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RESEARCH ARTICLE

A model-based prediction and analysis of seasonal and tidal influence on pollutants distribution from city outfalls of river Ganges in West Bengal, India and its mapping using GIS tool

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Abstract

River Ganges (locally called as river Ganga) is one of the most scared rivers in India. The river is symbol of hope, faith and is worshipped for its wholesomeness due to its purity and sanctity. Pollution of river water due to anthropogenic activity is a very common issue worldwide. Similarly, river Ganga pollution in India throughout its entire courses, is a major concern due to city outfalls. This river, also named as river Hooghly in West Bengal, India, is exposed to outfalls carrying domestic wastewater of its both bank and their distribution in river Ganga is strongly influenced by season and tide. This study aimed to generate an idea of distance and direction wise changes of concentration of pollutants in wastewater in river Ganga. During 2014, the selection of five major outfalls was done by considering Dissolved Oxygen (DO), Biochemical Oxygen Demand (BOD), heavy metals, total fecal coliform level, and the study continued for next four consecutive years to find out the influence of tide and season. Geographical Information System (GIS) based maps provided a better reflection of these changes. Student's t-test highlighted the significant changes in concentration of parameters season wise. A significant higher value of DO, BOD, nitrate nitrogen, and chloride were found in pre-monsoon season compared to monsoon season. Regression Equation generated for highly correlated parameters (coliform and heavy metals) helped to predict the level of one parameter with others. The zone of influence of BOD, DO, phosphorus and nitrate nitrogen from each of the five selected outfalls was very prominent. Acoustic Doppler current profiler at two of the five outfalls helped to estimate strip-wise depth average discharge which helped to estimate the value of water quality parameters by Plug Flow Model during high tide and low tide. A strong tidal variation was observed during low tide. This study helped to predict the influential zone from outfalls which will help to generate an alternative solution of river water use. This approach can be applied globally to prepare river water usage guidelines.

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1. Introduction

River Ganges (locally called as river Ganga), one of the most sacred rivers in India, travels through West Bengal spanning around 570 km. Southern part of the state are deltaic zones called Sundarbans. Tidal nature of the river influences countryside discharge draining into the Bay of Bengal [1]. River Ganga in West Bengal is tidal in nature and its effect stretches up to Nabadwip [2]. Low tide and high tide prevail in river and influence the dispersion of pollutants from different discharge points. High tide increases water level and reach above the invert level of the drains near the mouth which results into backflow of river water into drains. Low tide increases the tendency of critical condition in terms of pollution [3]. The tidal nature of river has an influence on changing concentration of pollutants releasing into the river through the outfalls directly connected to the river alongside its bank. The nature of tide, direction of the flow of water, and volume of water in the river among others are the main reason behind this change.

The characteristics of river water also change seasonally. Pre-monsoon, monsoon, and post-monsoon seasons has their own influence on quality of river water. Maximum amount of rainfall received in West Bengal during June-September (the range of mean monsoon rainfall) is around 887.9 mm– 2932.6mm [4]. The study of seasonal variation on river water quality showed improved pH (neutral range), and the lowest value of Electrical Conductivity (EC) during monsoon may be due to the dilution effect. Seasonal changes in the levels of Iron (Fe), Manganese (Mn), Cadmium (Cd), and Chromium (Cr) were observed in river Ganga, West Bengal [5]. Statistical analysis of water quality data of river Ganga in Kolkata, West Bengal showed the occurrence of heavy metals were not influenced by location, but the variations occurred season wise. The concentrations of metals like Copper (Cu), Mn, and Nickel (Ni) were found to be maximum during monsoon whereas in case of Fe, maximum value was obtained in winter season, may be due to development of metal chelates [6]. A strong seasonal impact on concentration of pollutants was observed in different banks of river Ganga in Barrackpore, West Bengal. The concentration of hardness was high during winter may be due to low level of water. The lowest value of DO was reported in the month of March. Seasonal increase of bacterial population might have degraded organic matters by consuming DO and leads to low oxygen content in water [7].

A significant difference in heavy metal concentrations like Molybdenum (Mo), Selenium (Se), Ni, Cu, Mn, Zinc (Zn), Cd, Fe, and Cr and variation of other water quality parameters like Total Dissolved Solids (TDS), Total Suspended Solid (TSS), Dissolved Oxygen (DO), Biochemical Oxygen Demand (BOD) and pH was observed in river Ganga in Kanpur, Uttar Pradesh. The concentration of heavy metals was observed to be in an increasing trend in summer followed by winter and monsoon. The dissipation rate of heavy metals may be high due to high temperature and low river flow [8–10] An increasing trend of sodium and dissolved solids concentration was observed in river Ganga at Haridwar during rainy season which make river water unfit for drinking purpose. Low temperature and high photosynthetic activity enhanced DO level in water during winter [11]. A significant presence of bacterial population during rainy season and a higher concentration of nitrate was observed in the end of winter and summer in river Ganga at Varanasi, Uttar Pradesh. Surface runoff during rainy season may be the source of huge bacterial population and favorable water temperature might have helped them to grow more. Partial rainfall may enhance nitrate concentration from fertilizers due to runoff [12]. During 2010–2011, seasonal study on river Ganga in Kanpur showed no specific trend of changing river water quality [13]. Water Quality Index (WQI) was found to be an efficient tool for monitoring quality of river water [14]. Seasonal changes of water quality parameters for river Ganga were also reported at Uttarakhand [15, 16]. At Allahabad, the highest value of EC was recorded during summer. The value of total hardness was minimum during monsoon and maximum during winter at Kanpur. The temporal and spatial variation of DO, Chloride, Sulphates (SO_4^{2-}), BOD was also observed for river Ganga [17]. Poor water quality of river Ganga was reported during pre-monsoon at Haridwar. During monsoon, bad water quality was mainly responsible for bank erosion, different non-point sources, and run-off of sediments [18].

Geographical Information System (GIS) mapping always provides a better reflection on changes of water quality parameters in river. Spatial analysis of river water quality using GIS is a very common practice. Worldwide acceptance of GIS tool helps to develop a reliable water quality model. The incorporation of computer hardware, software along with managing, analyzing, and displaying all form of geographically referenced data can be done using GIS. It is a computing platform to represent data on digital map [19, 20]. The tool was applied on river Ganga and many other rivers in India and abroad to generate maps. LANDAST 8 images were used to create map based on water quality parameters like pH, BOD, COD, DO, Total Solid (TS), TDS, Ammoniacal Nitrogen, Fluoride, Chloride, Magnesium (Mg), Turbidity, and Conductivity on river Ganga at Kanpur [21]. Rapidly developed GIS technology was also applied to handle data set of river Ganga pollution for its interpretation, analysis, and presentation at Haridwar [22].

To identify outfalls carrying wastewater in between around 25 km of the selected stretch of the river Ganga in West Bengal, starting from downstream at Howrah Station to upstream at Khardah, 24 Parganas (North), was selected as study area. The area selected for the entire study are located in southern part of the Bengal Basin which are covered by quaternary sediments. The eastern part of the Indian subcontinent i.e., Bengal Basin constitutes the biggest fluvial deltaic to the shallow marine sedimentary basin. The basin is comprised of the riverine channel, floodplain, and delta plain environments [23–25]. The Bengal Basin is considered as a tectonically subsiding basin which carries sediment deposited by river Ganga [26]. Respective areas are located on the stable shelf in the south-eastern part of the Lower Bengal Delta. The Bengal basin geosyncline trough had gone through several marine regressive and transgressive phases during the tertiary period. The deposition of deltaic sediments is the result of that event [27]. The total study area is covered with a quaternary alluvium deposit. This deposit is composed of sand, silt, and clay with the older alluvium in the western fringe part [28]. The principal river Ganga is flowing as Hooghly River from Northwest to south and southeast following the general trend of the area [29]. The sampling sites fall under Kolkata, Howrah, and North 24 Pargana districts and are apart consecutively by river Ganga as flood plain sediments. The quaternary lithological succession of the area is consisting of clay, silt, fine to coarse sand, and intermittent gravel.

The importance of the study area lied mainly on its soil characteristics, vegetation, relief, and land use. Thick alluviums to flood plain deposits are very significant characteristics of this region. Flood plains are made up of silty sediments near the riverbank and mixed sediments away from the river in the monsoon season. Elevation of the area varies from 1.5 to 15 m. Quaternary deposits are represented by present-day flood plain deposits, older flood plain deposits, and older alluviums over a mantle of lower Quaternary age. Topographically the area is gentle to moderately sloping. A thick alluvial deposit merges with the tidal flat in the southern part. The slope of the area ranges from 2–3 degrees generally but few places have a maximum slope of 5 to 6 degrees. The texture of soil is an important factor for assessing the soil physical environment and is directly interrelated to soil properties like structure, porosity, adhesion, and consistency [30]. The soil of northern part of the study area is sandy, in the central middle part it is sandy with clay loam and in southern side, it is clay loam. The study area is mainly dominated by sand, silt, and clay loamy soil at places. The districts are mostly plain areas and are very favorable for cultivation. At some places, shallow black and brown soils are also found. The vegetation of the study area almost entirely having aquatic such as Hydrilla, Utricularia, Caesulia in low lying swampy land stretched out to rice fields in the whole region. A variety of vegetables are cultivated along the bank of the river. Agriculture sector mainly consists of a great variety of fruits, vegetables, flowers, medicinal and aromatic plants, plantation crops, spices, mushrooms, and ornamental plants. Fruits like mango, guava, litchi, banana, papaya, and jamun trees are found as natural grown or as plantation in the study area, except in the Kolkata metropolitan area in the southern part. Study areas fall under thick alluvium to the deltaic district of West Bengal. The largest part of the soils derived from alluvial deposits is azonal with little or no profile development. The area is dissected by various rivers, canals and saline soils, swamps, and marshes. The district falls under the lower Gangetic deltaic plain land. This zone is formed by silts of the river. River Ganga passes through a vast area and divides districts according to both banks. Land use and landcover changes are the main human-induced activities along with the course of the river [31]. The fundamental rural LULC (Land Use/Land Cover) character remains more or less the same. Kolkata is a metropolitan city with a dense population and Hooghly, Howrah, and North 24 pargana districts having small to large scale industry along its bank area [29].

The objective of this study was to find out the influence of tides and seasons on distribution of pollutants in form of wastewater from city outfalls at the selected stretch of river Ganga in West Bengal, India considering river flow and tidal dynamics.

2. Materials and methods

2.1 Collection and analysis

The collection of river water and analysis of all water quality parameters were performed by following standard methods (Table A in S1 File) [32, 33]. Wastewater from selected outfalls was collected near the mouth of the outfall at 2 cm depth for its physical, chemical, and biological analysis. Sample water were taken to the laboratory immediately and stored at 4˚C to minimize the potential for volatilization and biodegradation of samples between sampling and analysis [34]. The selection of water quality parameters was done on the basis of its risk factor on ecosystem and their importance for the present study through review of literature. pH, temperature, DO, conductivity, BOD, total hardness, nitrate nitrogen, chloride, and phosphorus were measured parameters for the entire study. Lead (Pb) and Mercury (Hg) are two major contaminants in wastewater in India. Sometimes Arsenic (As) also gets mixed in wastewater from surrounding agricultural sources as the selected outfall areas were extended to some rural parts and have agricultural fields next to the canals. Few outfalls were located in industrial belt, and that is why Lead (Pb), Mercury (Hg), and Arsenic (As) were selected for this study. The assessment of pH, temperature, and DO were done in the field and the rest in the laboratory (Table A in S1 File). All measurements were carried out in triplicates, following the established QA/QC protocols of the analytical laboratory, and using external standards. Spike recoveries of ±10% were considered acceptable for metal analyses. Continuing calibration verifications were performed at ten sample intervals.

In 2014, a wide range of field survey using mechanized boat helped to identify twenty selected outfalls situated along the bank of river Ganga from Howrah Station to Khardah. Five major outfalls i.e., Circular Canal in Bagbazar, Ghusuri in Howrah, Dakshineswar Canal (adjacent to Border Security Force facility) in 24 Parganas (North), Ballykhal in Howrah, and Khardah Khal (also known as Titagarh Khal) in 24 Parganas (North) considering right and left bank of the river were selected for the entire study on the basis of important water quality parameters like pH, temperature, DO, conductivity, BOD, total hardness, nitrate nitrogen,

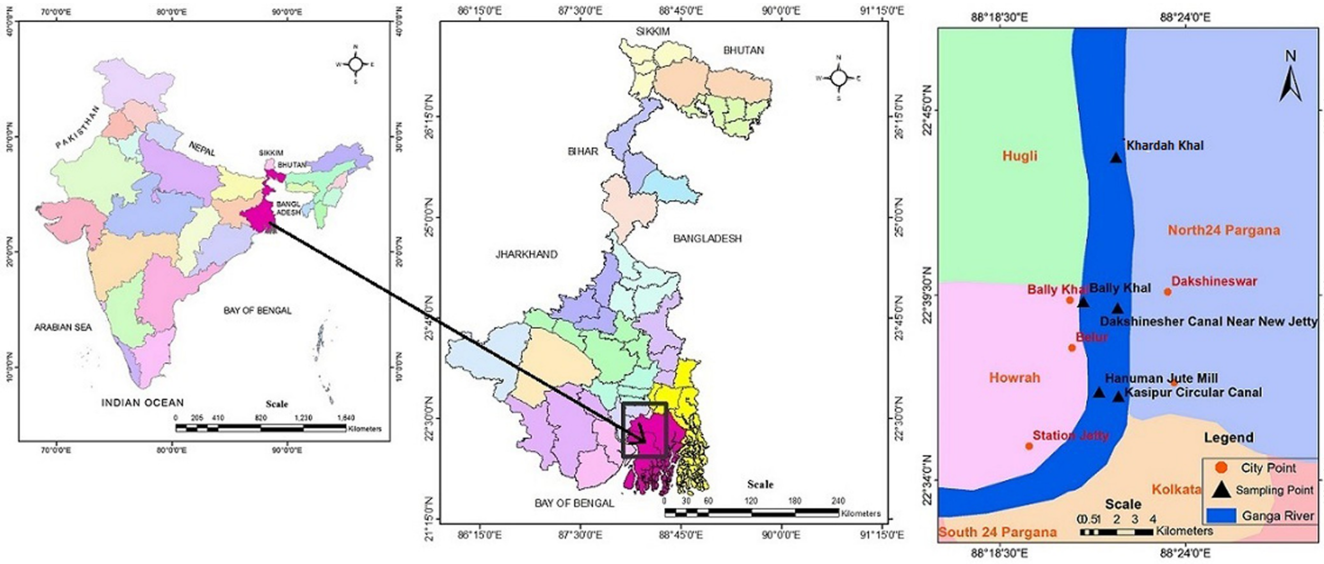

Fig 1. Map of India and West Bengal emphasizing the study area. (Base map was prepared from Landsat 7 satellite image. Local study area boundaries were digitized from toposheets. Satellite images were downloaded from www.usgs.gov).

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chloride, and phosphorus and heavy metals [Lead (Pb), Mercury (Hg) and Total Arsenic (As)], total coliform and fecal coliform from outfalls for its seasonal (2015–2018) and tidal variation study (2016–2018) (Figs 2 and 3 in S2 File; Fig 1). All measurements were carried out in triplicates.

2.2 Seasonal analysis

Wastewater samples were collected at the mouth of outfalls (2 cm depth) during low tide in the month of March-April (Pre-monsoon), August-September (Monsoon) and November-December (Post-monsoon) at fifteen days of intervals at the same location for four times in each season during the 2015–2018 study period. Same pattern was followed for tidal variation study during the 2016–2018 study period.

To obtain statistical significance of seasonal variations among the concentration of parameters, student t-test was performed (N = 16). Mean value of each parameter for each season underwent this independent statistical test. Pre-monsoon data was compared to post-monsoon and monsoon data separately to assess seasonal variation statistically. p-value indicates the probability of obtaining results, when ≤ 0.05 was considered as significant [35, 36].

The prediction of water quality parameters was performed by regression analysis. Cumulative data of water quality parameter from 2015–2018 at each sampling site was considered for statistical analysis. A total of 48 samples (N = 48) for each parameter at every sampling site were used to generated correlation matrix. The positively correlated parameters having greater than 0.9 correlation coefficients (r) value was considered to generate regression equations. Among them, the parameters having the value of $R^2 > 0.9$ was taken into consideration to predict values [37, 38]. The calculated value using regression equation was validated to actual value of respective parameters of pre-monsoon, 2019 and the error was calculated.

2.3 Tidal analysis

The influence of tide on selected outfalls of river Ganga was observed seasonally by analyzing river water from different directions from outfalls during 2016–2018. For tidal variation study, water samples were collected across the river (from the outfall), diagonally (from the outfall) and along the bank (in favour of the tidal directions) of river Ganga considering the position of each outfall (Fig 2). The same pattern was followed for each site. Samples were collected from three points in each direction (Fig 2).

2.4 Identification of zone of influence

Satellite image followed by field survey, clearly indicated expected critical boundary of unsafe pollutant concentration from each of the outfall. It helped to identify the zone of influence of pollutant distribution from each outfall. Along the bank, the directional tidal flow was more prominent. Safe and unsafe zones on the riverbed were visibly demarcated by dark color and obnoxious odor. DO and BOD, the two important water quality parameters were taken into consideration for this interpolation. In between safe and unsafe boundary point the linear interpolation of DO and BOD value of river water helped to identify the zones where it reached its safest point seasonally. Water samplings were done by non-anchored country boat.

The locations were marked using Global Positioning System (GPS) and distances were calculated by location points. Environmental standards (Table B in S1 File) were used to calculate the actual distance at which parameters reached its permissible value in every three directions from the outfalls. The best fit polynomial (2nd order and 3rd order) curve using measured parameters in every three directions helped to establish a model to calculate the distance from outfalls.

2.5 Validation of estimated parameters by Plug flow model

Attempt was made to measure the discharge by Hydrographic Survey of river Ganga at Ballykhal and Dakshineswar Canal by an instrument called ADCP (Acoustic Doppler current profiler) (Fig 1 in S2 File). This instrument can measure the velocity at different points horizontally and vertically. Hence, the river was subdivided into several vertical strips stretching over the river cross section. A continuous field visit during low tide and high tide helped to

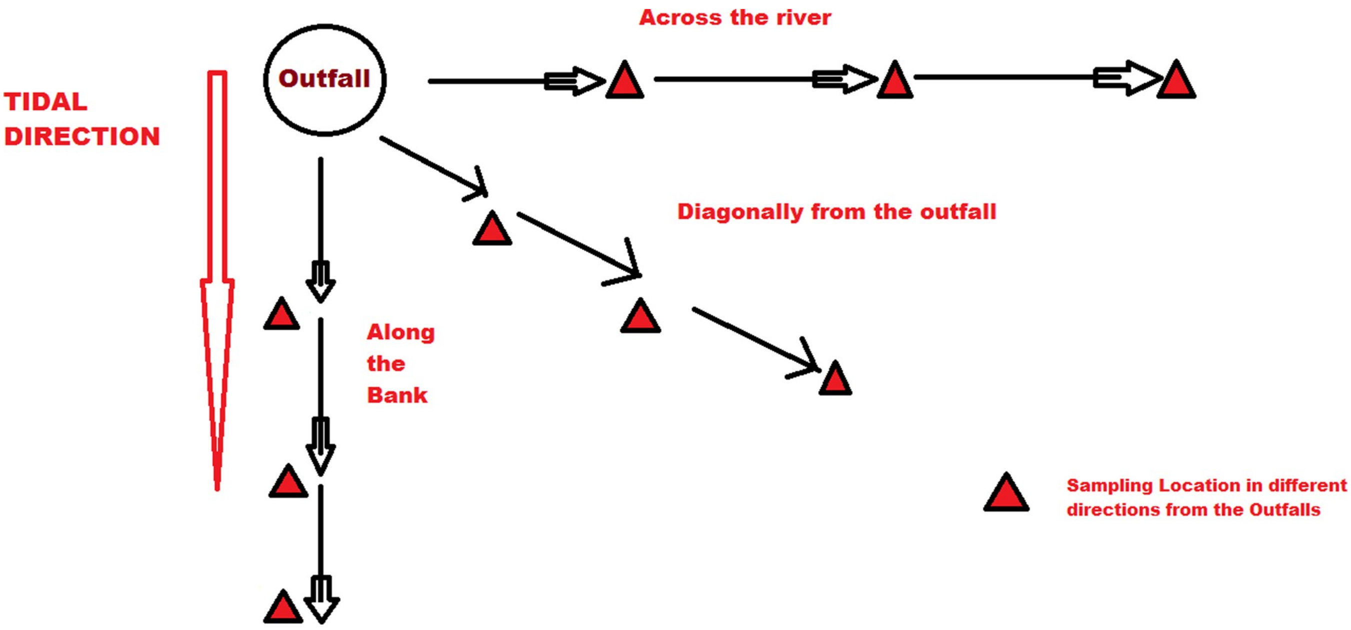

Fig 2. Sampling pattern for tidal analysis.

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understand the status of outfalls in river Ganga. The field-based study showed maximum human patches in Dakhineswar Canal and Ballykhal area. Direct human interferences in these two particular sites encouraged to choose these two selected outfalls for ADCP.

The cross-sectional area of each stretch was calculated considering the width of the strip and the average depth of the same. This area of the strip was multiplied by the measured depth averaged velocity to obtain discharge value. Strip-wise depth average discharge at the sampling points was obtained by linear interpolation. The ultimate concentration of parameters of a mixture of stream water and wastewater were also estimated by using Plug flow model by applying Eq 1. The model was based on the assumption of a continuous discharge of waste at a given location on the river. Considering the downriver movement of flow, it was assumed that they were uniformly mixed with at any given cross section of the river and there was no dispersion of wastes in the direction of flow [39]. Parameters those were changing with distance from outfalls were taken into consideration and the measured values were compared with estimated values. This study was conducted during pre-monsoon, 2019. Plug flow model highlights that variation of water quality parameters from a point source depending on several factors like volumetric flow rate of wastewater, volumetric flow rate of river just upstream of the discharge point, and concentration of parameters. Eq 1 can be used to calculate the ultimate concentration of parameters of a mixture of stream water and wastewater [39]. The quality of incoming and outgoing water with reference to tidal effects and fluctuation of different physico-chemical and biological parameters give better understanding by diurnal and tidal cycle studies.

$$L0 = (QwLw + QrLr)/(Qw + Qr) \tag{Eq1}$$

Where,
L0 = Ultimate BOD of The Mixture of Stream Water and Wastewater (mg/L)
Lr = Ultimate BOD of the River just Upstream of the Point of Discharge (mg/L)
Lw = Ultimate BOD of The Wastewater (mg/L)
Qr = Volumetric Flow Rate of The River Just Upstream of The Discharge Point (m^3/s)
Qw = Volumetric Flow Rate of Wastewater (m^3/s)

2.6 GIS mapping of water quality parameters

The exact coordinates of sampling points were obtained using GARMIN GPS. Seasonal changes of DO and BOD (during 2015–2018) at Dakshineswar Canal were considered to prepare water quality map by using Inverse Distance Weighted (IDW) interpolation technique in Arc GIS10 software considering its tidal variation. A map was developed on the basis of concentration of DO and BOD at different sampling points at Dakshineswar Canal.

3 Results and discussion

3.1 Water quality analysis during 2014

Parameters like color, odor, pH, temperature, and DO were analyzed in the field immediately. The color of wastewater samples from all outfalls varied from light to dark brown. An unpleasant odor was a general characteristic of wastewater at all sampling points. At Khardah Khal, it was sensed from a few meters away of sampling locations which helped to track its location. The presence of organic debris, leaves, other wastes from industries, domestic sources made it unfit for use. The unpleasant odor may be due to the presence of metals, salts, alkaline materials, and end product of biological reactions [40, 41]. In an aquatic system, the changes of pH depend on several biochemical processes and dissolved chemical compounds. The maintenance of pH in an aquatic system mainly controlled by carbon dioxide, carbonate, and bicarbonate as well as fulvic acid and humic acid [40]. The value of pH in all outfalls was in between its standard value for inland surface water standard (Tables B and E in S1 File). The mean value of temperature remained nearly 30˚C for all sampling points (Table E in S1 File). Water sample reported no acidic or alkaline tendency [40, 41]. The lowest mean value of DO was reported at Khardah Khal (2 ± 0.05 mg/L) followed by Dakshineswar Canal (2.1 ± 0.05 mg/L) and New Jetty, Dakshineswar (2.1 ± 0.20 mg/L) (Table E in S1 File). The lower level of DO at few sampling sites may be due to the introduction of high organic load. The release of organic matter via domestic discharge might have influenced the variation of oxygen concentration in river water. The reason behind oxygen consumption in water body may be due to the microbial degradation. The DO level remained low as recorded that supports the existence of facultative bacteria as well [42]. Wastewater was collected and preserved properly to analyze parameters like conductivity, BOD, total hardness, nitrate nitrogen, chloride, phosphorus, heavy metals like Pb, Hg, As, and total, fecal coliform in the laboratory. The highest mean conductivity (882.8 ± 9.2 μS/cm) was reported in Khardah Khal. The value of conductivity was within range for all sampling locations compared to standard value for fish culture and wildlife propagation, irrigation, industrial cooling, and controlled waste disposal (Tables B and E in S1 File). The degree of dissociation of dissolved organic salts and their concentrations may have been contributed the representative value of conductivity in river Ganga [40, 43–46]. The highest mean value of BOD was reported at Khardah Khal (10.1 ± 0.46 mg/L) followed by New Jetty, Dakshineswar (8.9 ± 0.13 mg/L), Ballykhal (8.3 ± 0.22 mg/L), Dakshineswar Canal (8.2 ± 0.17 mg/L) and Circular Canal (6 ± 0.61 mg/L). For all selected outfalls, the value was reported beyond its standard for outdoor bathing (5 days 20˚C 3 mg/L or less) (Tables B and E in S1 File). The responsible reason behind its high value may be dumping of municipal waste with high organic load [47]. The highest mean value (272 mg/L) of total hardness at Dakshineswar Canal did not cross its standard limit (Tables B and E in S1 File). The presence of divalent ions like Mg^{2+}, Mn^{2+}, Fe^{2+} and Strontium (Sr^{2+}) along with the nature of surroundings rocks and soil may be accountable for this value [48]. The highest mean value of nitrate nitrogen was reported at New Jetty, Dakshineswar (16.1 ± 3.03 mg/L) followed by Dakshineswar Canal (15.4 ± 2.06 mg/L), Khardah Khal (15.1 ± 2.10 mg/L) and Ballykhal (15.0 ± 0.87 mg/L). The values reported at Circular Canal (12.7 ± 1.36 mg/L), Annapurna Ghat (11.3 ± 0.89 mg/L), Jaymataji Ghat (11.3 ± 0.53 mg/L), Rashbari (11.0 ± 0.78 mg/L), and Cossipore area I (10.2 ± 0.75 mg/L) was also beyond its standard limit for inland surface water (Tables B and E in S1 File). Accumulation of animal wastes and chemical fertilizers with wastewater discharges and agricultural runoff may be the potential source of it. It remained mainly as the dissolved or particulate form and the reduced form of it affects the oxygen concentration as well [17, 41, 47]. The value of chloride for all selected outfalls was within the safe range (Tables B and E in S1 File). The presence of organic wastes specially the animal waste along with domestic and industrial waste deposition may be the reason behind its high value [48]. The decomposition of organic load can also attribute the same [45]. The mean value of phosphorus in all outfalls except New Jetty, Dakshineswar (17.8 ± 1.50 mg/L), Dakshineswar Canal (17.3 ± 0.96 mg/L), Khardah Khal (14.4 ± 1.49 mg/L), and Ballykhal (11.3 ± 1.19 mg/L) were within its standard value (Tables B and E in S1 File). Again, the accumulation of animal wastes, the presence of chemical fertilizers, and wastewater discharges are the main reasons for its increasing trends in some sampling sites [41, 47]. Dakshineswar Canal was not fit for outdoor bathing considering the concentration of Pb (0.14 mg/L). Pb concertation did not allow water sample to use it for drinking purposes at any of the sampling point (Tables B and E in S1 File). The sources of Pb may include paint, pesticides, battery, automobile emission, and burning of coals surrounding the outfalls areas [49]. At Khardah Khal (0.016mg/L) and Dakshineswar Canal (0.013mg/L) the value of Hg crossed its standard for outdoor bathing (Tables B and E in S1 File). Paper industry, pesticides, and waste battery or battery industry can contribute the higher concentration of Hg [49]. The alarming condition prevailed for Pb and Hg concentration at Khardah Khal, Ghusuri, and Ballykhal. This may be due to infiltration of huge amount of sewage water from domestic sector. The discharge of domestic water with contamination from small industries like aluminium, jute, textiles, and fertilizers units, may be the major contributor of Pb and Hg in water sample [49]. No significant presence of As was found in any of the sampling sites (Tables B and E in S1 File). There may not be any chance of contamination from the ground status, but the river sediment can be accountable for both sources and sinks of heavy metals in river water. The impact of presence of heavy metal may cause bioaccumulation and create a severe influence on aquatic lives as well as entire ecosystem [50]. The significant level of total coliform was found at Dakshineswar Canal (9 x 10^6 MPN/100ml), New Jetty, Dakshineswar (7.5 x 10^6 MPN/100ml), Khardah Khal (7.5 x 10^6MPN/100ml), Circular Canal (7 x 10^6 MPN/100ml), and Ballykhal (7 x 10^6 MPN/100ml). The level was nearly 18000 times higher than its standard at Dakshineswar Canal (9 x 10^6 MPN/100ml). The maximum value for fecal coliform was reported at Dakshineswar Canal as well (1.6 x 10^6 MPN/100ml) (Tables B and E in S1 File). River water, which was exposed to sewage discharge, open defecation, and cattle wallowing may be accountable for maximizing the quantities of bacteria [51]. Anthropogenic activities may also contribute the increased amount of bacterial population in river water [52, 53].

3.2 Selection of major outfalls

Out of twenty outfalls, five were screened and considered for further experimental purposes. The value of DO was found lower than its standard limit in all outfalls except Rashbari and Bottala. The value of BOD crossed its standard limit at all selected outfalls. The concentration of nitrate nitrogen also crossed its standard limit at Annapurna Ghat, Circular Canal, Jaymataji Ghat, Cossipore area I, Dakshineswar Canal, New Jetty, Khardah Khal, Rashbari, and Ballykhal. The level of total and fecal coliform were several times higher than its standard value for each sampling locations. An alarming level of bacterial population was observed at Circular Canal, Dakshineswar Canal, New Jetty at Dakshineswar, Khardah Khal, and Ballykhal. The value of Pb and Hg was beyond its standard limit at Dakshineswar Canal and Khardah Khal. The alarming condition was also prevailing for Pb and Hg concentration at Ghusuri and Ballykhal. Five major outfalls were selected based on significant level of major water quality parameters, wastewater flow rate, and their location. A high wastewater flow rate i.e., a maximum of 356.40 million litres per day (MLD) during pre-monsoon and 138.24 MLD during post-monsoon were reported at Khardah Khal. Even the level of Hg highlighted the need for further analysis of wastewater sample from Khardah Khal. A high flow rate of wastewater was also reported at Circular Canal (320.3 MLD) and Ballykhal (581.33 MLD during pre-monsoon and 260.68 MLD for post-monsoon) (Tables C and D in S1 File [72, 73]). The selection of Dakshineswar Canal was done mainly due to the presence of a notable amount of Pb and Hg.

3.3 Study of seasonal variation

A seasonal analysis (pre-monsoon, monsoon, and post-monsoon) of water quality parameters of five major selected outfalls i.e., Circular Canal, Ghusuri, Dakshineswar Canal, Ballykhal, and Khardah Khal was performed, and mean value of each parameter was taken into consideration for statistical analysis (Table F in S1 File). Student t-test was performed to compare water quality parameters at each sampling site between pre-monsoon and other two seasons. A strong visual change of coloration of water sample was observed season wise. The color varied

Table 1. p-value of seasonal analysis of pH, temperature (˚C), DO (mg/L), conductivity (μS/cm) and BOD (mg/L), total hardness (mg/L), nitrate nitrogen (mg/L), chloride (mg/L) and phosphorus (mg/L) for five selected outfalls.

Outfalls	p-value																					
	pH		Temperature (˚C)		DO (mg/L)		Conductivity (μS/cm)		BOD (mg/L)		Total Hardness (mg/L)		Nitrate nitrogen (mg/L)		Chloride (mg/L)		Phosphorus (mg/L)		Total Coliform (MPN/100ml)		Fecal Coliform (MPN/100ml)	
	Pre-monsoon	Pre-monsoon	Pre-monsoon	Pre-monsoon	Pre-monsoon	Pre-monsoon	Pre-monsoon	Pre-monsoon	Pre-monsoon	Pre-monsoon	Pre-monsoon	Pre-monsoon	Pre-monsoon	Pre-monsoon	Pre-monsoon	Pre-monsoon	Pre-monsoon	Pre-monsoon	Pre-monsoon	Pre-monsoon	Pre-monsoon	Pre-monsoon
	Vs	Vs	Vs	Vs	Vs	Vs	Vs	Vs	Vs	Vs	Vs	Vs	Vs	Vs	Vs	Vs	Vs	Vs	Vs	Vs	Vs	Vs
	Monsoon	Post-monsoon	Monsoon	Post-monsoon	Monsoon	Post-monsoon	Monsoon	Post-monsoon	Monsoon	Post-monsoon	Monsoon	Post-monsoon	Monsoon	Post-monsoon	Monsoon	Post-monsoon	Monsoon	Post-monsoon	Monsoon	Post-monsoon	Monsoon	Post-monsoon
Circular Canal	0.624	1	0.164	0.000*	0.003*	0.398	0.008*	0.105	0.000*	0.006	0.104	0.683	0.000*	0.001*	0.000*	0.001	0.017	0.057	0.001*	0.002*	0.001*	0.00*
Ghusuri	0.1	0.134	0.189	0.000*	0.001	0.000*	0.161	0.529	0.021*	0.184	0.001*	0.012*	0.002*	0.001*	0.011*	0.011*	0.011*	0.051	0.001*	0.005*	0.000*	0.003*
Dakshineswar Canal	0.624	0.541	0.018	0.000*	0.000*	0.000*	0.000*	0.019*	0.000*	0.009*	0.088	0.286	0.000*	0.021*	0.002*	0.261	0.08	0.772	0.001*	0.004*	0.000*	0.006*
Ballykhal,	0.001	0.006*	0.737	0.000*	0.002*	0.856	0.004*	0.104	0.028*	0.382	0.000*	0.001*	0.006*	0.494	0.000*	0.054	0.000*	0.106	0.001*	0.002*	0.001*	0.001*
Khardah Khal	0.391	0.401	0.261	0.000*	0.019*	0.010*	0.000*	0.039*	0.010*	0.030*	0.044*	0.149	0.006*	0.005*	0.000*	0.002*	0.119	0.203	0.001*	0.003*	0.000*	0.001*

N = 16 * p value <0.05.

https://doi.org/10.1371/journal.pwat.0000008.t001

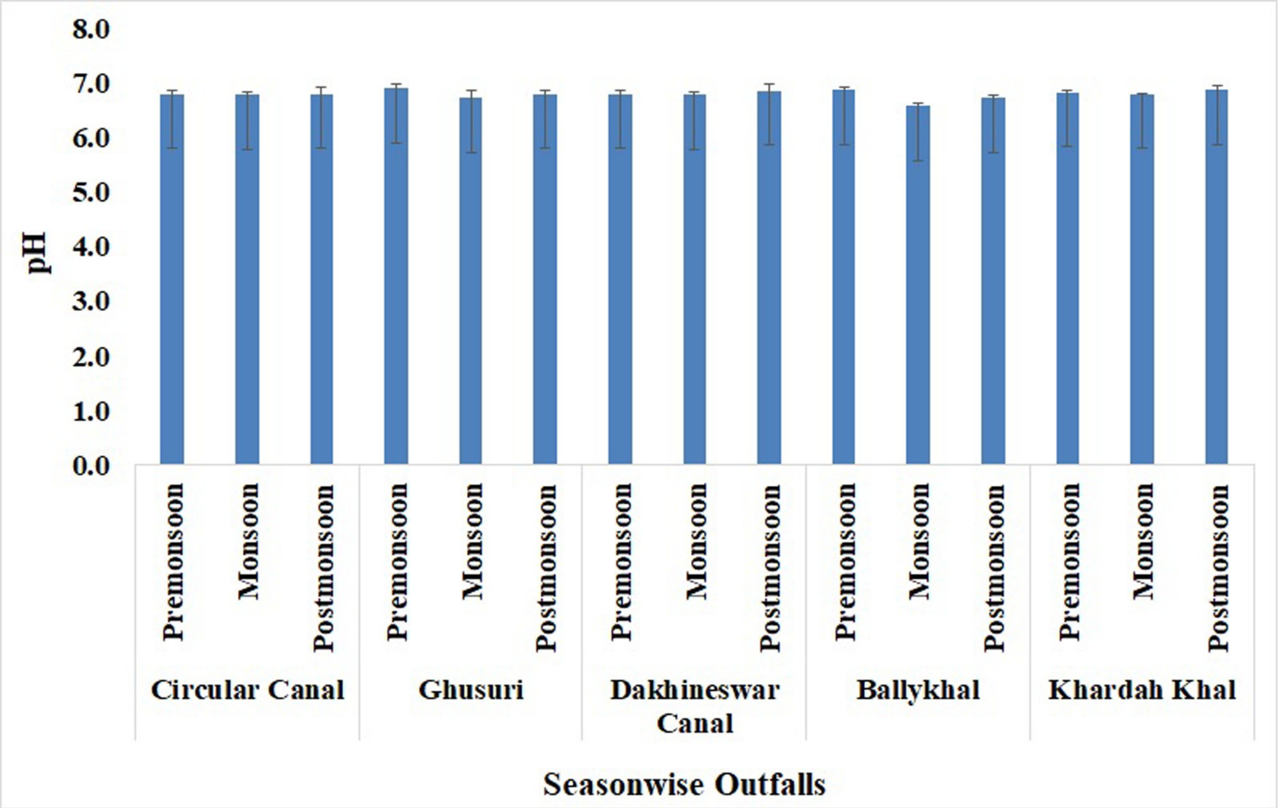

Fig 3. Seasonal changes of pH at five selected outfalls of river Ganga.

https://doi.org/10.1371/journal.pwat.0000008.g003

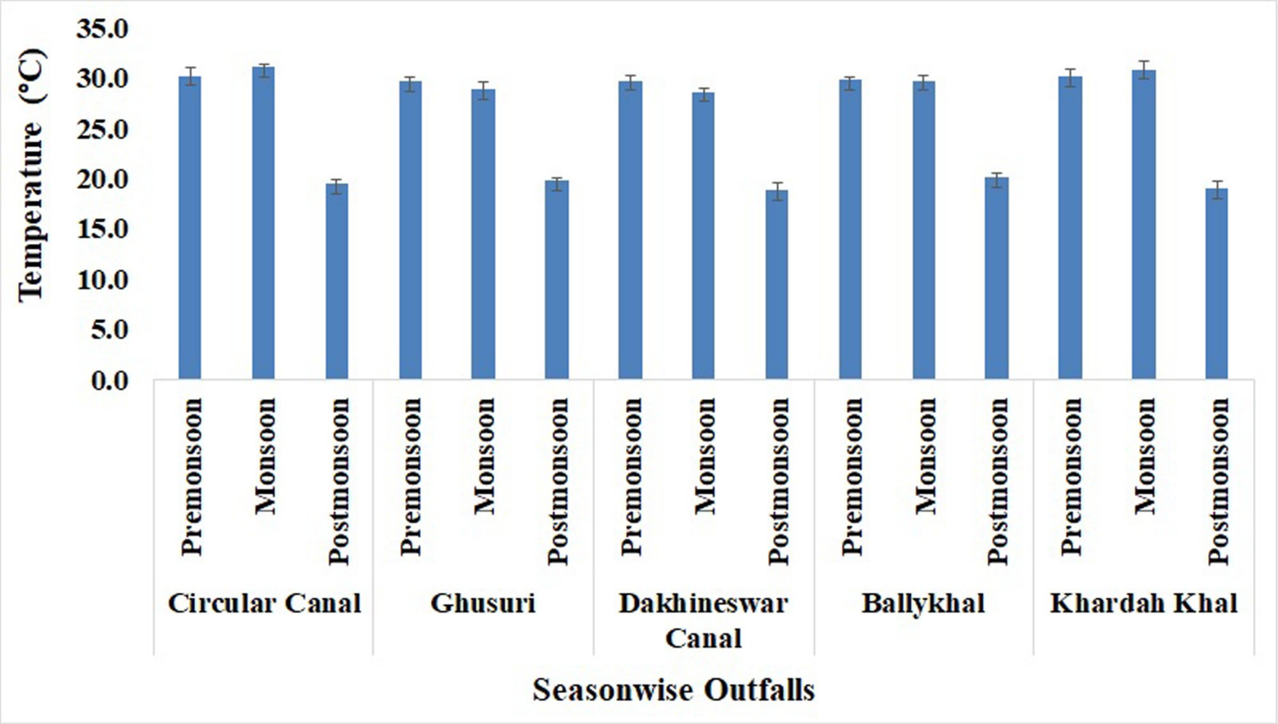

Fig 4. Seasonal changes of temperature (˚C) at five selected outfalls of river Ganga.

https://doi.org/10.1371/journal.pwat.0000008.g004

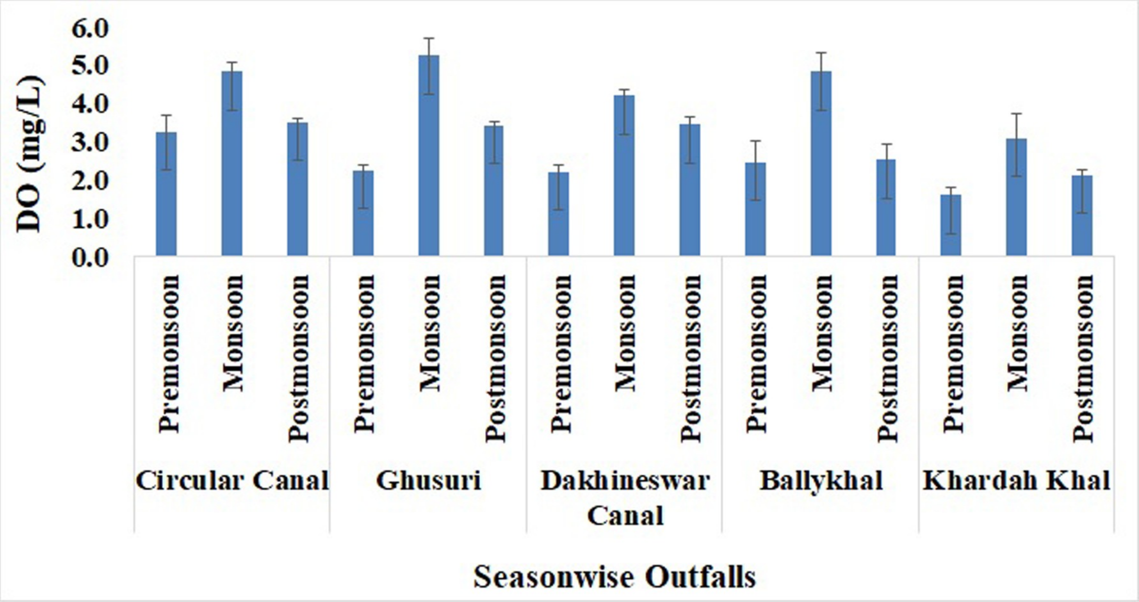

Fig 5. Seasonal changes of DO (mg/L) at five selected outfalls of river Ganga.

https://doi.org/10.1371/journal.pwat.0000008.g005

from light to dark brown from monsoon to pre-monsoon and post-monsoon period. An unpleasant odor was reported throughout the year. No observable changes of pH were reported season wise at any sampling locations except Ballykhal. At Ballykhal a significant increase of pH was observed during pre-monsoon compared to two other seasons. For temperature a significant decrease of its value was observed during post-monsoon in comparison to pre-monsoon.

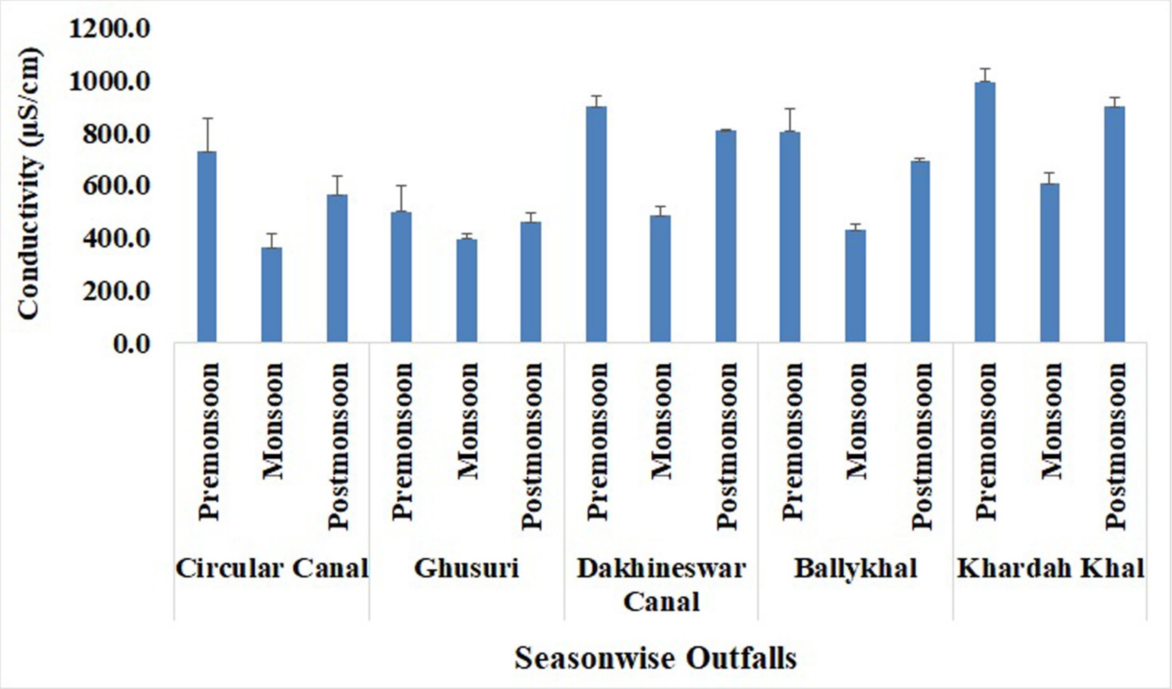

Fig 6. Seasonal changes of conductivity (μS/cm) at five selected outfalls of river Ganga.

https://doi.org/10.1371/journal.pwat.0000008.g006

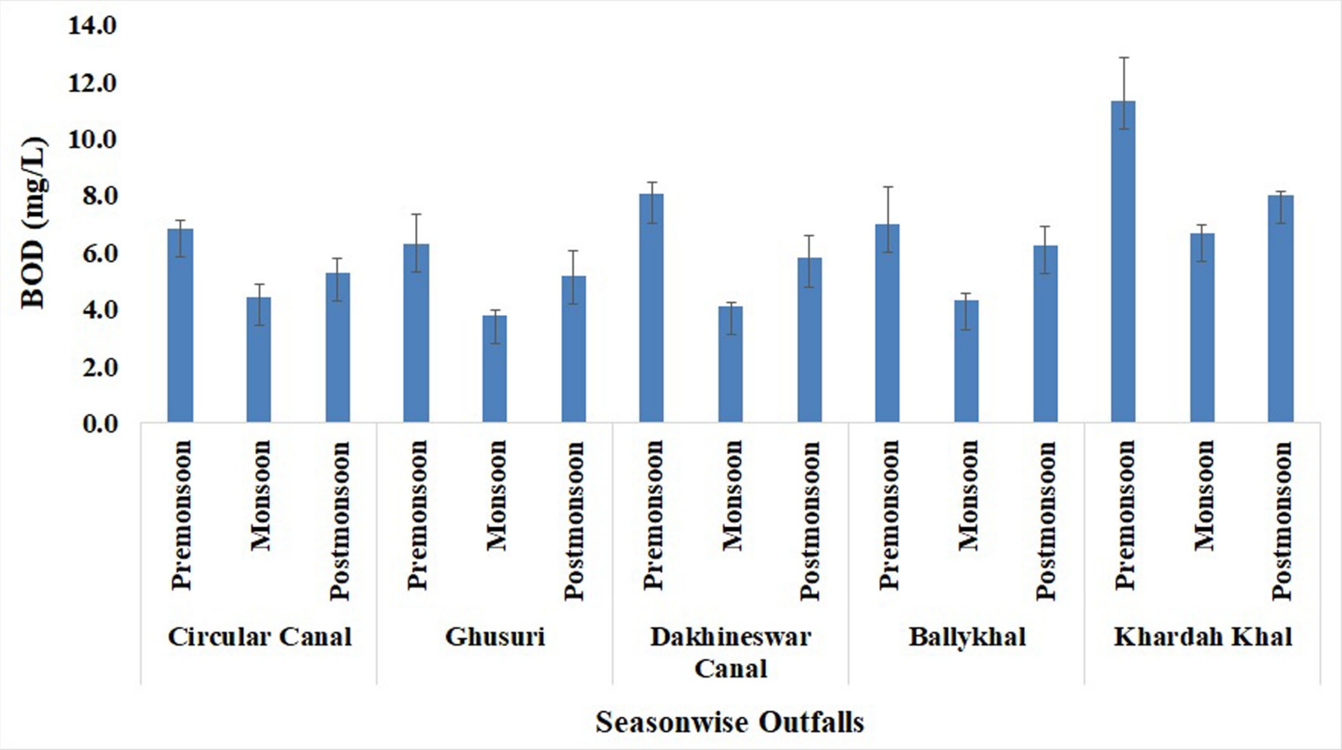

Fig 7. Seasonal changes of BOD (mg/L) at five selected outfalls of river Ganga.

https://doi.org/10.1371/journal.pwat.0000008.g007

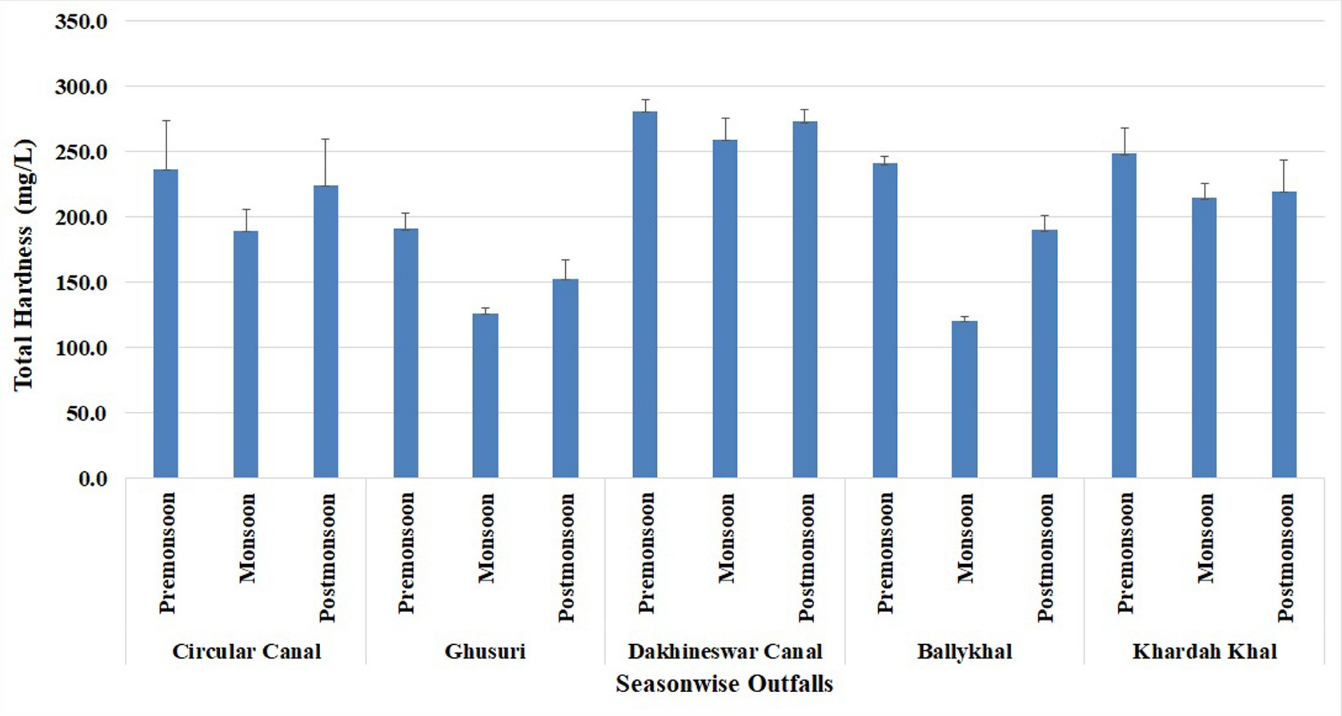

Fig 8. Seasonal changes of total hardness (mg/L) at five selected outfalls of river Ganga.

https://doi.org/10.1371/journal.pwat.0000008.g008

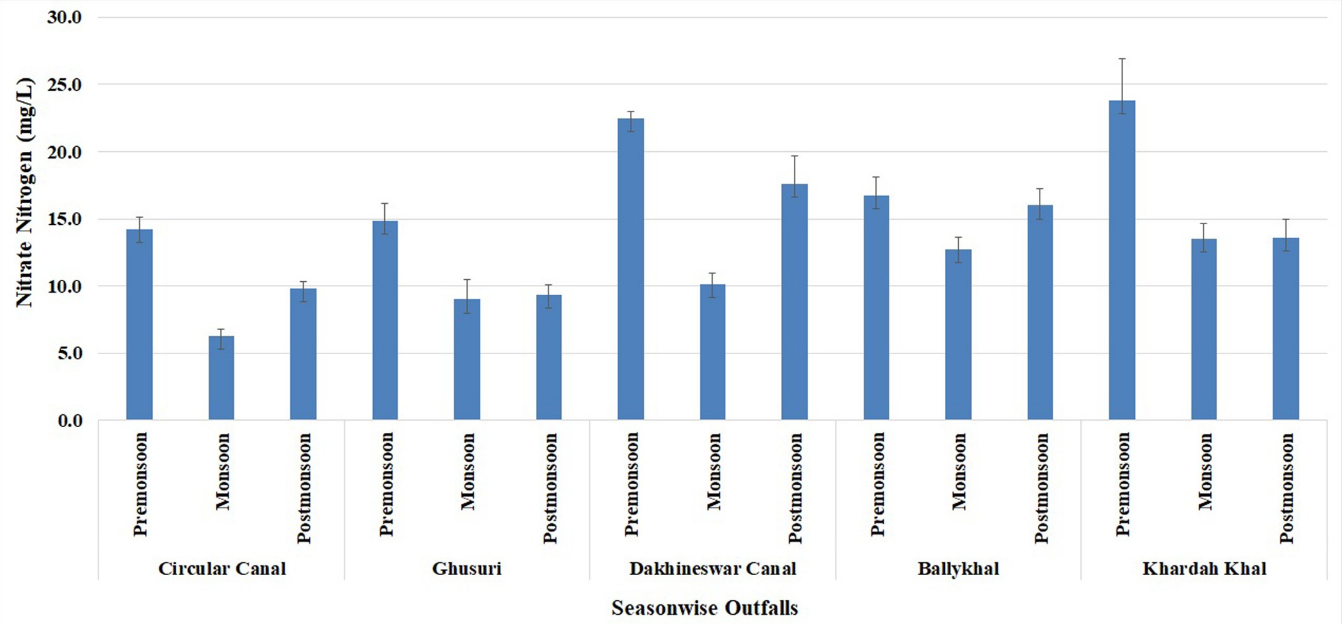

Fig 9. Seasonal changes of Nitrate nitrogen (mg/L) at five selected outfalls of river Ganga.

https://doi.org/10.1371/journal.pwat.0000008.g009

Pre-monsoon value of DO, BOD, nitrate-nitrogen and chloride were significantly higher in comparison to monsoon, as evidenced by t-test analysis. The value of DO was significantly decreased during pre-monsoon in comparison to post-monsoon at Ghusuri, Dakshineswar Canal, and Khardah Khal. A significant increase of value of conductivity was reported at all

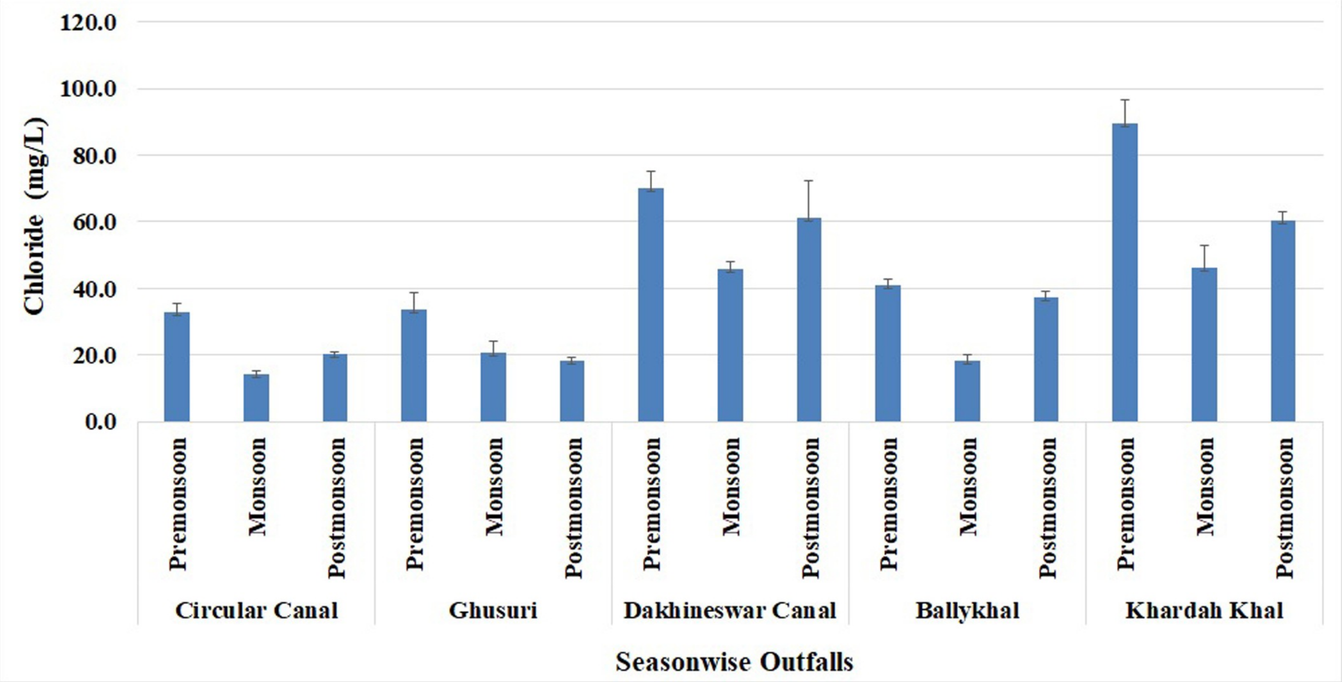

Fig 10. Seasonal changes of chloride (mg/L) at five selected outfalls of river Ganga.

https://doi.org/10.1371/journal.pwat.0000008.g010

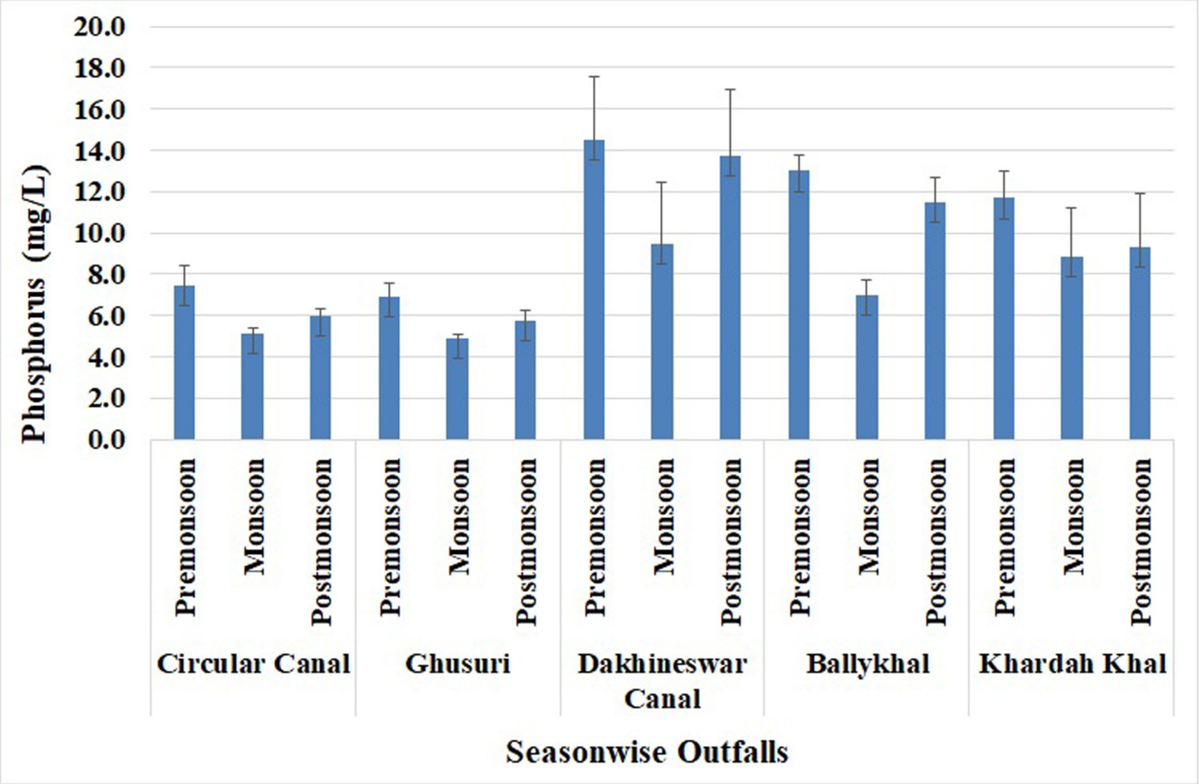

Fig 11. Seasonal changes of phosphorus (mg/L) at five selected outfalls of river Ganga.

https://doi.org/10.1371/journal.pwat.0000008.g011

sampling locations except Ghusuri during pre-monsoon in comparison to monsoon. The increasing trend of conductivity and BOD was also observed at Dakshineswar Canal and Khardah Khal when it was compared to post-monsoon. The level of nitrate nitrogen was increased significantly during pre-monsoon in comparison to post-monsoon for all sampling location except Ballykhal. A significantly higher value of total hardness was observed at Ghusuri, Ballykhal, and Khardah Khal during pre-monsoon than monsoon. At Ghusuri and Ballykhal, the level of total hardness and phosphorus was notably high during pre-monsoon in comparison to post-monsoon and monsoon respectively. Considering post-monsoon value, the level of total hardness was also significantly high during pre-monsoon at Ghusuri and Ballykhal. A significant higher value of chloride was also observed at Ghusuri and Khardah Khal during pre-monsoon than post-monsoon (Table 1; Figs 3–11). Student t-test was not performed for comparative seasonal analysis of heavy metals. Seasonal values showed the concentration of Pb, Hg, and As were within its standard limit for most of the cases. Only at Khardah Khal during pre-monsoon the value of mercury was found little alarming (Figs 12–14; Tables B and F in S1 File). The value of total coliform and fecal coliform were many folds higher than its standard at each five outfalls considering all three seasons (Tables B and F in S1 File). Though p-value signified an excessively high level of coliform at each location during pre-monsoon in comparison to two other seasons (Table 1; Figs 15 and 16).

The level of total and fecal coliform was beyond its standard limit during seasonal analysis at all sampling sites. An over range of DO, BOD, nitrate nitrogen, and phosphorus was reported in most of the sampling sites for all three seasons. The presence of heavy metals was very much site specific, may be due to its surrounding sources. No spatial and seasonal impact

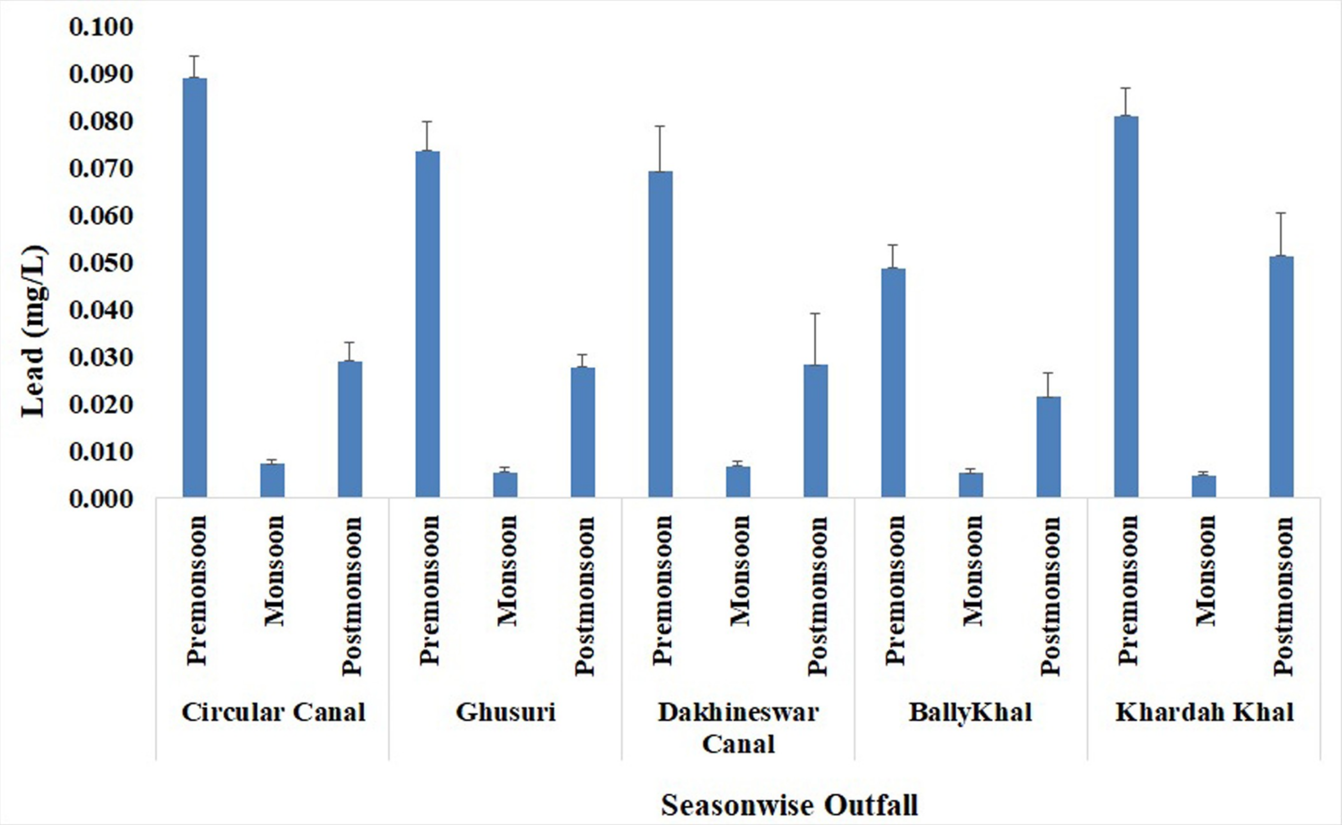

Fig 12. Seasonal changes of lead (as Pb) (mg/L) at five selected outfalls of river Ganga.

https://doi.org/10.1371/journal.pwat.0000008.g012

on pH was observed and the temperature changed seasonally. In the study area, wastewater from outfalls mainly settle within certain distance which was directly proportional to the tidal actions. So, during monsoon and post-monsoon, when the excess rainwater mixed with mainstream, the density of pollution in water becomes diluted. However, during pre-monsoon due to minimization of volume of water, the level of pollution may be high. These may be the reason for water quality variation in different seasons. The same kind of trend was observed in many works on river Ganga [54–57]. A significant influence of environmental factors on seasonal distribution of water quality parameters in river was reported [58]. During rainy season, the dilution effect for surface run-off may be responsible for changing the concentration of pollutants and reduction of its value [59, 60]. During pre-monsoon the temperature was comparatively higher which may reduce the value of DO. The dilution effect of heavy volume of fresh and rainwater during monsoon create less adverse effect on water body [56]. The total volume of water in riverbed was the major cause for the maintenance of water quality. Water level of river Ganga generally remains low in pre-monsoon in comparison to monsoon and post-monsoon. This may be the reason for variation of concentrations of water quality parameters season wise. Catchment characteristics, seasonal impact, and anthropogenic activities are determinant factors for temporal changes of water quality parameters of rivers [61]. The volume of water and its flow affect the distribution of pollutants in river. Larger the river, the efficiency of diluting pollutant concentration is higher [62].

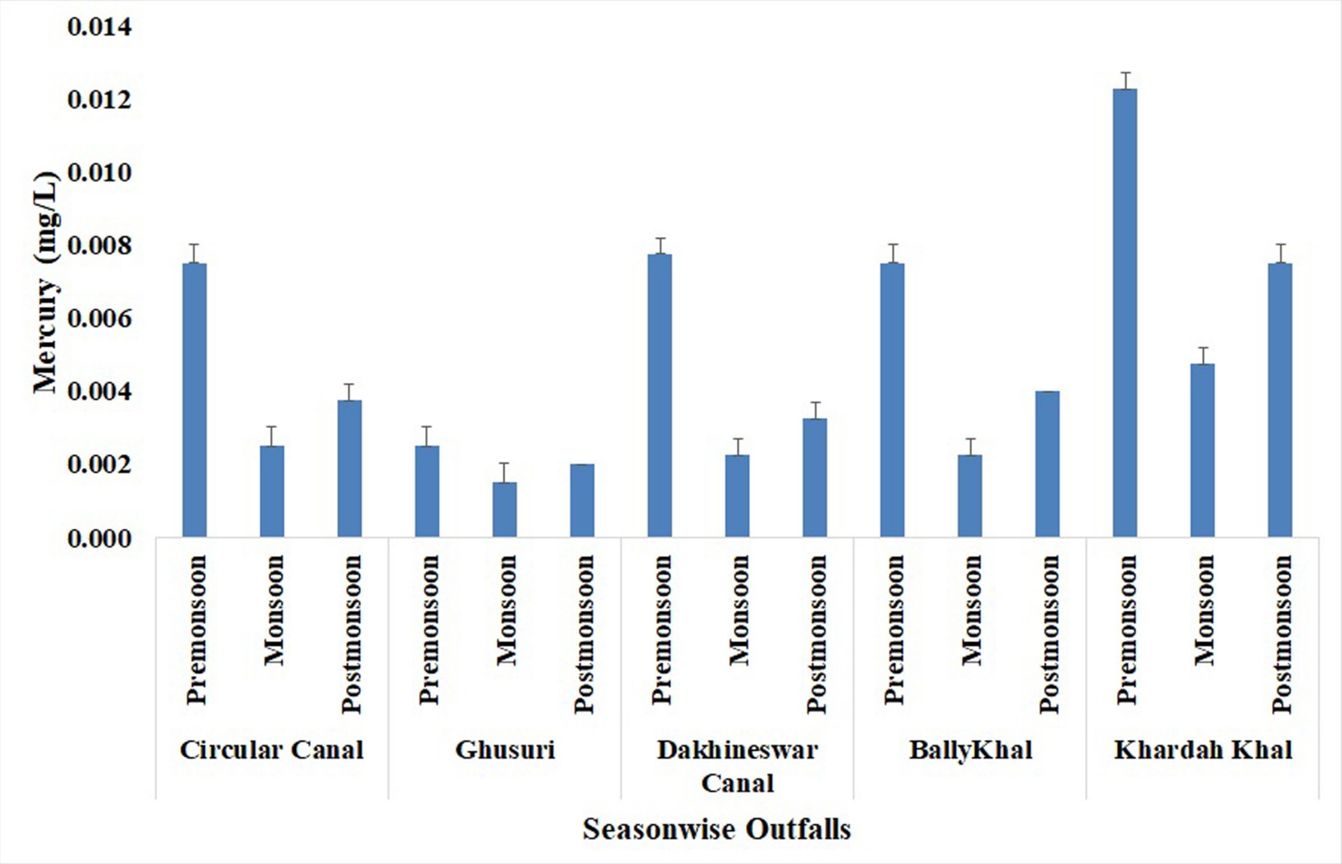

Fig 13. Seasonal changes of mercury (as Hg) (mg/L) at five selected outfalls of river Ganga.

https://doi.org/10.1371/journal.pwat.0000008.g013

3.4 Prediction of water quality parameters

The correlation matrix was generated separately for each sampling site considering all measured parameters except color and odor (Tables G-K in S1 File). A strong correlation in between heavy metals and coliform (total and fecal) was observed in most of the cases. The evidence of positive [63] as well as negative correlation in between them was already revealed by the researchers [64]. Regression can relate variables to form a functionable expression. Thus, the prediction of one parameter can easily be done by using others [65, 66]. Regression equation which was generated among different water quality parameters shows linear relationship which is presented in Table 2.

When the value of R^2 remain 0.999, the result can be elaborated in a way that there is a chance of 99.9% variability of water quality related to respective parameters [67]. The percentage of error from calculated and actual values (pre-monsoon, 2019) of parameters remained less than 10% in most of the cases. It was also found that the value of total coliform and fecal coliform had a strong correlation in all sampling sites. Heavy metals like Pb, Hg, and As had a tendency to be correlated with any one of them in most of the cases. Even the relationship between coliform and heavy metals can also be established. As the measurement of coliform and heavy metal was little bit expensive and time consuming, this model will encourage to predict the value of one parameter by measuring other. It may reduce the time and cost as well. Correlation matrix showed the correlated parameters were changing site wise. This spatial variation may be due to different pollutant sources and other influencing parameters surrounding the sampling area.

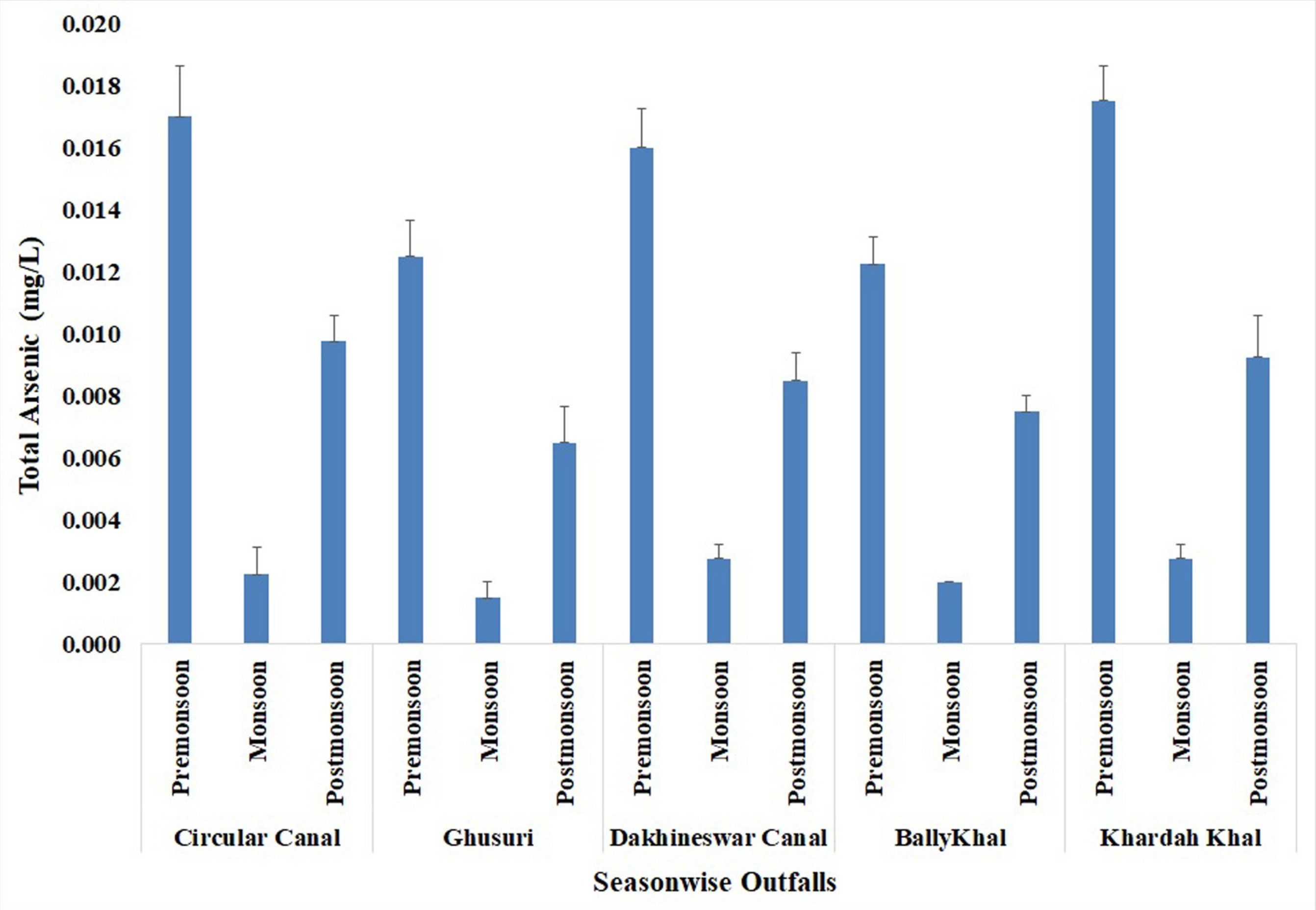

Fig 14. Seasonal changes of total arsenic (as As) (mg/L) at five selected outfalls of river Ganga.

https://doi.org/10.1371/journal.pwat.0000008.g014

3.5 Influence of tidal variation

The analysis of variation of water quality parameters due to tidal fluctuation was done season wise for five selected outfalls as well. It helped to spot the distance of safe zone from the outfalls where parameters reach their standard value. The prediction of concentration of parameters was also done at several points from Dakshineswar Canal and Ballykhal.

3.6 Identification of zone of influence

The distance wise changes of concentration of parameters were obtained from direction wise analysis for five separate outfalls during tidal fluctuation (Tables L-R in S1 File). The best fit polynomial equation helped to measure the point at which concentration of parameters reached its permissible limits in every direction from each outfall (Table AG in S1 File). Parameters which had reached its standard limit at outfall only, were not taken into consideration for further calculation considering tidal fluctuation. No spatial changes of pH and temperature were observed from the outfalls due to the tidal fluctuations. BOD value met its standard value along the bank at 138.4 m from Ballykhal, at 128.7 m from Circular Canal, and at 127.1 m from Khardah Khal during pre-monsoon. The minimum distance was reported 34.1 m diagonally from Ghusuri to reach its safe limit. The influence of DO and nitrate nitrogen was also very prominent at Ballykhal. It needed to travel up to 142.1 m and 120.6 m

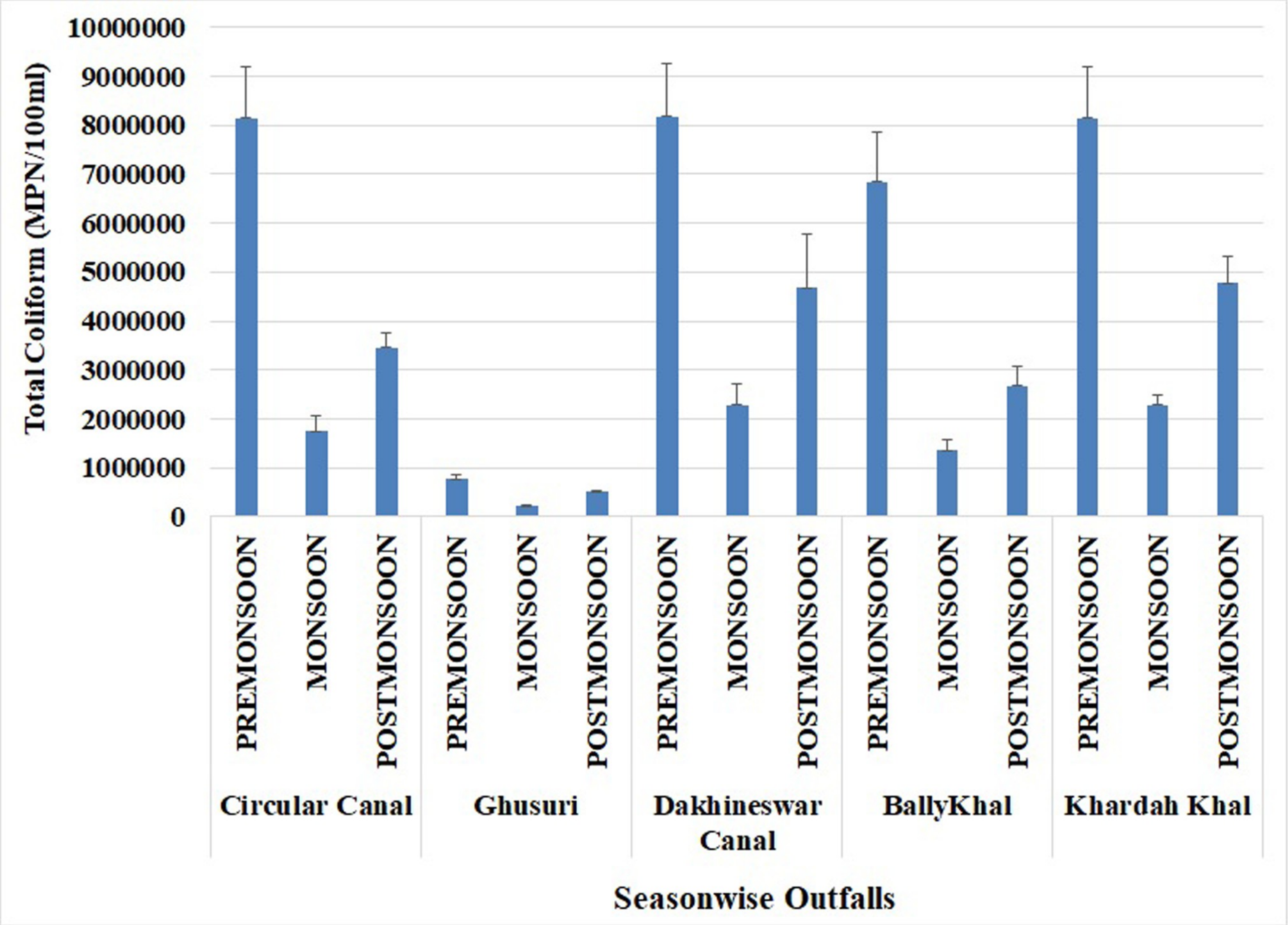

Fig 15. Seasonal changes of total coliform (MPN/100ml) at five selected outfalls of river Ganga.

https://doi.org/10.1371/journal.pwat.0000008.g015

respectively to achieve safe limit of DO and nitrate nitrogen along the bank from Ballykhal during pre-monsoon. Ghusuri was comparatively having less influence because at 44.7 m across the outfall DO reach its standard limit and for nitrate nitrogen it was only 31.8 m during pre-monsoon. Pre-monsoon data showed the influence remained up to 115.4 m along the bank from Khardah Khal considering DO value. The impact of nitrate nitrogen was even much prominent up to 105.9 m along the bank from Circular Canal. Considering the value of phosphorus during pre-monsoon, the maximum distance needed to cover 105.1 m along the bank from Ballykhal followed by 82.3 m diagonally from Circular Canal. Again, for Ghusuri the distance remained only 21.7 m along the bank (Table 3).

The influence of each outfall on river water quality varied with its flow and tidal dynamics. During low tide, the concentration of parameters was quite high in comparison to high tide. DO, BOD, nitrate nitrogen, and phosphorous are the most influential parameters which changed with distances and directions. The rate of changes in their concentrations was recorded maximum with increasing distance from outfalls during low tide. High tide data did not demonstrate any notable impact on pollutants distribution as the level of parameters remained within its standard value at its entry point in river Ganga only.

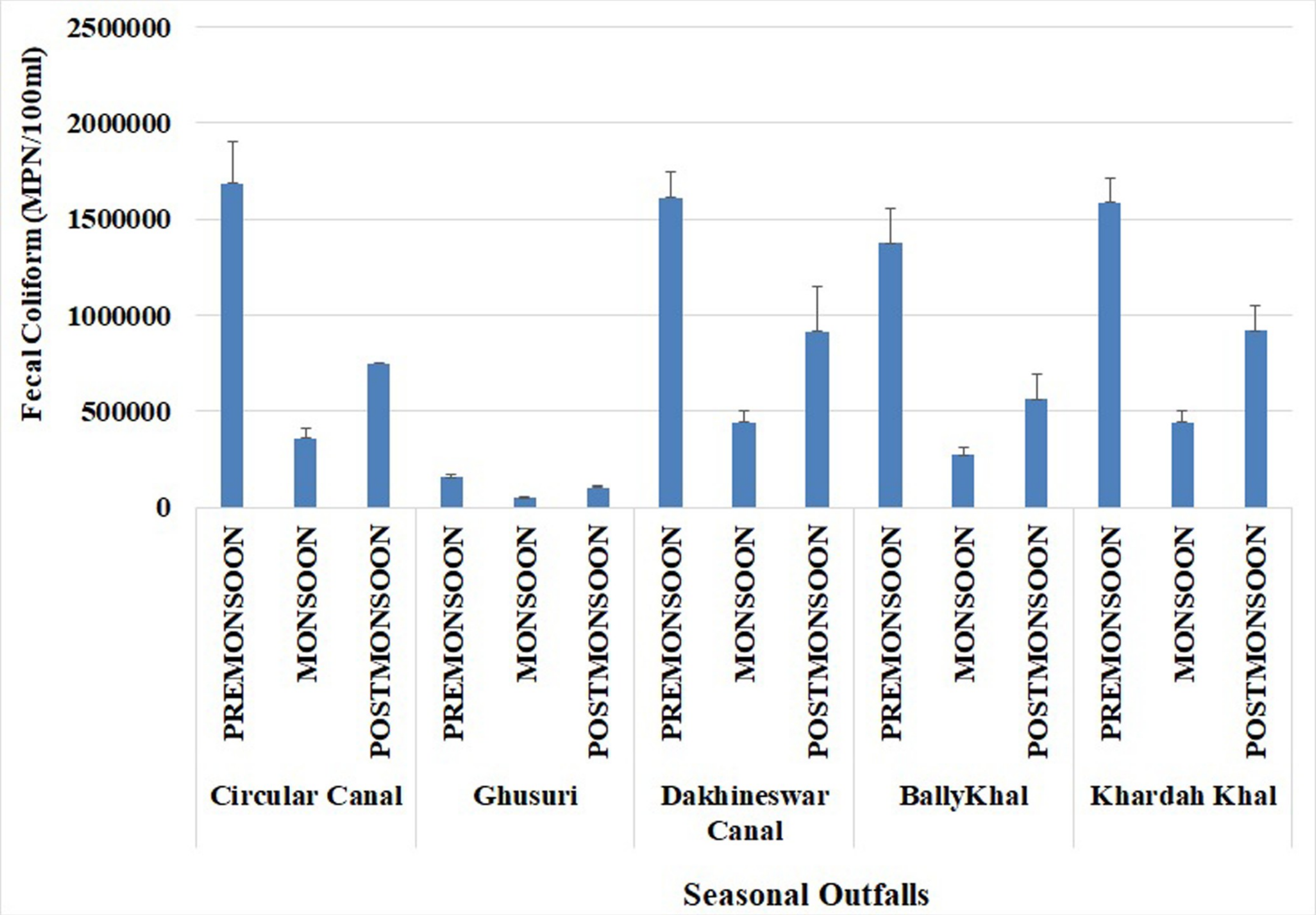

Fig 16. Seasonal changes of fecal coliform (MPN/100ml) at five selected outfalls of river Ganga.

https://doi.org/10.1371/journal.pwat.0000008.g016

3.7 Validation of water quality parameters by Plug flow model

During pre-monsoon, the influence was maximum in comparison to other two seasons for all sampling locations except at Circular Canal and Khardah Khal where the impact of DO remain comparatively high during post-monsoon. The concentration of parameter reached its limit by travelling a shorter distance during monsoon may be due to high water level in river Ganga. The study demonstrated a prominent influence of DO, BOD, nitrate nitrogen, and phosphorus at Ballykhal followed by Khardah Khal and Circular Canal. The minimum influence was reported at Ghusuri. Other than DO, BOD, nitrate nitrogen, and phosphorus, all other measured parameters reached their standard value at source of wastewater discharging point only, so they were not considered for calculation. The increasing level of water in river Ganga enhances the dilution effect which changes the level of parameters. The reason behind minimizing BOD level or increasing DO value during monsoon may be the dilution effect. The trend of sedimentation of the phosphorus was directly proportional to the total volume of the water in riverbed and may be responsible for minimizing its value in monsoon as well. At Ballykhal, Khardah Khal, and Circular Canal, the discharge of a large volume of wastewater may be responsible for its maximum influence. The volume of wastewater reflected its zone of influence. Higher the concentration, the longer the path it needed to travel to meet its criteria for standard. At Ghusuri, a comparatively low volume of wastewater release reduced its path. Not

Table 2. Prediction of water quality parameters by regression equation.

Name of the site	y (Dependent)	x (Independent)	Regression Equation	The value of R^2	Calculated	Actual value (pre-monsoon, 2019)	Percentage of Error
Circular Canal	Nitrate nitrogen (NN)	Chloride (CL)	NN = 0.4023CL + 1.0627	0.9161	14.339	14.5	-1.11
	Nitrate nitrogen (NN)	Lead (Pb)	NN = 91.95Pb + 6.2611	0.9194	14.537	14.5	0.25
	Nitrate nitrogen (NN)	Total Arsenic (As)	NN = 536.54As + 4.9135	0.9737	13.498	14.5	-6.91
	Chloride (CL)	Lead (Pb)	CL = 220.05Pb + 13.279	0.93	33.084	33.0	0.25
	Chloride (CL)	Mercury (Hg)	CL = 3586.5Hg + 6.0284	0.9705	34.720	33.0	5.21
	Lead (Pb)	Mercury (Hg)	Pb = 15.422Hg—0.0289	0.9343	0.094	0.090	4.97
	Lead (Pb)	Total Coliform (TC)	Pb = 1E-08TC—0.0136	0.9762	0.056	0.090	-37.33
	Lead (Pb)	Fecal Coliform (FC)	Pb = 6E-08FC—0.0138	0.9682	0.070	0.090	-22.00
	Total Coliform (TC)	Fecal Coliform (FC)	TC = 4.7974FC—15448	0.9886	6700912	7000000	-4.27
Ghusuri	Total Hardness (HAR)	Total Arsenic (As)	HAR = 5981.9As + 115.83	0.919	187.6	184	1.96
	Total Hardness (HAR)	Fecal Coliform (FC)	HAR = 0.0006FC+ 95.442	0.9006	179.4	184	-2.48
	Total Arsenic (As)	Total Coliform (TC)	As = 2E-08TC—0.0033	0.9541	0.0107	0.012	-10.83
	Total Arsenic (As)	Fecal Coliform (FC)	As = 1E-07FC—0.0033	0.9575	0.0107	0.012	-10.83
	Total Coliform (TC)	Fecal Coliform (FC)	TC = 5.0112FC + 2622.6	0.9866	704190.6	700000	0.60
Dakshineswar	Total Coliform (TC)	Fecal Coliform (FC)	TC = 4.9371FC + 15809	0.9575	8798024	7500000	17.31
	Lead (Pb)	Mercury (Hg)	Pb = 10.692 Hg—0.0125	0.9161	0.06	0.05	24.69
	BOD	Total Arsenic (As)	BOD = 299.29As + 3.2648	0.9385	6.856	7.9	-13.21
	BOD	Total Coliform (TC)	BOD = 6E-07TC + 2.7545	0.9245	7.255	7.9	-8.17
	BOD	Fecal Coliform (FC)	BOD = 3E-06FC + 2.8208	0.9051	8.071	7.9	2.16
Ballykhal	Conductivity (CON)	Total Arsenic (As)	CON = 37152As+ 373.07	0.9023	818.9	817.3	0.20
	Total Hardness (HAR)	Total Arsenic (As)	HAR = 11449As + 101.07	0.9468	238.5	244.0	-2.27
	Lead (Pb)	Mercury (Hg)	Pb = 8.0764Hg—0.0119	0.9504	0.045	0.048	-7.01
	Lead (Pb)	Total Arsenic (As)	Pb = 4.189As—0.0052	0.9298	0.045	0.048	-6.11
	Mercury (Hg)	Total Arsenic (As)	Hg = 0.5006As + 0.001	0.9112	0.007	0.007	0.10
	Mercury (Hg)	Total Coliform (TC)	Hg = 9E-10TC + 0.0013	0.9425	0.008	0.007	15
	Mercury (Hg)	Fecal Coliform (FC)	Hg = 4E-09FC + 0.0014	0.9109	0.0078	0.007	11.43
	Total Coliform (TC)	Fecal Coliform (FC)	TC = 4.9373FC—8016	0.9854	7891664	7500000	5.22
Khardah Khal	Mercury (Hg)	Total Arsenic (As)	Hg = 0.4989As + 0.0033	0.9511	0.012	0.012	-1.82
	Mercury (Hg)	Total Coliform (TC)	Hg = 1E-09TC + 0.0021	0.9143	0.009	0.012	-24.17
	Mercury (Hg)	Fecal Coliform (FC)	Hg = 6E-09FC + 0.0019	0.9517	0.010	0.012	-14.17
	Total Arsenic (As)	Total Coliform (TC)	As = 2E-09TC- 0.002	0.903	0.012	0.017	-29.41
	Total Coliform (TC)	Fecal Coliform (FC)	TC = 5.1002FC + 55729	0.9796	7196009	7000000	2.80

https://doi.org/10.1371/journal.pwat.0000008.t002

Table 3. Distance (m) at which BOD, DO, Nitrate Nitrogen, Phosphorous reaches its permissible limit during low tide at different sampling sites season wise.

Seasons	Locations	BOD (mg/L)			DO (mg/L)			Nitrate nitrogen (mg/L)			Phosphorous (mg/L)		
		Across the River (m)	Diagonally from The Outfall (m)	Along the Bank (m)	Across the River (m)	Diagonally from The Outfall (m)	Along the Bank (m)	Across the River (m)	Diagonally from The Outfall (m)	Along the Bank (m)	Across the River (m)	Diagonally from The Outfall (m)	Along the Bank (m)
Pre-monsoon	CIRCULAR CANAL	71.1	81	128.7	98.4	107.4	108.6	89.4	81.9	105.9	74.3	82.3	68.6
	GHUSURI	36.7	34.1	45.8	44.7	48.4	46.1	31.8	34.9	44.8	24.5	24	21.7
	DAKSHINESWAR CANAL	75.6	78.5	90.9	87.1	85.3	81.6	59.9	76.1	86.3	72.1	73.3	70.5
	BALLYKHAL	69.1	91.3	138.4	125	111.8	142.1	52.3	77.3	120.6	74.2	83.7	105.1
	KHARDAH KHAL	77.2	78.7	127.1	85.2	76.8	115.4	44.2	43.8	67.4	37.1	38.4	55.1

(*Continued*)

Table 3. (Continued)

Seasons	Locations	BOD (mg/L)			DO (mg/L)			Nitrate nitrogen (mg/L)			Phosphorous (mg/L)		
		Across the River (m)	Diagonally from The Outfall (m)	Along the Bank (m)	Across the River (m)	Diagonally from The Outfall (m)	Along the Bank (m)	Across the River (m)	Diagonally from The Outfall (m)	Along the Bank (m)	Across the River (m)	Diagonally from The Outfall (m)	Along the Bank (m)
Monsoon	CIRCULAR CANAL	50	67.8	80.5	2.3	7.5	7.4	–	–	–	–	–	–
	GHUSURI	14.7	20.2	31.2	–	–	–	–	–	–	–	–	–
	DAKSHINESWAR CANAL	18	15.2	16.2	17.4	20.3	21.8	3	2.7	3.5	29.6	21.2	29.5
	BALLYKHAL	23.8	27.7	33.1	6	6	7	19.5	27.6	30	15.2	16.2	20.4
	KHARDAH KHAL	48.3	36.1	49.3	27.5	28.8	39.1	13	10.6	14.6	22.9	22.4	33.2
Post-monsoon	CIRCULAR CANAL	52.8	72.1	88.8	79.9	116.6	134.5	–	–	–	27.8	33.4	49.6
	GHUSURI	27.3	32.6	38.1	31.3	36.7	36.6	–	–	–	12	22.2	32.3
	DAKSHINESWAR CANAL	29.5	30	46.1	69.1	62.4	80.7	37.8	36	35	37.5	33	37.9
	BALLYKHAL	55.2	56.6	76.4	121.6	116.9	140.6	16.7	41.9	48.3	35.2	39.6	49.5
	KHARDAH KHAL	40.2	39.9	56.6	84	73.4	122.9	23.8	23.8	31.9	27	28	38.4

https://doi.org/10.1371/journal.pwat.0000008.t003

Table 4. Strip-wise depth average discharge across the river Ganga from outfall and at its upstream at Ballykhal and Dakshineswar.

Distance (m)	Ballykhal			
	Discharge (m^3/s) (Across the river directly from outfall during low tide)	Discharge (m^3/s) (Across the river from outfall during high tide)	Discharge (m^3/s) (Across the river in upstream of outfall during low tide)	Discharge (m^3/s) (Across the river in upstream of outfall during high tide)
0	0.017	0.023	0.071	0.0862
15	0.078	0.22	0.122	0.1582
35	0.186	0.232	0.19	0.2542
55	0.269	0.29	0.258	0.3502
75	0.346	0.484	0.326	0.4462
95	0.402	0.563	0.394	0.5422
115	0.492	0.689	0.462	0.6382
135	0.546	0.764	0.53	0.7342
155	0.625	0.875	0.598	0.8302
175	0.705	0.987	0.666	0.9262
	Dakshineswar Canal			
0	0.15	0.191	0.28	0.252
20	0.19	0.26	0.298	0.306
40	0.22	0.342	0.316	0.36
60	0.265	0.393	0.334	0.414
80	0.276	0.423	0.352	0.468
100	0.313	0.458	0.37	0.522
120	0.362	0.492	0.388	0.576
140	0.376	0.532	0.406	0.63
180	0.432	0.602	0.442	0.738
200	0.49	0.191	0.46	0.792

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Table 5. The value of discharge at different sampling points of Dakshineswar Canal and Ballykhal during low tide and high tide.

Distance from outfall (m) across the river	Low Tide		Distance from outfall (m) across the river	High Tide	
	Discharge (m^3/s) (Across the river)	Discharge (m^3/s) (Across the river just upstream)		Discharge (m^3/s) (Across the river)	Discharge (m3/s) (Across the river just upstream)
45.7	0.215	0.2	11.39	0.122	0.141
70.3	0.311	0.349	36.09	0.253	0.259
128.8	0.54	0.499	70.17	0.434	0.423
Dakshineswar Canal					
Distance from outfall (m) across the river	Low Tide		Distance from outfall (m) across the river	High Tide	
	Discharge (m^3/s) (Across the river)	Discharge (m^3/s) (Across the river just upstream)		Discharge (m^3/s) (Across the river)	Discharge (m^3/s) (Across the river just upstream)
42.22	0.223	0.354	32.22	0.305	0.372
66.41	0.262	0.276	53.98	0.346	0.342
100.21	0.316	0.395	89.56	0.414	0.512

https://doi.org/10.1371/journal.pwat.0000008.t005

only the wastewater flow, discharge rate of river which varied with tidal fluctuation was highly responsible for its distribution pattern. No variation of concentration of parameters with distance was observed during high tide in any of sampling spots. During high tide the value remained more or less constant and for most of the cases it met its standard limit at outfalls only (Figs 4–30 in S2 File).

A model-based validation (the point source, plug flow model for dissolved oxygen calculation) of pre-monsoon water quality parameters of Dakshineswar Canal and Ballykhal was

Table 6. The estimated and measured water quality parameters with its percentage of error at different sampling points of Ballykhal and Dakshineswar Canal during low tide and High Tide.

Parameters	Ballykhal								Dakshineswar Canal							
	Lowtide				High Tide				Lowtide				High Tide			
	Distance (m)	Estimated Value	Measured Value	Error %	Distance (m)	Estimated Value	Measured Value	Error %	Distance (m)	Estimated Value	Measured Value	Error %	Distance (m)	Estimated Value	Measured Value	Error %
BOD (mg/L)	45.7	4.7	4.1	12.56	11.4	1.3	1.4	-3.98	42.22	4.3	4.7	-9.81	32.22	2.8	2.9	-4.43
	70.3	3.4	3	11.08	36.1	1.3	1.3	1.73	66.41	3.1	3.9	-25.42	53.98	2.6	2.5	3.03
	128	2.8	2.1	25.26	70.2	1.3	1.3	0.89	100.21	2.5	2.2	11.75	89.56	2.4	2.2	8.11
DO (mg/L)	45.7	3.6	2.6	28.58	11.4	7.2	7.3	-1.95	42.22	4.9	2.7	44.64	32.22	6.1	6.2	-2.43
	70.3	4.5	4.1	9.24	36.1	7.2	7.2	0.43	66.41	5.7	4.2	26.45	53.98	6.1	6.2	-1.01
	128	4.9	5.1	-4.22	70.2	7.3	7.3	-0.48	100.21	6.1	6.5	-5.71	89.56	6.2	6.2	0.27
CHORIDE (mg/L)	45.7	28	37	-32.08	11.4	14.7	15.2	-3.75	42.22	37.4	46	-22.93	32.22	15.1	15.3	-1.16
	70.3	21.2	15.6	26.37	36.1	14.3	14.6	-1.95	66.41	26	37.7	-44.92	53.98	14.8	15.3	-3.1
	128	18.3	15.2	16.77	70.2	14.2	14.5	-2.38	100.21	20	19.2	4.02	89.56	14.6	14.3	1.9
CONDUCTIVITY (μS/cm)	45.7	674.17	736.7	-9.27	11.4	489.8	448.7	8.39	42.22	779.85	780.3	-0.06	32.22	311.36	205	34.16
	70.3	592.69	631	-6.46	36.1	505.1	443.7	12.15	66.41	585.46	357.3	38.97	53.98	273.16	205	24.95
	128	557.76	589.7	-5.73	70.2	512.5	443.3	13.49	100.21	430.68	289	32.9	89.56	237.81	205	13.8
TOTAL HARDNESS (mg/L)	45.7	199.7	225	-12.66	11.4	167.5	185.7	-10.89	42.22	200.9	268.7	-33.75	32.22	202.5	196.7	2.85
	70.3	174.5	212	-21.49	36.1	159.6	184	-15.26	66.41	174.3	223	-27.97	53.98	198.9	195.7	1.59
	128	163.7	172	-5.08	70.2	155.9	188	-20.62	100.21	160.2	152	5.13	89.56	195.5	195.7	-0.09
NITRATE NITROGEN (mg/L)	45.7m	11.5	10.2	10.95	11.4	4.9	3.5	29.23	42.22	13	12.5	4.11	32.22	6.6	6.1	7.5
	70.3m	8.7	8.9	-2.56	36.1	5.6	3.5	37.28	66.41	10	9.2	8.36	53.98	6.4	6.1	5.05
	128m	7.5	6.5	13.19	70.2	5.9	3.5	40.54	100.21	8.5	9	-6.36	89.56	6.3	6.1	2.66
PHOSPHORUS (mg/L)	45.7m	8.8	6.1	30.39	11.4	4.6	5.1	-10.44	42.22	8	7.2	9.78	32.22	1.9	1.7	8.84
	70.3m	6.4	5.8	8.69	36.1	4.4	5.1	-15.74	66.41	5.9	5.8	2.31	53.98	1.8	1.7	5.98
	128m	5.3	4.3	19.14	70.2	4.3	5.1	-18.48	100.21	4.9	4.2	13.59	89.56	1.8	1.7	3.16

https://doi.org/10.1371/journal.pwat.0000008.t006

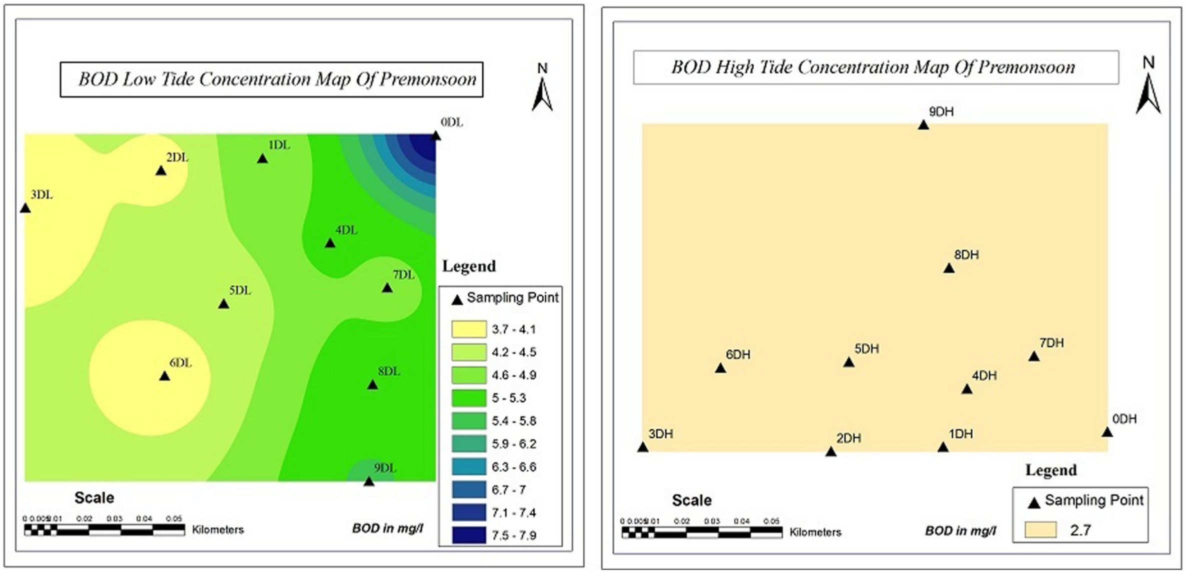

Fig 17. Spatial distribution map of BOD at Dakshineswar Canal during pre-monsoon low tide (left) and pre-monsoon high tide (right).

https://doi.org/10.1371/journal.pwat.0000008.g017

done by using strip-wise depth average discharge (Table 4). The discharge value at different sampling points from the outfall was obtained by linear interpolation (Distance vs Discharge) of strip-wise depth average discharge considering the tidal condition (Tables 5 and 6). The value of discharge fluctuated with distance from outfalls. The value of water quality parameters can be predicted by considering its concentration at the point of discharge. Concentration just upstream of the point of discharge depends on the volumetric flow rate of wastewater and volumetric flow rate of the river for each outfall separately on the river course. The validation of parameters is done by using Plug Flow Model with its estimated value exhibiting minimum

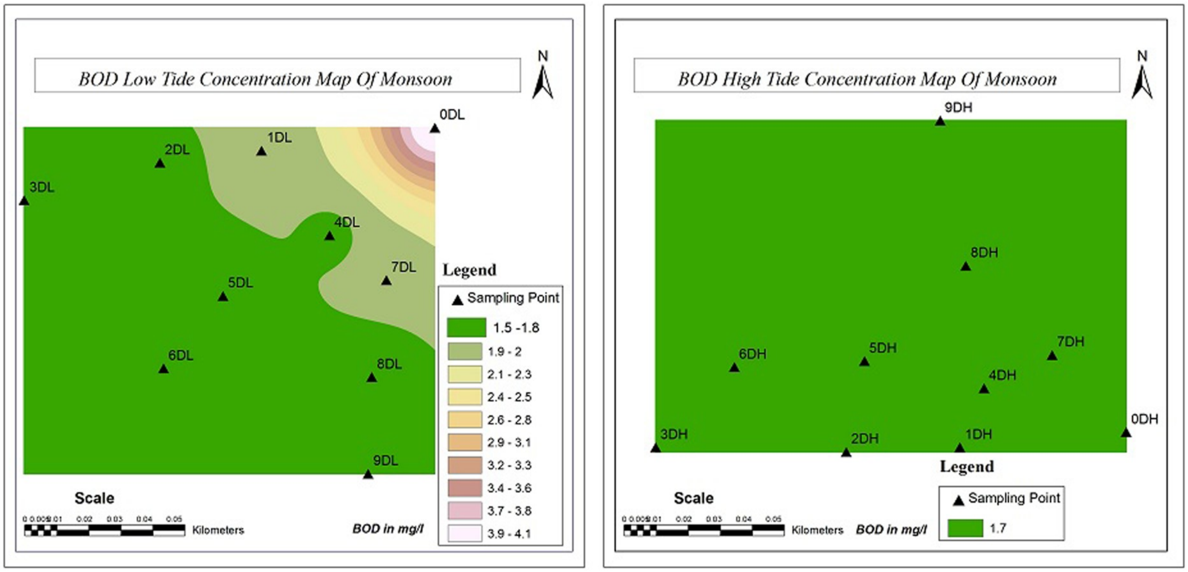

Fig 18. Spatial distribution map of BOD at Dakshineswar Canal during monsoon low tide (left) and monsoon high tide (right).

https://doi.org/10.1371/journal.pwat.0000008.g018

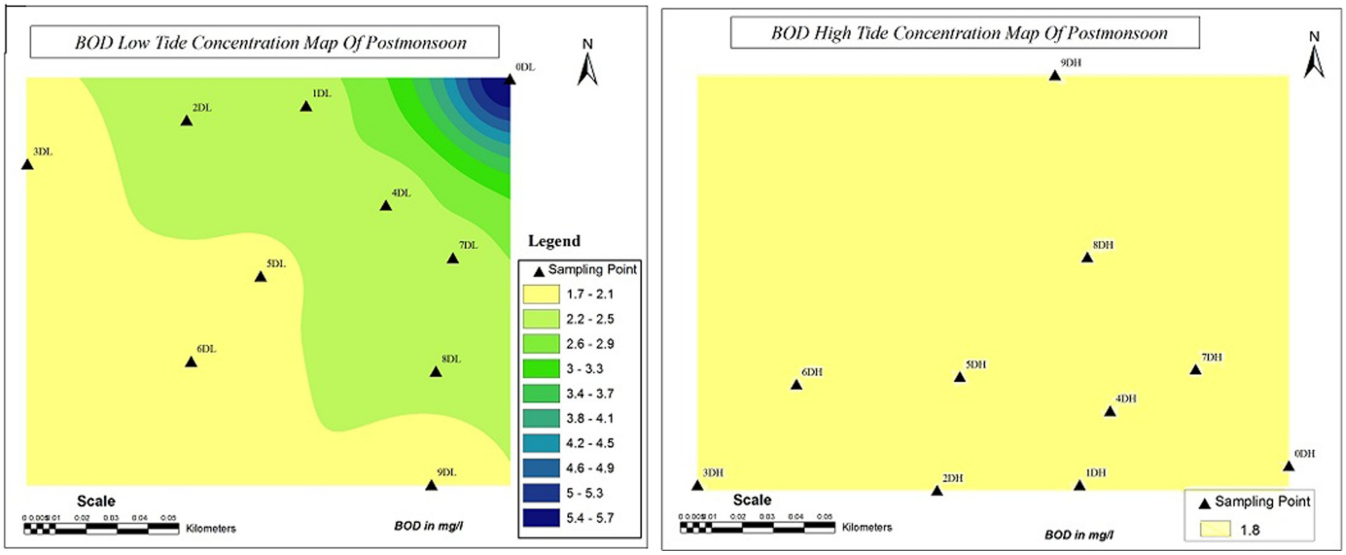

Fig 19. Spatial distribution map of BOD at Dakshineswar Canal during post-monsoon low tide (left) and post-monsoon high tide (right).

https://doi.org/10.1371/journal.pwat.0000008.g019

errors. As the volume of water increases during high tide and monsoon seasons, the dilution effect was very prominent, and concentration of parameters remained low during this period.

3.8 Mapping of water quality parameters using GIS

GIS based mapping is a widely accepted tool for assessing water quality parameters [22, 68–71]. GIS tool was used to assess the influence of tide on changes of BOD and DO level in river Ganga seasonally. The changes of concentration of these two parameters considering the outfall Dakshineswar Canal were observed by generating spatial distribution map seasonally considering high tide and low tide (Figs 17–22). Due to the presence of a significant level of DO,

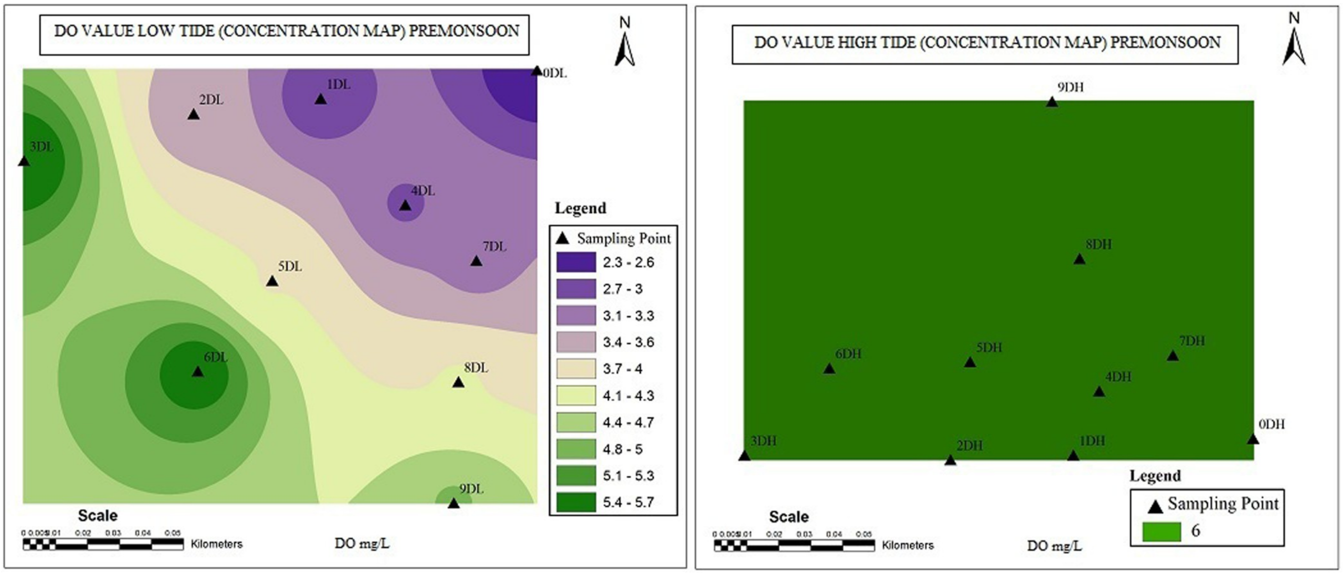

Fig 20. Spatial distribution map of DO at Dakshineswar Canal during pre-monsoon low tide (left) and pre-monsoon high tide (right).

https://doi.org/10.1371/journal.pwat.0000008.g020

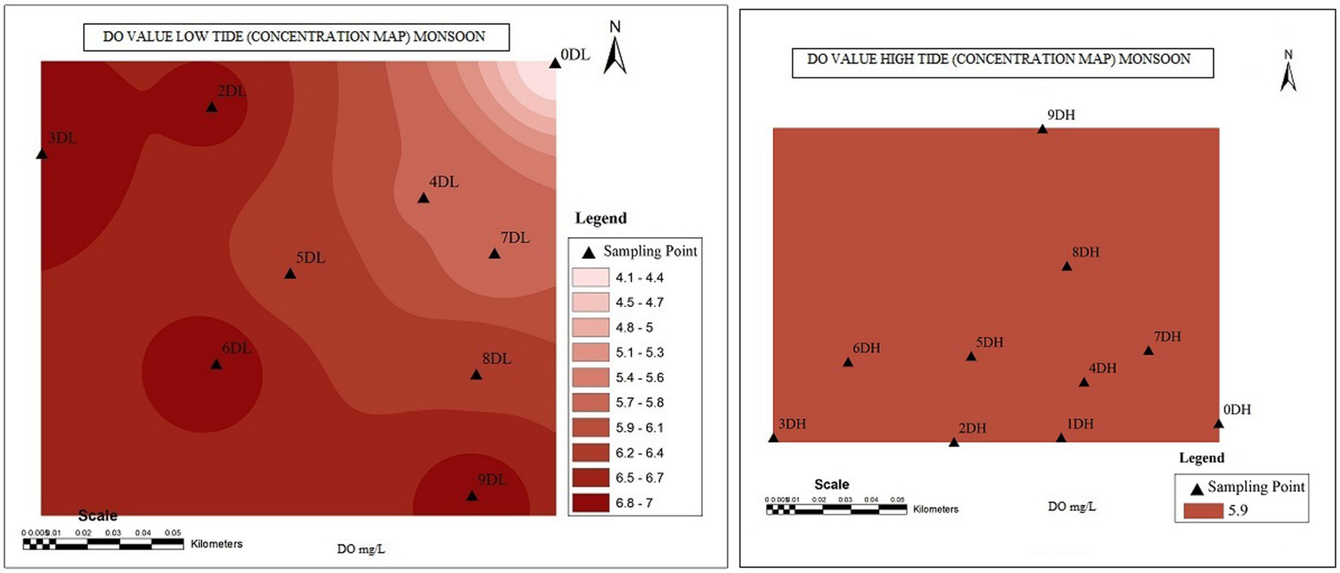

Fig 21. Spatial distribution map of DO at Dakshineswar Canal during monsoon low tide (left) and monsoon high tide (right).

https://doi.org/10.1371/journal.pwat.0000008.g021

BOD, total coliform, fecal coliform, Pb, and Hg, wastewater from Dakhineswar Canal, the site was selected to find the trend of changes of major two parameters DO and BOD parameters season wise by GIS mapping.

A comparison between low tide and high tide map clearly showed that high level of BOD and low level of DO prevail during low tide than high tide. A prominent change of level of parameters was reported with increasing distances from the outfall at all directions. During monsoon, the changes were more stable but more prominent change was reflected in pre-monsoon map (Figs 17–22).

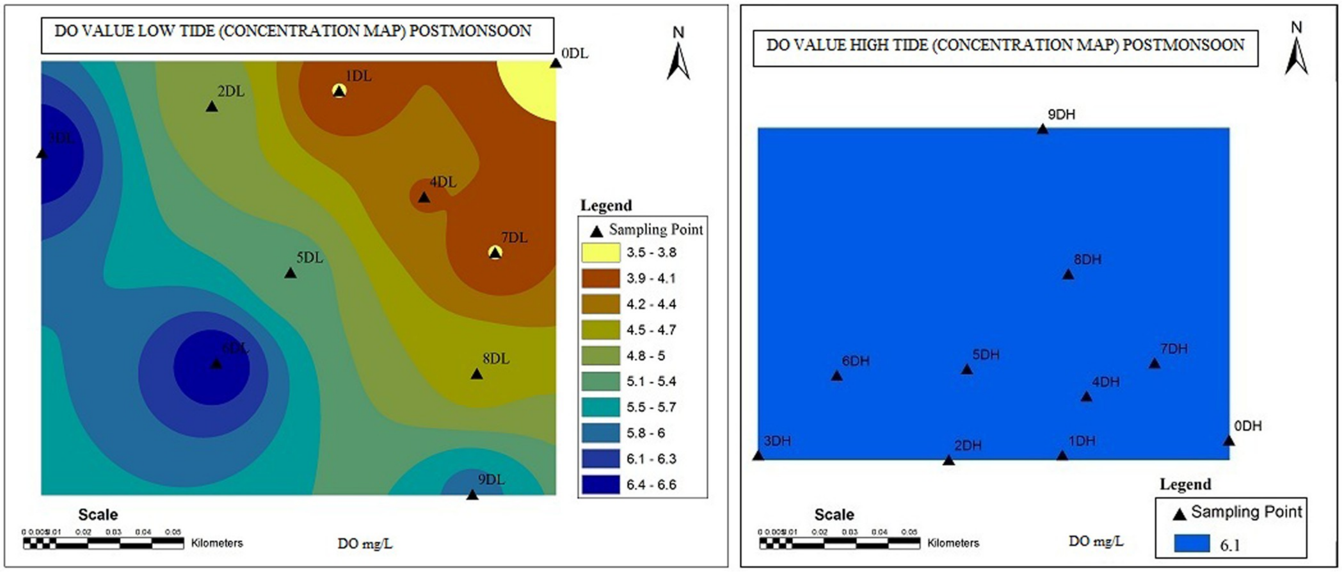

Fig 22. Spatial distribution map of DO at Dakshineswar Canal during post-monsoon low tide (left) and post-monsoon high tide (right).

https://doi.org/10.1371/journal.pwat.0000008.g022

4 Conclusion

The extensive field survey throughout the study area helped to screen five major outfalls out of all twenty: Circular Canal, Ghusuri, Dakshineswar canal, Ballykhal, and Khardah Khal based on its concentration of parameters. Seasonal analysis of four consecutive years showed a significant difference in concentration of major water quality parameters in pre-monsoon in comparison to post-monsoon and monsoon periods in all sampling locations. Seasonal variation was also prominently reflected by GIS mapping based on water quality parameters from different part of the river considering the position of outfalls. Distance and direction wise analysis of wastewater from outfalls indicated the prominent influence of wastewater along the bank of the river from each outfall. A strong correlation in between heavy metals and total coliform, and fecal coliforms were established in most of the sampling sites. Regression analysis helped to predict the level of one parameter by measuring other with which it is highly correlated to.

Considering the location of the outfalls, not only the residential sources, the influence of the release from small and medium scale industries cannot be ignored in most of the cases. The study encouraged the source reduction i.e., to restrict the release of untreated wastewater into the river. The abstraction of river water from particular distance from outfalls can reduce the chances of contamination. It is not like that river water is unfit to use everywhere but on the basis of intensity of outfalls, its direction of flow, discharge rate and the tidal movement, the influence can be easily predicted and a guideline to use river water can be generated in particular outfalls areas.

Supporting information

S1 File. S1 Table A. Methods of measuring water quality parameters [32, 33]. S1 Table B. Standard of Water Quality Parameters. S1 Table C. Details of Sampling Locations at Left Bank of river Ganga, West Bengal, India [72, 73]. S1 Table D. Details of Sampling Locations at Right Bank of river Ganga, West Bengal, India [72, 73]. S1 Table E. Range of water quality parameters of selected major (twenty) outfalls considering both banks of river Ganga, West Bengal, India in pre-monsoon, 2014. S1 Table F. Seasonal Mean value and Standard Deviation of pH, Temperature (oC) and DO (mg/L), Conductivity (μS/cm), BOD (mg/L), Total Hardness(mg/L), Nitrate nitrogen (mg/L), Chloride (mg/L) and Phosphorus (mg/L), Lead (as Pb) (mg/L), Mercury (as Hg) (mg/L), and Total Arsenic (as As) (mg/L), Total Coliform (MPN/100ml) and Fecal Coliform (MPN/100ml) for five selected major outfalls during 2015–2018. S1 Table G. Correlation Matrix of Circular Canal. S1 Table H. Correlation Matrix of Ghusuri. S1 Table I. Correlation Matrix of Dakshineswar Canal. S1 Table J. Correlation Matrix of Ballykhal. S1 Table K. Correlation Matrix of Khardah Khal. S1 Table L. Seasonal mean value of water quality parameters of five selected outfall of river Ganga, West Bengal, India during low tide and high tide for the period of 2016–2018. S1 Table M. Water quality parameters at different sampling points of river Ganga, West Bengal, India with location code during pre-monsoon low tide. S1 Table N. Water quality parameters at different sampling points of river Ganga, West Bengal, India with location code during monsoon low tide. S1 Table O. Water quality parameters at different sampling points of river Ganga, West Bengal, India with location code during post-monsoon low tide. S1 Table P. Water quality parameters at different sampling points of river Ganga, West Bengal, India with location code during pre-monsoon high tide. S1 Table Q. Water quality parameters at different sampling points of river Ganga, West Bengal, India with location code during monsoon high tide. S1 Table R. Water quality parameters at different sampling points of river Ganga, West Bengal, India with location code during post-monsoon high tide. S1 Table S. Calculated distance with polynomial equations at every direction from Circular Canal during pre-monsoon low tide. S1 Table T. Calculated distance with polynomial

equations at every direction from Circular Canal during monsoon low tide. S1 Table U. Calculated distance with polynomial equations at every direction from Circular Canal during post-monsoon low tide. S1 Table V. Calculated distance with polynomial equations at every direction from Ghusuri during pre-monsoon low tide. S1 Table W. Calculated distance with polynomial equations at every direction from Ghusuri during monsoon low tide. S1 Table X. Calculated distance with polynomial equations at every direction from Ghusuri during post-monsoon low tide. S1 Table Y. Calculated distance with polynomial equations at every direction from Dakshineswar Canal during pre-monsoon low tide. S1 Table Z. Calculated distance with polynomial equations at every direction from Dakshineswar Canal during monsoon low tide. S1 Table AA. Calculated distance with polynomial equations at every direction from Dakshineswar Canal during post-monsoon low tide. S1 Table AB. Calculated distance with polynomial equations at every direction from Ballykhal during pre-monsoon low tide. S1 Table AC. Calculated distance with polynomial equations at every direction from Ballykhal during monsoon low tide. S1 Table AD. Calculated distance with polynomial equations at every direction from Ballykhal during post-monsoon low tide. S1 Table AE. Calculated distance with polynomial equations at every direction from Khardah Khal during pre-monsoon low tide. S1 Table AF. Calculated distance with polynomial equations at every direction from Khardah Khal during monsoon low tide. S1 Table AG. Calculated distance with polynomial equations at every direction from Khardah Khal during post-monsoon low tide.
(DOCX)

S2 File. S2 Fig1. ADCP (Acoustic Doppler current profiler) device. S2 Fig2. Identification of Outfalls in Left Bank of the river Ganga from South to North during 2014 from Howrah Station to Khardah, 24 Parganas (North), West Bengal, India. S2 Fig3. Identification of Outfalls in Right Bank of the river Ganga from South to North during 2014 from Howrah Station to Khardah, 24 Parganas (North), West Bengal, India. S2 Fig4. Zone of influence of DO, BOD, Nitrate nitrogen and Phosphorus at Circular Canal during pre-monsoon low tide. S2 Fig5. Zone of influence of DO and BOD at Circular Canal during monsoon low tide. S2 Fig6. Zone of influence of DO, BOD and Phosphorus at Circular Canal during post-monsoon low tide. S2 Fig7. Zone of influence of DO, BOD, Nitrate nitrogen and Phosphorus at Ghusuri during pre-monsoon low tide. S2 Fig8. Zone of influence of BOD at Ghusuri during monsoon low tide. S2 Fig9. Zone of influence of DO, BOD and Phosphorus at Ghusuri during post-monsoon low tide. S2 Fig10. Zone of influence of DO, BOD, Nitrate nitrogen and Phosphorus at Dakshineswar Canal during pre-monsoon low tide. S2 Fig11. Zone of influence of DO, BOD, Nitrate nitrogen and Phosphorus at Dakshineswar Canal during monsoon low tide. S2 Fig12. Zone of influence of DO, BOD, Nitrate nitrogen and Phosphorus at Dakshineswar Canal during post-monsoon low tide. S2 Fig13. Zone of influence of DO, BOD, Nitrate nitrogen and Phosphorus at Ballykhal during pre-monsoon low tide. S2 Fig14. Zone of influence of DO, BOD, Nitrate nitrogen and Phosphorus at Ballykhal during monsoon low tide. S2 Fig15. Zone of influence of DO, BOD, Nitrate nitrogen and Phosphorus at Ballykhal during post-monsoon low tide. S2 Fig16. Zone of influence of DO, BOD, Nitrate nitrogen and Phosphorus at Khardah Khal during pre-monsoon low tide. S2 Fig17. Zone of influence of DO, BOD, Nitrate nitrogen and Phosphorus at Khardah Khal during monsoon low tide. S2 Fig18. Zone of influence of DO, BOD, Nitrate nitrogen and Phosphorus at Khardah Khal during post-monsoon low tide. S2 Fig19. Zone of influence of BOD at selected outfalls during pre-monsoon low tide. S2 Fig20. Zone of influence of BOD at selected outfalls during monsoon low tide. S2 Fig21. Zone of influence of BOD at selected outfalls during post-monsoon low tide. S2 Fig22. Zone of influence of DO at selected outfalls during pre-monsoon low tide. S2 Fig23. Zone of influence of DO at selected outfalls during monsoon low tide. S2 Fig24. Zone of influence of DO at selected

outfalls during post-monsoon low tide. S2 Fig25. Zone of influence of Nitrate nitrogen at selected outfalls during pre-monsoon low tide. S2 Fig26. Zone of influence of Nitrate nitrogen at selected outfalls during monsoon low tide. S2 Fig27. Zone of influence of Nitrate nitrogen at selected outfalls during post-monsoon low tide. S2 Fig28. Zone of influence of Phosphorus at five selected outfalls during pre-monsoon low tide. S2 Fig29. Zone of influence of Phosphorus at five selected outfalls during monsoon low tide. S2 Fig30. Zone of influence of Phosphorus at five selected outfalls during post-monsoon low tide.
(DOCX)

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