Point source-driven seasonal hypoxia signals habitat fragmentation and ecosystem change in River Ganga

The development of dissolved oxygen deficit (DOD; hypoxia) has been reported to expand over 2.45×10^5 km^2 area of the ocean from over 400 different areas worldwide[1]. Although cultural eutrophication has greatly accelerated DOD in estuaries and semi-enclosed seas[2,3], it is not a common phenomenon in large rivers[4]. Hydrological continuum reinforces oxygenation, and therefore, development of hypoxia (dissolved oxygen (DO) < 2.0 mg l^{-1}) is less critical in large rivers. River ecosystems usually respond to gradual changes in a smooth manner. However, smooth and continuous changes can be interrupted by sudden abrupt switches to a mosaic of alternative states leading to loss of resilience[5]. Such shifts are most often driven externally, for instance, point source flushing, but they can trigger internal feedbacks leading the system to behave chaostically even in the absence of external forcing[6]. River Ganga, along its 2525 km course, is exposed to marked changes in climate, flow heterogeneity, habitat fragmentation, biotic exploitation, and continuous and episodic flushing of pollutants[7,8]. In this study we show, using two point source trajectory analysis, the development of bottom hypoxia and associated feedbacks as a response to point source inflow of polluted water in River Ganga. Oxygen depletion below 2.0 mg l^{-1} indicates that the water body has reached the critical condition[1]. Therefore, understanding the state and determinants of bottom hypoxia/anoxia in the River Ganga is critical to accurately diagnose the threats and subsequent approaches to rejuvenate the river.

We performed trajectory studies during summer low flow (April–June) for two consecutive years (2017–18) and analysed 540 water and sediment samples in the Ganga downstream two point sources (Figure 1): Assi drain (at Varanasi; 25°28′N; 83°00′E; discharge: 66.4 million litre per day (MLD)), which drains mainly domestic wastewater, and Wazidpur drain (at Kanpur; 26°42′N; 80°41′E; discharge: 54 MLD), which flushes predominantly industrial effluent into the Ganga. Water and sediment samples from each point source (25–50 m reach) were collected using a customized deep-water sampler and sediment corer from 15 equidistant locations (100 m apart), starting from the drain mouth (zero distance) up to 1.4 km downstream in the Ganga. Samples collected in triplicate from three sub-sites of each study location were analysed for dissolved oxygen in subsurface water (DO) and at the sediment–water interface (DO_{sw}). DO was fixed at site following azide modification using Winkler's method[9]. The biochemical oxygen demand (BOD), chemical oxygen demand (COD), total organic carbon (TOC), NH_4^+ and PO_4^{3-} were measured following standard methods[9]. Dissolved oxygen deficit in subsurface water (DOD_w) and at the sediment–water interface (DOD_{sw}) was calculated following Sànchez *et al.*[10]. Concentration of Fe and Mn was measured using an atomic absorption spectrophotometer (Perkin Elmer model Analyst 800, USA) after acid digestion. Sediment-P release was quantified following Hu *et al.*[11]. Alkaline phosphatase (AP) activity was measured according to Tabatabai and Bremner[12]. Sediment oxygen demand (SOD) was quantified following Ling *et al.*[13], and biological and chemical SOD (BSOD and CSOD) were measured using Wang's method[14].

Summer-time hypoxia was detected at both point sources (Figure 2). The extent of hypoxic condition (DO < 2.0 mg l^{-1}) differed at the point sources and with longitudinal distance from the source input. At the drain mouth, DO_{sw} concentration was close to zero; and levels <2.0 mg l^{-1} were found to extend up to 600 m downstream Assi drain (Asdr) and up to 800 m downstream Wazidpur drain (Wpdr). This trend did appear consistently for both the years of study (although data presented here are means), suggesting that summer-time bottom hypoxia might persist in the river, below large point sources, for at least 90 days in an annual cycle. Longitudinal patterns of oxygen demanding components and processes were almost synchronous to

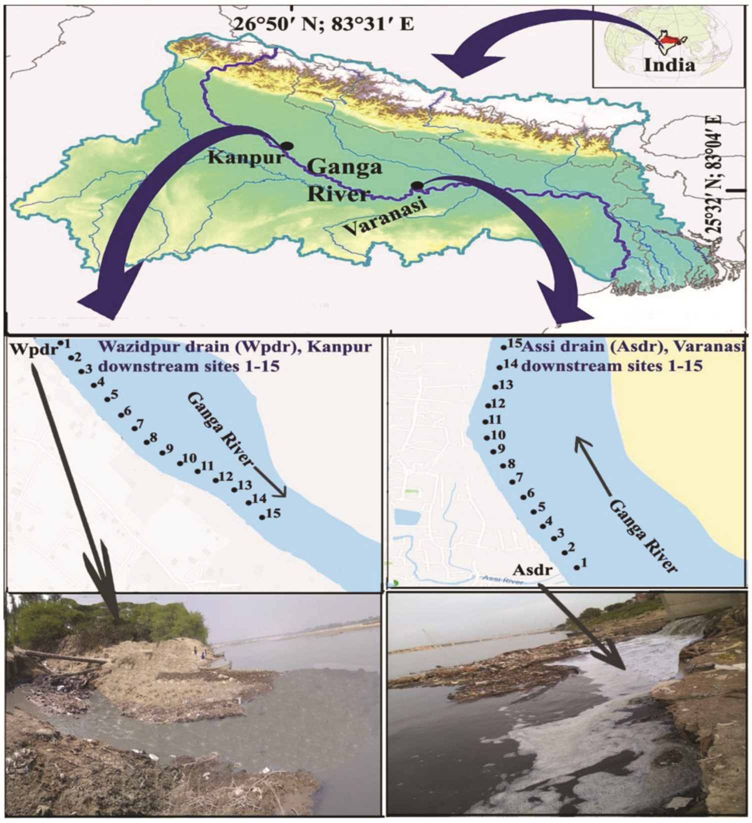

Figure 1. Point sources and study locations in River Ganga.

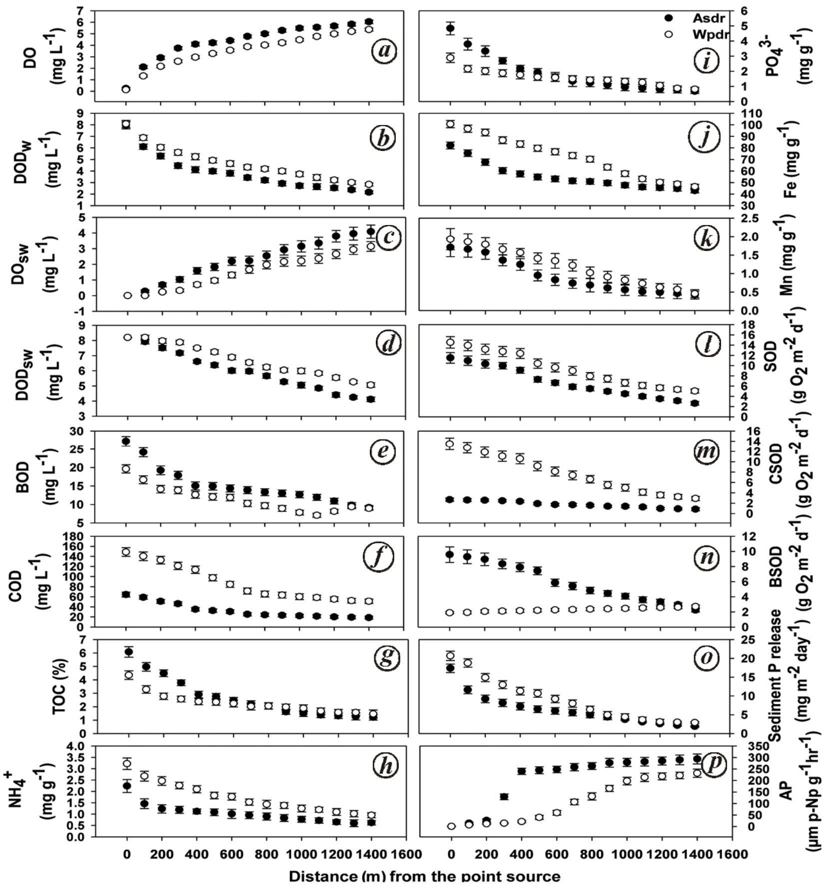

Figure 2. Dissolved oxygen deficit and associated determinants downstream Assi drain (Asdr) and Wazidpur drain (Wpdr). Values are mean (n = 6) ± SD for (***a***) dissolved oxygen (DO), (***b***) dissolved oxygen deficit in water (DOD_w), (***c***) dissolved oxygen at sediment–water interface (DO_{sw}), (***d***) dissolved oxygen deficit at sediment–water interface (DOD_{sw}), (***e***) biochemical oxygen demand (BOD), (***f***) chemical oxygen demand (COD), (***g***) total organic carbon (TOC), (***h***) NH_4^+, (***i***) PO_4^{3-}, (***j***) Fe, (***k***) Mn, (***l***) sediment oxygen demand (SOD), (***m***) chemical sediment oxygen demand (CSOD), (***n***) biological sediment oxygen demand (BSOD), (***o***) sediment-P release and (***p***) alkaline phosphatase (AP).

Table 1. Characteristics of wastewater coming from point sources and of river water 50 m upstream to the mouth of these sources

Parameter	Assi drain (Asdr)	Wazidpur drain (Wpdr)	Upstream Asdr	Upstream Wpdr
DO_w (mg l^{-1})	0.00 ± 0.00	0.00 ± 0.00	5.64 ± 0.25	4.82 ± 0.22
DOD_w (mg l^{-1})	8.20 ± 0.36	8.20 ± 0.36	2.56 ± 0.12	3.38 ± 0.19
BOD (mg l^{-1})	82.69 ± 5.34	48.16 ± 2.71	8.43 ± 0.41	6.74 ± 0.27
COD (mg l^{-1})	131.06 ± 10.31	207.69 ± 15.21	11.64 ± 0.67	25.85 ± 1.03
DOC (mg l^{-1})	21.57 ± 0.97	11.29 ± 0.72	7.60 ± 0.34	4.93 ± 0.27
NH_4^+ (µg l^{-1})	638.51 ± 35.50	393.54 ± 21.73	132.84 ± 10.97	167.61 ± 13.39
PO_4^{3-} (µg l^{-1})	1054.34 ± 52.68	691.27 ± 38.21	140.18 ± 12.06	107.08 ± 7.68
Fe (µg l^{-1})	1780.64 ± 59.43	2154.06 ± 65.58	305.81 ± 21.69	594.67 ± 38.21
Mn (µg l^{-1})	282.57 ± 19.60	391.19 ± 22.47	52.09 ± 3.74	79.36 ± 4.90

Values are mean (n = 6) ± 1SD; DO_w, dissolved oxygen in sub-surface water; DOD_w, dissolved oxygen deficit in sub-surface water; BOD, biochemical oxygen demand; COD, chemical oxygen demand; DOC, dissolved organic carbon.

DOD_w and DOD_{sw}, whereas DO and AP activity showed opposite trend.

To test whether DOD_{sw} was equally influenced by BOD/COD, data were subjected to principal component analysis. The analysis separates DO and AP opposite to oxygen demanding components (TOC, Fe, Mn and NH_4^+) and processes (BOD, COD, SOD, BSOD and CSOD) indicating that DOD_{sw} is equally influenced by both components. A large pool of Fe, Mn and NH_4^+ at point source (Figure 2) emphasizes to consider COD, together with the drivers of BOD, for management of the Ganga. Further, correlative evidence showed that at Wpdr, the relationships predicting DOD_{sw} did appear stronger with COD/CSOD (r = 0.94–0.96; P < 0.001) compared to BOD/BSOD (r = 0.83–0.85; P < 0.001). A similar result has been reported for River Ziya[15] where CSOD contributes a major share accounting for 36–88% of SOD. Greater contribution of COD/CSOD could be expected for Wpdr draining industrial effluent. For Asdr also, where major source inputs are domestic releases, COD/CSOD was strongly correlated (r = 0.85–0.87; P < 0.001) with DOD_{sw}, indicating that Asdr also drains a large pool of non-carbon oxygen-demanding substances from unknown sources. In a stream receiving point source input, the physical, chemical and biological attributes change with increasing downstream distance from the input[16]. We found a strong dilution effect both upstream and downstream compared to wastewater quality of the study drains (Table 1 and Figure 2). Since river flow modulates longitudinal patterns of oxygen demanding substances, the present study reinforces the need to maintain flow in the Ganga.

We finally tested whether point source-driven hypoxia in the Ganga could significantly alter ecosystem feedbacks. Given that the sediment acts as a sink for P under oxic condition, and as a source under hypoxic condition[17], we explored the relationship between sediment P-release and oxygen condition. At both point sources, changes in P-release were coherent with changes in hypoxic bottom showing extreme condition at the drain mouth (Figure 2). Significant positive relationships (r = 0.89–0.98; P < 0.001) were found between DOD_{sw} and P-release, indicating a hypoxic/anoxic release of sediment-P. Because hypoxia enhances P-release, efforts to reduce N load alone will remain ineffective as P enhances diazotrophic cyanobacterial blooms[18]. Further, we found strong asynchrony between AP activity and P-release; AP dropped to zero at the drain mouth where DOD_{sw} and P-release attained maxima. Our observations clearly demonstrate point source-driven bottom hypoxia and benthic P-fertilization of Ganga. Because the river is exposed to a large number of point sources along its 2525 km course, the present study emphasizes the need to unravel the mosaic of fragmented habitats marked by hypoxia and sediment-P release. Also, the study identifies DOD_{sw}–AP linkages as a marker to trace benthic habitat fragmentation in large rivers.

This study provides a systematic database on point source-driven bottom hypoxia and ecosystem feedbacks in the Ganga. Since hypoxia shifts community composition, ecosystem feedbacks and ecological thresholds[19], DOD zones identified here indicate benthic habitat fragmentation with anomalous ecological conditions downstream point sources. If enough DO is not available, it may lead to fish kill as evidenced with the report of large number of dead fishes in the river at Kannoj[20]. In a recent field trial, we found that the plume of pollutants from the point sources exerts a strong influence up to 50 m reach[21]. This merits attention because the Ganga with large number of point sources of input encompasses habitats for several fish populations of economic importance[22]. Further, because local niche-based disturbances eliminate benthic diatoms[23,24] that reoxygenate the river bottom, benthic habitat fragmentation-coupled diatom species loss will continue to deteriorate the condition further. The present study strongly suggests the need to consider point-source downstream river responses for action plans to safeguard riverine life and habitats.

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Yellow pan traps as an additional gadget for collecting sandhopper amphipods

Yellow pan traps (YPTs) or Moericke traps are known for their efficiency to catch a wide variety of insects, including herbivores and predators[1,2]. These colour traps work on the principle that yellow colour attracts insects[3]. An isolated sampling event is described in this study, where sandhopper amphipods were collected in large numbers, in YPTs, originnally set for collecting insects. Amphipods under order Amphipoda of subphylum Crustacea are classified into four groups – palustral talitrids, beachfleas, sandhoppers and landhoppers[4]. Generally sleds, dredge, grabs, cores, sediment sieving, baited traps, light traps, pitfall traps and even handpicking methods are used for collection of amphipods from different habitats like deep seafloor, seaweed assemblage, mudflat sediment, beach soil, coral rubble and rotten leaf litter[5]. Collection employing YPTs has advantages over other methods because it is simple, more time-efficient and not dependent on trained or skilled collectors[6,7].

The sampling was conducted on 29 November 2017, from 11 am to 3 pm, at Cheriam Island, Union Territory of Lakshadweep, situated in the Laccadive Sea, off the southwestern coast of India (10°06′99″N and 73°66′05″E) as part of inventorying the terrestrial fauna of Lakshadweep islands, by a team from