **(b)** TSS, **(c)** COD, and **(d)** BOD parameters during the pre-lockdown and lockdown months in the different drains merging with the River Yamuna within the Delhi NCT stretch Note: The lockdown began on 25th March 2020. The variations in the above parameters and their respective associated key statistics for the Box-and-Whisker plots are given in Tables S7 and S8, in the Supplementary File.

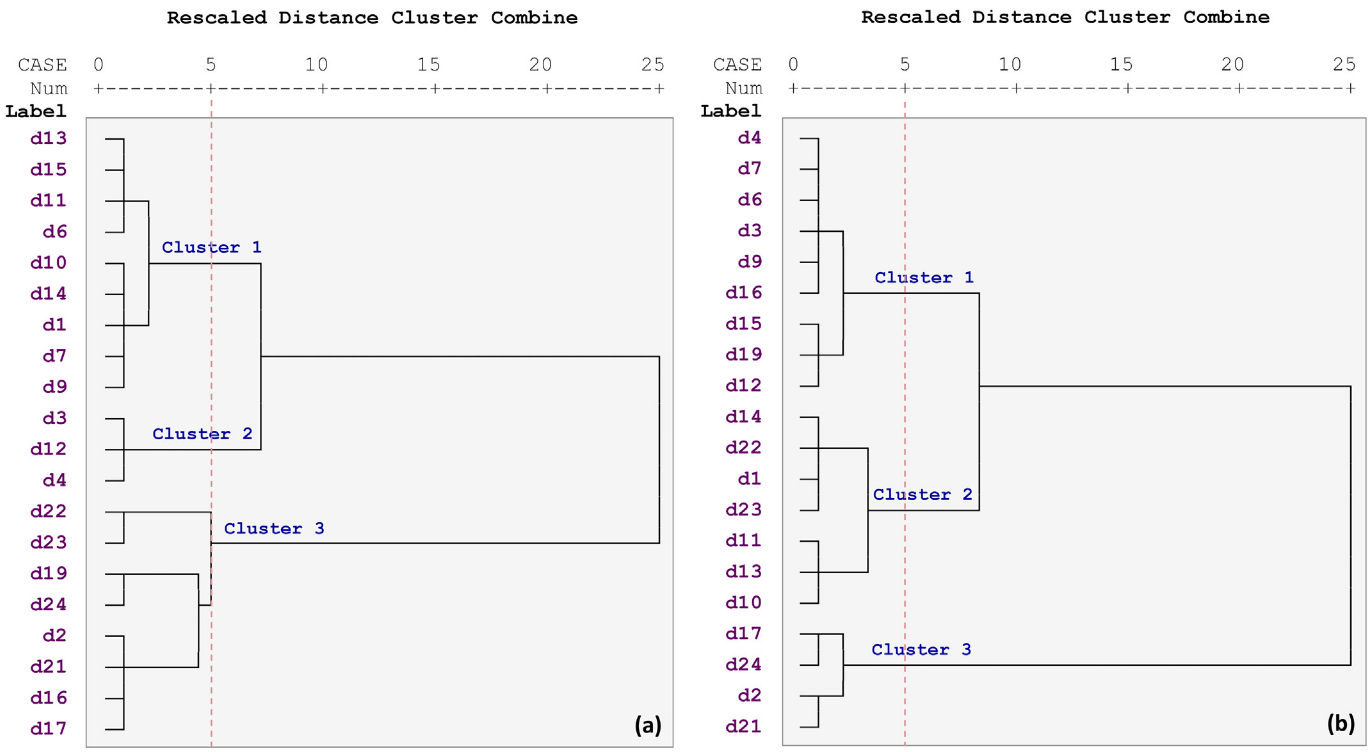

Fig. 4. Hierarchical Cluster Analysis for different drains meeting the river Yamuna for **(a)** pre-lockdown period and **(b)** lockdown period Note: The vertical red dashed line indicates $[(D_{link}/D_{max})*25 < 5]$, i.e. the threshold that has been used to identify the statistically significant clusters. For related calculations see Table S9 in the Supplementary Information file.

those that are members in both the pre-lockdown and during-lockdown phases (drains d2, d17, d21 and d24).

Almost all drains under Cluster 3, in both the pre and ongoing lockdown periods, are located along just two stretches of the Yamuna's course within the Delhi NCT. Drains d2, d3 and d4 meet the River just after Khajori Paltoon Pool (m3) while drains d21, d22, d23 and d24 meet it after the Okhla Barrage, either directly or as tributaries of the Shahdara drain (Fig. 1b). Drains d16 and d17 merge into the Agra Canal and while not directly polluting the Yamuna, they likely have debilitating effects on its adjacent riparian tracts within Jaitpur. Therefore, the uppermost (downstream of Wazirabad Barrage and till Kudesia Ghat- as ascertained in Section 3.2) and lowermost segments (after Okhla Barrage) of the Yamuna within Delhi are its most affected reaches. A lower drain density and inflow points in the intervening reaches may allow a slightly better river water quality therein, with only one most polluting drain (d12) meeting the Yamuna in this stretch (just after the ITO Barrage). Interestingly, the Najafgarh drain (d1 in Fig. 1b), which is traditionally regarded as the most polluted drain in Delhi (CPCB, 2006), does not fall within Cluster 3 in either assessment period. This drain courses across densely urbanized central and south-western Delhi (NRSC, 2019) and has a large network of subsidiary drains, some of which have been treated recently (Adak, 2017a), while others may have received much reduced effluent loads during the lockdown as they traverse the temporarily closed industrial belts of Gurugram and Manesar alongside Delhi (Jha, 2020a, 2020b). The above reasons could be operative behind this drain being recorded in a slightly lower polluting category. The changing cluster membership of the individual drains during the pre and ongoing lockdown phases also points to an overall betterment of the pollution state [9 out of 20 drains have moved into a lower polluting category, with 2 of these (d22 and d23) shifting from the most polluting class (Cluster 3) to the least one (Cluster 2)]. The main Najafgarh Drain network traverses the western flank of the River and takes in most of the sewage load from other parts of the city towards the more northern reaches of the Yamuna's channel between the Wazirabad Barrage and Kudesia Ghat, while the Shahdara Drain network takes the sewage from the River's eastern flank towards its more southerly reaches downstream of the Okhla Barrage (see Fig. 1a). As such, some reaches in between these two Barrages are relatively less polluted directly by incoming drains, though of course they do still get contaminated by dirty waters flowing in from upstream. Thus the pattern and layout of Delhi's drain network is the critical factor that engenders some sections of the main Yamuna River channel to be relatively more polluted than other stretches.

3.5. Image analysis results

The image-derived water quality parameters were mapped at the reach-level for eight different dates from 2017 to 2020 for the indices derived via band ratioing (NDTI, NDVI and FAI), while the SPM and turbidity levels were mapped for two days within the lockdown phase. Both temporal and spatial variations are apparent. These outputs allow estimates of the river's state beyond the first lockdown phase (which ended on 14th April 2020- the date up to which the measured water sample data is available), and during the subsequent lockdown phases.

The NDTI, NDVI and FAI parameters were mapped on each of the dates for all 117 reach segments (Fig. 5 shows the respective outputs for 2020, while those of previous years are given in Figs. S2, S3 and S4 in the Supplementary Information file). The NDTI outputs indicate the extent of suspended sediments in the channel. Negative NDTI values denote relatively clearer water, while values above 0.2 represent quite turbid reaches (Lacaux et al., 2007; Subramaniam and Saxena, 2011). The Yamuna usually demonstrates moderate turbidity signatures (NDTI values between 0.0 and 0.2) in its sections along Palla and downstream of the Okhla Barrage (Fig. 5a). At times, sustained stretches between these two extreme points also show higher NDTI values (most

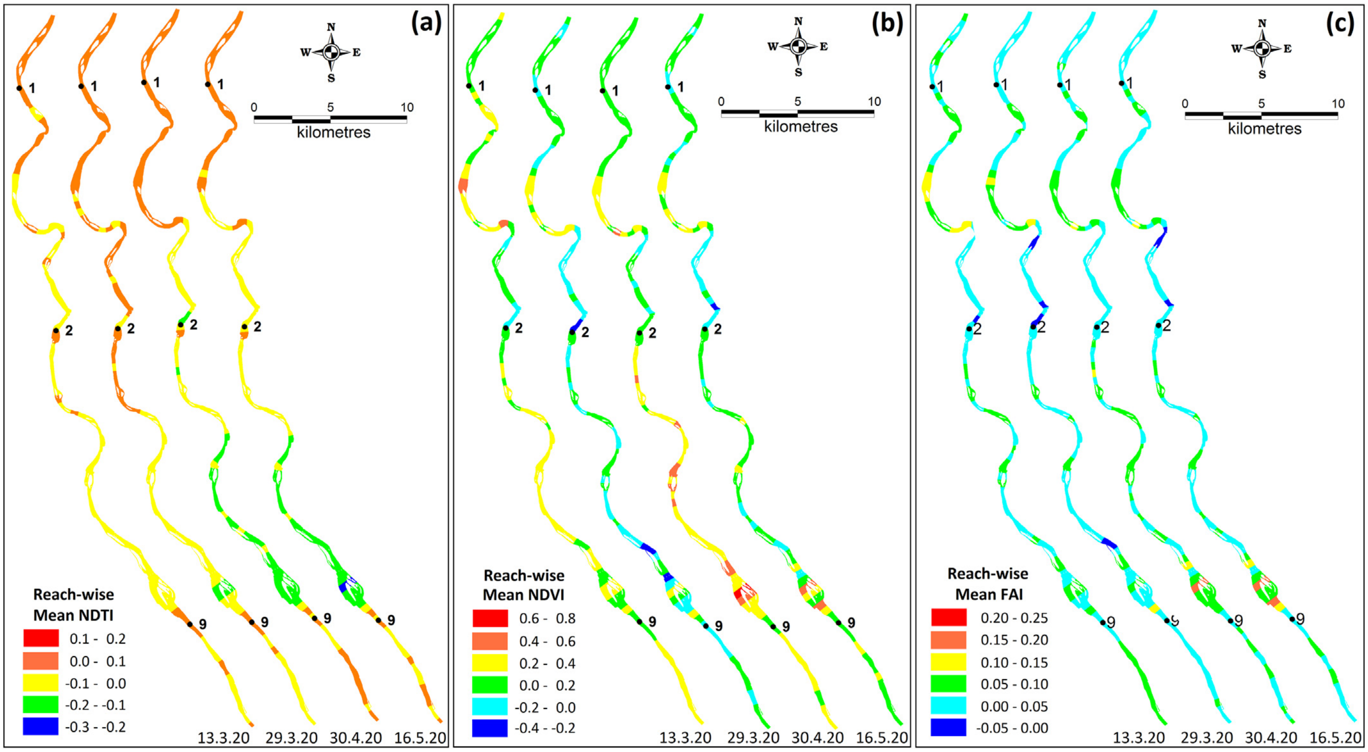

Fig. 5. Reach-wise mean values ascertained for the image-derived parameters within the Yamuna's stretch along Delhi NCT on different image dates in 2020 in the pre- and during-lockdown phases, showing (a) Normalized Difference Turbidity Index (NDTI), (b) Normalized Difference Vegetation Index (NDVI), and (c) Floating Algal Index (FAI) Note: Points numbered 1, 2 and 9 respectively correspond to locations of the stations Palla, Wazirabad Barrage and just downstream of the meeting of the Shahdara Drain with the Yamuna after the Okhla Barrage. For the situation recorded in respect of the above parameters in the preceding years (2017–2019), see Figs. S2, S3 and S4, in the Supplementary File.

prominently on 22.04.2017- Fig. S2) and some sections just downstream of the Wazirabad Barrage show turbid signatures on almost all dates. Such attributes of the above reaches can be accorded to two primary reasons- inflow of agricultural runoff (around Palla) and the inflow from drains around Wazirabad and Okhla, as documented previously. Two sections usually show lower NDTI values (portions immediately upstream of the Wazirabad and Okhla Barrages), possibly from flow stagnation due to the river being impounded and thereby a settling of the suspended load. Most notably, in the last two outputs (for 30.04.2020 and 16.05.2020- Fig. 5a), this clearer water portion (i.e. negative NDTI values) extends and covers a considerable section between these two Barrages and the sections immediately downstream of the Wazirabad Barrage have also cleared up. This may seemingly be attributed directly to the lowering of industrial effluents during the lockdown. Domestic effluent inflow means that some spots of positive NDTI values remain just along those sections where the principal polluting drains meet the Yamuna. The moderate NDTI values around Palla are likely due to unabated runoff from fields.

Similar to the NDTI, the NDVI signatures (Figs. 5b and S3) show a marked deviation during the lockdown phase. Positive NDVI values indicate vegetation (i.e. plants afloat on the water surface), or eutrophication arising from the over-enrichment of that river segment by inflowing chemicals and a severe reduction in the available oxygen (Chislock et al., 2013). As this is more likely to occur in stagnant waters than in free-flowing lotic environments, relatively higher NDVI values are usually seen just upstream of the Wazirabad and Okhla Barrages where the Yamuna gets impounded. Again, a sharp decrease in the NDVI values are evident, particularly on 29.03.2020, five days into the lockdown. Interestingly, an intermittent sharp rise in the NDVI signature was noted for the 30.04.2020 output, with this being similar to conditions on nearby dates in previous years. By 30th April 2020, India had entered the second lockdown phase, during which some activities were re-permitted, particularly in the agribusiness sector. Analysis of the Yamuna's flow at the Wazirabad Barrage (i.e. the discharge permitted into the main Delhi stretch and not abstracted) shows that from 01.03.2020 to 12.03.2020, the average daily discharge was 35,717 cusecs, while the same from 14.03.2020 to 28.03.2020 was 173,733 cusecs (CPCB, 2020)- a rise of 386%. The greater inflow (together with lowered abstraction for agricultural/industrial purposes due to the lockdown) may have diluted the pollutant load and flushed out accumulated water surface vegetation, causing the drop in NDVI levels as imaged on 29.03.2020 (Figs. 5b). The average daily discharge from 30.03.2020 till 6.04.2020 was 138,800 cusecs (a drop of 20% from the previous period), with data not available beyond this date. If this trend had ensued for the rest of the month, it could provide a possible explanation for the noted rise in the NDVI at the end of April 2020. The situation seems to have bettered again for the 16.05.2020 output (possibly due to greater inflow from the Barrage), with it being more similar to the 29.03.2020 output (Figs. 5b). The anthropogenic influence on the Yamuna's water quality in this stretch is thus quite clear and with the two NDVI outputs for the end of February 2020 and mid-May 2020 being the least affected by this signature in all 16 datasets (Fig. 5b and S3), the lockdown's impact becomes apparent.

The FAI outputs (Figs. 5c and S4) largely conform to the NDVI layers, with a clear betterment discernable during the lockdown. Very low or negative FAI values denote open water (Hu, 2009; Zhang et al., 2019) and values are generally quite low in most stretches. While Dogliotti et al. (2018) have recommended using a threshold value to distinguish between turbid and algae-covered reaches, we relied more on visual validation to ascertain the FAI outputs' veracity using Google Earth (see Supplementary Section 6). Even in various band composites the Yamuna appears as a dark feature and algal blooms are not evident in most stretches, except just upstream of the Okhla Barrage, where multiple algal mats, of limited spatial extent adhere to the few mid-channel bars present therein. There are also notable colonies of water hyacinths in this stretch of the Yamuna (Kumar et al., 2019).

Such algal blooms arise due to the mixture of sewage and industrial effluents in the channel and the most common types seen are Chlorophyceae and Myxophyceae (Indian Institutes of Technology, 2012). To flush out and avoid such algal growth in still waters, flow velocities need to be higher than 0.75 m/s (Chow, 1973 in Chahar et al., 2007), whereas the mean lean season flow rate in this segment of the river is only 0.4 m/s (Gurusamy and Jayaraman, 2012; Soni et al., 2014). The total non-monsoonal (October to June) flow in the Delhi stretch of the Yamuna is estimated to be 0.44 TMCM, which is just 16% of its virgin non-monsoon flow of 2.8 TMCM (Jha et al., 1988; CPCB, 2006), dropping even further to 0.3 TMCM when greater abstraction occurs at the Wazirabad Barrage (Babu et al., 2003). Since a discharge of 1.8 TMCM is considered necessary for the Yamuna to flush out the various channel contaminants and prevent algal growth (Soni et al., 2014) and ambient conditions are far below this, pollution levels remain high throughout the non-monsoon period (Agarwal and Krause, 2013; Rajankar et al., 2014). Older studies have shown that the dilution of contaminants does not take place during the flow process due to the low discharge conditions (for dilution a minimum flow of 0.6 TMCM is required per month and a total non-monsoonal flow of 5 TMCM, whereas these values for the Yamuna at Delhi are far lower- Soni et al., 2014) and thus almost no betterment was recorded during the 30 h that it takes for any discharge to travel from the Najafgarh Drain outlet into the channel near the Wazirabad Barrage up to Okhla (Central Board for the Prevention and Control of Water Pollution, 1983). Pollution mass balance simulation studies conducted by Sharma et al. (2017a, 2017b) and Sharma and Singh (2009) have also surmised that significant contaminant dilution does not occur within the Yamuna's stretch at Delhi due to the Barrage-regulated flow conditions and unabated domestic sewage inflows.

Absolute estimates of the reach-wise sediment concentration were obtained from the SPM and Turbidity outputs (Fig. 6), which represent conditions in the first week after the lockdown began and towards the end of the third lockdown (4–17 May) phase. We mapped these for the extent between the Wazirabad and Okhla Barrages (comprised of 60 channel segments), as all principal drains meet the river in this stretch. The 29.03.2020 output reveals, as expected, greater suspended sediments in the upstream section, from the Wazirabad Barrage to Kudesia Ghat, within which most drains debouch (Fig. 6a). SPM values range from 50 to 60 mg/L in this reach to 10–20 mg/L just upstream of the Okhla Barrage, where sediments settle down in stagnant water. The scenario changes markedly in the 16.05.2020 output, with SPM reductions throughout the entire stretch examined. While the greatest concentrations are still seen in the Wazirabad-Kudesia reach, values reduce to 30–40 mg/L. Downstream of Nizamuddin Bridge, the SPM is <10 mg/L for the entire remaining stretch. For the lower reaches, a 60–70% reduction in the SPM load occurred between the 29.03.2020 and 16.05.2020 outputs, with this being 30–40% for the uppermost segments (Fig. S6a in the Supplementary Information file).

Since no SPM/TSS measurements are taken directly on the Yamuna (nor any turbidity measures), direct validation of our derived results were not possible. Perforce, we have used the only daily TSS data available during the lockdown period- that of the major STPs in Delhi (obtained from the Delhi Jal Board), on the surmise that the TSS of the effluents from their outflow drains is likely to exhibit a similar character to that of a mostly impounded river during its low-flow season. It was expected though that the drain TSS values may be slightly higher than those of the main channel, due to their more constrained flow conditions but would not deviate too far. For 29.03.2020, we averaged the

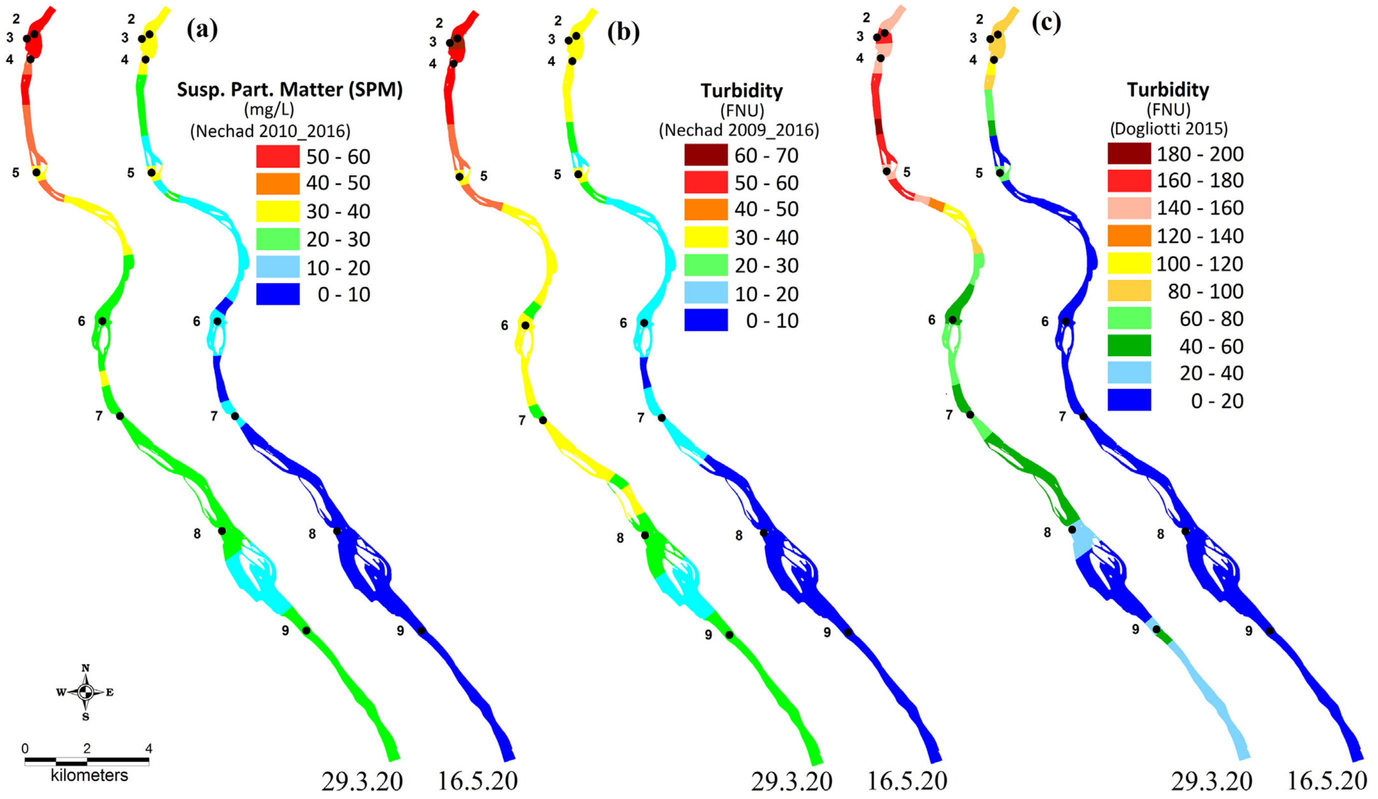

Fig. 6. Reach-wise mean values of Suspended Particulate Matter (SPM) (derived after Nechad et al., 2010, modified in 2016) and Turbidity (derived after Nechad et al., 2009 (modified in 2016) and Dogliotti et al., 2015) for two dates within the lockdown period. Note: The date 29.03.2020 can be taken to represent the first week after the initial lockdown was initiated and the date 16.05.2020 as indicative of the end of the third lockdown phase. Points numbered 2–9 correspond to water quality stations on the Yamuna as follows: 2- Wazirabad Barrage; 3- Surghat; 4- Khajori Paltoon Pool; 5- Kudesia Ghat; 6- ITO; 7- Nizamuddin Bridge; 8- Agra Canal off-take at Okhla; 9- just downstream of the meeting of the Shahdara Drain with the Yamuna after the Okhla Barrage.

available real-time TSS observations of the Rithila, Coronation Pillar (Phase-II) and Nilothi STP outflows (all part of the Najafgarh Drain network), with this value being 41.99 mg/L (minimum: 18.23 mg/L and maximum: 54.74 mg/L). The only other such data available was for the Yamuna Vihar STP (Phase-III), located opposite to the Najafgarh Drain complex on the opposite flank of the Yamuna and this value was 35 mg/L. Comparisons of the image-extracted SPM values for the reaches situated beside and just downstream of where these STPs outfall through their drains into the Yamuna (SPM values of 40–60 mg/L for the Najafgarh-Yamuna confluence zone and 30–50 mg/L for the other one), seemingly provide good validation of our results. No real-time observation data was available for 16.05.2020. In this data-deficient scenario we considered the stated outflow TSS levels of the individual STPs (not available for the Yamuna Vihar side) and averaged them. For the Najafgarh complex (comprised of the Rithila, Coronation Pillar, Nilothi, Rohini, Keshopur, Pappankalan and Najafgarh STPs), the average measured TSS value was 49.33 mg/L (minimum: 8 mg/L and maximum: 168 mg/L) while the image-extracted values for this reach was 30–40 mg/L. The above for the Okhla complex STPs are-26.33 mg/L on 29.03.2020 as against image-derived values of 10–30 mg/L and 25.25 mg/L on 16.05.2020 as against image-derived values of 0–10 mg/L.

Mirroring the SPM outputs, the two Turbidity measures obtained show similar reductions across the board. The Nechad_2009_2016 output (Fig. 6b) has turbidity levels dropping from 60–70 FNU to 30–40 FNU in the upper reaches while this change in the lower segments goes from 30–40 FNU to 0–10 FNU. The reach-wise change rates for this parameter (Fig. S6b) is similar to that for the SPM load. The Dogliotti_2015 output (Fig. 12c) shows more elevated levels of turbidity in the channel segments as compared to the Nechad_2009_2016 method, particularly in the upper reaches, possibly due to its switching-algorithm extraction method (see Supplementary Section 3). However, the reductions seen are equally sharp for both these data products (Figs. S6b and S6c in the Supplementary Information file), with a 60–80% decrease in the turbidity levels almost throughout the entire studied stretch within the lockdown period. While such marked reductions may be seemingly surprising (despite reports highlighting the 'sparkling' clarity of the Yamuna- Gandhiok, 2020), at this moment we do not have an alternate measured dataset to validate this. As pointed out before, our primary aim has been to document whether any changes occurred due to the lockdown instead of deriving extremely accurate values of parameters and a similar systemic bias in image processing for both the pre- and during-lockdown periods would not affect this intention significantly. Moreover, with the Dogliotti_2015 output having a much wider range than the Nechad_2009_2016 output, the percentage variation between its 29.03.2020 and 16.05.2020 results is more pronounced.

Instead of just comparing the 2019 and 2020 datasets, we felt it was more prudent to average the NDTI values for the years 2017–2019 (Fig. S2) and compare them against those derived for similar time stamps in 2020, to dampen any episodic effects in the older datasets. Since the image dates were not exactly the same, we designated four 'Days' for this comparative analysis (Fig. 7). Day 1 corresponds to early-mid March, Day 2 to late March, Day 3 to late April and Day 4 to mid-May (thereby denoting conditions prior to the lockdown, during its early phase, during its middle phase and towards its end phase). No marked changes were discerned in the Day 1 output, as expected, since environmental conditions could be expected to be quite similar

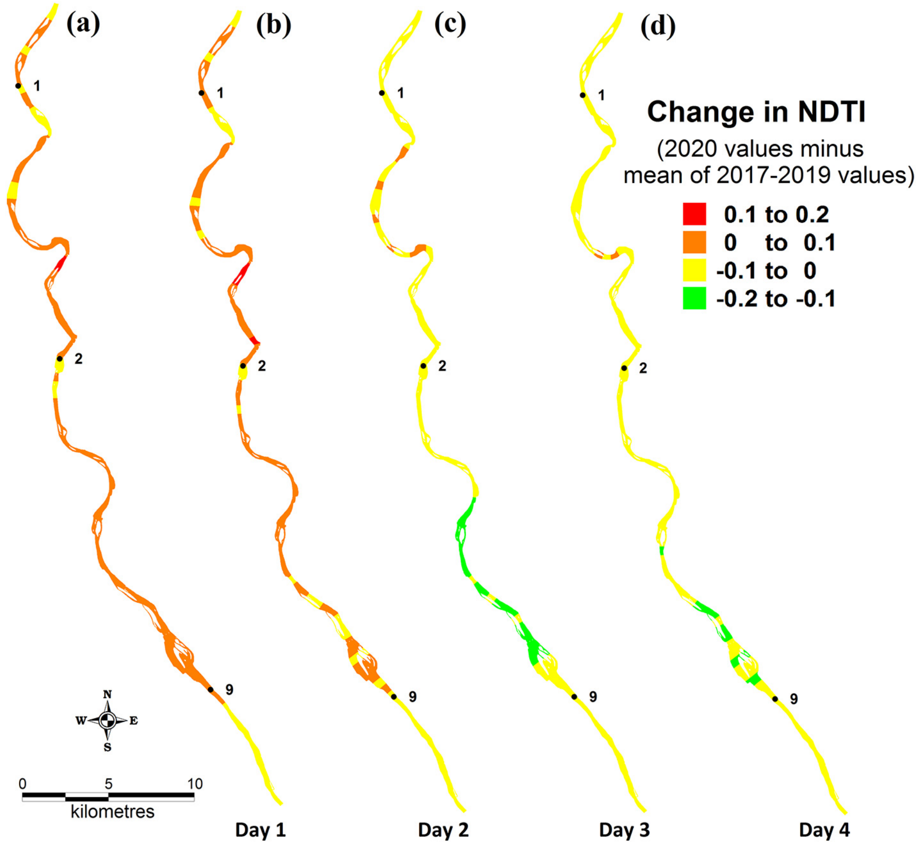

Fig. 7. Difference between the reach-wise NDTI value measured in 2020 and the mean of the NDTI values for that same reach in 2017, 2018 and 2019 Note: Points numbered 1, 2 and 9 respectively correspond to locations of the stations Palla, Wazirabad Barrage and just downstream of the meeting of the Shahdara Drain with the Yamuna after the Okhla Barrage. Denoted time periods Day 1, Day 2, Day 3 and Day 4 corresponding to the following dates for comparison- Day 1–05.03.2017, 08.03.2018, 11.03.2019, 13.03.2020; Day 2–21.03.2017, 24.03.2018, 27.03.2019, 29.03.2020; Day 3–22.04.2017, 25.04.2018, 28.04.2019, 30.04.2020; Day 4–08.05.2017, 11.05.2018, 14.05.2019, 16.05.2020.

in all the four years, while the onset of the lockdown had occurred too recently to significantly affect results in the Day 2 dataset. The Day 3 output showed the most reductions in reach-wise mean NDTI levels, after more than a month of the lockdown. While the Day 4 dataset also shows marked reductions (around Okhla), the lessening extents are relatively lower elsewhere as compared with Day 3. By mid-May 2020, the Indian Government had lifted lockdown measures and some industries had resumed, depending on the COVID-19 infection rate and case numbers in different areas. With some semblance of normal life returning, we see its effect on the channel quality, with much lower reductions in the mean NDTI values for this phase in some of the channel reaches.

3.6. Correlations between measured/derived parameters

Pearson product moment correlations were derived between the measured and image-extracted parameters for the nine sampling stations and their reaches (Table 1). This could only be done for one dataset (image date- 29.03.2020 and sampling date- 06.04.2020) for which all the parameters analysed were available and the image and sampling dates were close to each other. Correlations have also been derived between just the image-extracted parameters for all channel segments of the Wazirabad-Okhla stretch and from both sets of data (minus the SPM-Turbidity measures) for all sampled stations/reaches, considering the 2019 and 2020 values together (see Tables S10 and S11 in the Supplementary Information file, respectively). While the correlations between parameters are not always strong (since we were in effect comparing point-derived values of measured water sample parameters with reach-averaged values of the image-derived parameters), some generalised observations could be elicited. Turbidity indices and measures are negatively related with BOD levels. Higher turbidity levels can act as light inhibitors (Wang, 1974) and this shadowing effect may result in impaired algal growth, thereby lowering BOD levels. As measures of water surface plant matter content, the NDVI and FAI are positively related with the BOD and COD and thus, negatively so with the DO, which decreases with a rise in algal blooms due to eutrophication (Ahipathy and Puttaiah, 2006; Verma and Singh, 2013). The turbidity measures and SPM obviously correlate strongly positively with each other. These measures are likely to be more episodic in nature (i.e. show short-term variations) since the various drains possibly have varying discharge regimes/loads and can thus create intermittent effluent plumes in the main channel where they debouch, thereby affecting that reach's water quality. Interestingly, the FC to turbidity relationships are all negative, albeit weakly so. Possibly, the suspended sediments act as a binding agent that faecal bacteria attach onto and thereby settle down on the riverbed (Bai and Lung, 2005), away from the upper water layers. The measured pH levels are strongly negatively correlated with polluting factors like BOD and COD while being weakly so with the FC and FAI parameters. Conversely, it is strongly positively correlated with the DO and also similarly related with the turbidity measures but less so in terms of intensity.

3.7. The Yamuna's water quality beyond the lockdown

While the Yamuna's water quality condition during the lockdown was far better than its recent toxic status when a blanket of foam covered the channel (Zargar, 2019), a better physical appearance does not necessarily guarantee sustained purer water quality (as opined for other rivers- Mishra, 2020). Therefore it is quite likely that the river shall return to its former degraded status once all lockdown measures are lifted and industrial production increases to make up the economic losses engendered by such a period of closure (see Supplementary Section 9- Tables S12 and S13 and Figs. S7 and S8). Thus integrative plans to improve the water as well as the overall riparian quality are sorely required, together with better regulatory and sound technological interventions. Even then, the fact that a marked improvement in the water quality occurred in a matter of just weeks, simply by halting industrial effluents, highlights the fallacies in implementation/regulation and apparent lack of legal enforcement of the many river quality improvement programmes/guidelines that have been mandated from time to time, at enormous cost (Shukla and Gupta, 2020; Singh et al., 2020). There is thus an urgent need to recognize the Right of the River (Benohr and Lynch, 2018; Westerman, 2019) to its own pathway and while the Yamuna had been previously granted legal status and rights (ELC, 2017; O'Donnell and Talbot-Jones, 2018) for a short duration (Kukreti, 2017) in its upper reaches in the Himalayan state of Uttarakhand, these aspects have been likely ignored in Delhi throughout.

The faulty locations of many STPs augment pollutant loads [with marked differences between their mooted capacities and actual loads (Gautam et al., 2017)], while no decentralized STPs have been constructed despite court orders (Shrangi, 2019). Furthermore, some of the treated sewage mixes with untreated waters before flowing into the river (CPCB, 2004). Plans formulated towards better STP positioning/functioning with interceptor-sewers (Yamuna River Project, 2016) and efficient solid waste management practices within the city (e.g. Zhao and Song, 2017) can markedly reduce domestic and industrial effluent loads entering the channel. Successful completion and sustained monitoring of targeted rejuvenation plans for the major polluting drains like the Najafgarh (Alday and Vir Gupta, 2017) and Palam outlets

Table 1
Correlations between the extracted water quality parameters for the different sampled stations/reaches during end-March to early-April 2020.

Parameters	NDTI	NDVI	FAI	SPM	T_Nch2016	T_Dog2015	pH	BOD	DO	COD	FC
NDTI	1										
NDVI	0.37	1									
FAI	0.15	0.95**	1								
SPM	0.76*	0.31	0.19	1							
T_Nch2016	0.76*	0.31	0.19	1**	1						
T_Dog2015	0.86**	0.40	0.26	0.86**	0.86**	1					
pH	0.21	−0.02	−0.16	0.41	0.41	0.44	1				
BOD	−0.13	0.27	0.40	−0.28	−0.28	−0.37	−0.94**	1			
DO	0.05	−0.35	−0.41	0.37	0.37	0.38	0.87**	−0.93**	1		
COD	0.19	0.20	0.27	0.10	0.10	−0.05	−0.85**	0.87**	−0.75*	1	
FC	−0.30	0.45	0.62	−0.13	−0.13	−0.22	−0.19	0.42	−0.27	0.18	1

Source: Computed by the authors.

Only those nine reaches were considered in the above correlation, within which were located the water sample measurement stations. There is a slight dissonance between the dates of the satellite-image derived parameters and the measured water sample dates. The former is from the 29.03.2020 dataset while the latter is from the 06.04.2020 dataset. T_Nch2016 and T_Dog2015 respectively denote the turbidity values obtained via the Nechad (2009, re-updated in 2016) and Dogliotti et al. (2015) methods.

* Correlation is significant at the 0.05 level (2-tailed).

** Correlation is significant at the 0.01 level (2-tailed).

(Holland, 2017) and prior waste management in their catchment zones, would also help substantially in achieving this. Optimizing agricultural practices in the area's limited rural tracts and increased used of organic fertilizers instead of chemical ones can also reduce harmful contaminant loads.

Enabling periodic high discharges from the Wazirabad Barrage can help flush out the dirt in this channel segment. In this aspect, reconnecting the Yamuna with its floodplain and using the ambient micro-topography and vegetation to manage wastes (Shen, 2017) is critical. An overall improvement in the condition of the stream's adjacent riparian tracts is also required (like rejuvenating the Okhla Bird Sanctuary area- Adak, 2017b; Dixit, 2019; Bhatia and Vats, 2019), with suitable floodplain zonation and wetland regeneration, which are crucial towards maintaining river health (Babu et al., 2013). The use of vegetative buffers along the river can help mitigate seasonal floods (Mondal and Patel, 2020), absorb contaminants and enable better hyporheic exchanges (Mondal and Patel, 2018), all factors in enhancing environmental flows and having a healthier aquatic ecosystem (NIH, 2006), with the presently allocated eflow amounts being lower than what is suitable (Soni et al., 2014). Urban greening and better land use management practices within the river corridor (cf. Banerji and Patel, 2019) can not only check water logging but also reduce sediment loads washed into the Yamuna, as has already been attempted in Noida (Matto and Jainer, 2018), on the left flank of the Yamuna alongside Delhi- plans that can feasibly be extended throughout the river's Delhi NCT stretch on either bank.

Making the Yamuna more visible in the city's psyche, by highlighting its heritage and role in Delhi's development (e.g. Brookover, 2015) can also garner public support for riverfront cleaning drives and channel quality restoration. The spate of newspaper articles, blogs and tweets about its cleanlier status during this lockdown must be used to press on for coordinated efforts to truly improve and sustain its water and riparian quality, critically reexamining current waste management and floodplain development/zoning practices, which are quite unsustainable and exclusionary (Baviskar, 2011; Sharan, 2016). Such contestations of the Yamuna's floodplain (Follman, 2016) must be resolved through plans that integrate the urban ecology and channel quality (e.g. Babu and Seth, 2007; Alday and Vir Gupta, 2018) and generate spaces and facilities that allow both humans and nature to breathe.

4. Conclusion

The lockdown has had significant impacts on the water quality of the Yamuna within its Delhi NCT stretch, with enhanced WQI ratings and a significant decline in the BOD and COD levels. However, the FC had increased at a few sites probably due to livestock excreta and domestic sewage (which remained largely unabated) inflows. Drain effluents also revealed similar reductions in pollutant loads while the most polluting drains in this reach were identified. A marked drop in the river's turbidity and SPM was also apparent. Some data limitations have constrained the performed analyses but the fact that the Yamuna's water quality has bettered, could be clearly established. However, despite such improvements, the WQI status could not meet the prescribed CPCB standards. The framework adopted in this study can be easily transferred to not only examine similar lockdown effects on the stream quality of large rivers in other areas, but also for continuous monitoring from integrated measured sample and image-extracted datasets, which can extend and improve spatio-temporal water quality assessments. The COVID-19 global pandemic is a once in a generation occurrence that is currently plaguing the world. Yet, one of its outfalls also presents a similarly once in a generation opportunity to re-comprehend and redesign existing frameworks and put in place robust mechanisms to cleanse one of India's most polluted rivers and the nation's other similarly afflicted watercourses.

CRediT authorship contribution statement

Priyank Pravin Patel: Conceptualization, Methodology, Investigation, Formal analysis, Validation, Visualization, Writing - original draft, Writing - review & editing. **Sayoni Mondal:** Data curation, Methodology, Investigation, Formal analysis, Visualization, Writing - original draft. **Krishna Gopal Ghosh:** Conceptualization, Methodology, Investigation, Formal analysis, Validation, Visualization, Writing - original draft.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2020.140851.

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