



Impact of river channelization and riverfront development on fluvial habitat: evidence from Gomti River, a tributary of Ganges, India

Venkatesh Dutta¹ · Urvashi Sharma¹ · Kashifa Iqbal¹ · Adeeba² · Ravindra Kumar³ · Ajey Kumar Pathak⁴

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Abstract

Riverfront development is one of the important pervasive modifiers of river morphology and processes affecting river corridors, floodplains and associated riparian zones. The Irrigation and Water Resources Department of Government of Uttar Pradesh, India's most populous state, undertook an ambitious project of riverfront development during April 2015 to March 2017 in the capital city of Lucknow on Gomti River, a meandering perennial tributary of Ganges which is fed by rainfall and groundwater. Under this project, straightening and shortening of the river channel was done by controlling its width, shape and riverbed through constructing a heavily reinforced diaphragm wall on both banks on an 8.1 km stretch. River floodplain width was restricted to 240 m out of 450 m and clear waterway to 100–125 m from existing 250 m to reclaim about 200 ha of land upstream and downstream of Gomti barrage in the city. This paper assesses the loss of river processes and ecosystems under changed hydraulic regimes post riverfront development project. We observed eight types of habitat in the undisturbed segments of the Gomti River, while only two major habitat types were present in the channelized segments. The paper argues that, due to heavy channel engineering led riverfront development and other related morphometric changes, there would be decline in freshwater species and water quality, lowering of groundwater tables in the city reach, resulting from diminishing base flow and flooding of the downstream areas. The river is fed by rainfall and groundwater, maintaining variable flow regimes with a very lean flow during the summer season. The reduction in flow, in the absence of water augmentation measures, will further impact the minimum environmental flows required to maintain the healthy ecosystems in the river broadening the area of ecological disturbances. This study can provide valuable insights for future projects on riverfront development and restoration measures in India and elsewhere.

Keywords Riverfront development · Channelization · Urban landscape · Water quality · Environmental-flows

Introduction

The river systems in the Ganga Basin in India are facing several challenges such as increasing urbanization, water intensive agriculture, deforestation, invasive species, flow

regulation, water extraction and sand mining (Bandyopadhyay 2017; Chaudhary et al. 2017; Kumar 2017; Tandon and Sinha 2018). The impacts of these individually or in combination usually lead to a decrease in overall biodiversity because of several stressors including water quality deterioration, biologically unsuitable flow regimes, dispersal barriers, altered inputs of organic matter, sediment or sunlight and degraded habitat. Despite knowing about these factors stressing the freshwater ecosystems, the riverfront projects in India are critically modifying the channel which would limit the restoration possibilities. Interdisciplinary understanding about fluvial habitat and geomorphology remains scant in such projects; yet such knowledge is required at a range of scales from catchment to microhabitat for any river restoration project. River restoration projects mostly seek to maintain or increase ecosystem goods and services while

✉ Venkatesh Dutta
dvenks@gmail.com

¹ Department of Environmental Science, Babasaheb Bhimrao Ambedkar University, Lucknow, Uttar Pradesh, India

² DST Centre for Policy Research, Babasaheb Bhimrao Ambedkar University, Lucknow, India

³ WWF-India, New Delhi, India

⁴ ICAR-National Bureau of Fish Genetic Resources (ICAR-NBFGR), Lucknow, India

protecting the ecosystems (Postel and Richter 2003; Palmer et al. 2005; Wohl et al. 2015). However, in developing riverfronts, river engineers often ignore specified guiding image of a more dynamic and healthy river that could exist at the site. It is argued that riverfront projects that destroy the riverbanks and physical habitat and also disturb the river corridors are not a wise investment if ecological recovery is the goal. The river engineers should critically analyze the multiple stressors impacting the streams and invest resources in managing those problems most likely to limit future restoration possibilities.

The dominance of channel engineering and associated loss of river ecosystems and river processes has been widely discussed in the literature (Downs and Gregory 2014; Palmer et al. 2014; Hood and Larson 2015; Peipoch et al. 2015; Everard et al. 2018; Wohl 2018). The river engineers involved in water resources development projects often cite the need of providing increasing water demands to growing population, whereas river ecologists argue about the needs of the riverine ecosystem in wake of unsustainable water abstractions (Downs and Gregory 2014). Stream ecosystems are increasingly impacted by multiple stressors that lead to a loss of sensitive species and an overall decline in diversity and floodplains' integrity (Palmer et al. 2010). Natural floodplains are biologically the most productive and diversified ecosystems on earth (Mitsch and Gosselink 2000) but due to their very slow recovery they are also the most threatened (Vitousek et al. 1997; Revenga et al. 2000). Converting from vegetated to impermeable surfaces and alterations to natural drainage, impact on the hydrological regimes mainly through lower evaporation, altered sedimentation dynamics, less storage of moisture in the soil, and change in rates of runoff (e.g. Miller et al. 2014). Changes in fish community structure have also been observed with habitat changes in flow regimes due to anthropogenic (e.g., channelization) alterations (Gaston et al. 2016). The key paradigm in ecological restoration is that increasing habitat heterogeneity (HH) promotes restoration of biodiversity (Palmer et al. 2010). According to Karr and Chu (1998) freshwater ecosystem conservation plans rely mainly on assessing ecological integrity of ecosystems, based on the notion that ecosystems of high ecological integrity support and maintain the full natural range of biological features and ecological processes. Natural ecosystems are heterogeneous; therefore, their physical, chemical, and biological characteristics display variability in space and time (Palmer et al. 2016). Therefore, the stream restoration projects attempt to re-configure channels by adding meanders and physical structures such as boulders and riffles to restore biodiversity and improving the river corridors by enhancing structural heterogeneity of the habitat. However, the riverfront development project in Lucknow is a classical example of how over-dominance of channel engineering may result in loss of river ecosystems

and river processes. The ecology of the river, its floodplain, and other key fluvial characteristics were transformed substantially without creating any beneficial public utility or improving the water quality. The channelization has resulted in heavily concretized active floodplains resulting in loss of place-based fluvial habitats. The widespread ecosystem degradation caused by filling of wetlands, channelization and concretization of the floodplains has led to a physical, mental and spiritual disengagement with the cultural landscape of the Gomti riverfront. The fish diversity in the river is highly threatened due to sewage pollution, extensive habitat alteration and water abstractions (Saini et al. 2010).

Natural streams have more variability in terms of channel depth, channel width, flow velocity, bed forms, substrate composition and ecological habitats (Poole 2002). In the process of channelization the naturally sinuous streams are converted to more straight channels with homogenized morphometry, hydrology and sediments structures (Elser 1968; Hansen and Muncy 1971; Tarplee et al. 1971; Etnier 1972; Congdon 1973; Duvel and Volkmar 1976; Allan 2004; Kairo et al. 2017). In channelized streams the habitat degradation and variability loss (Brookes 1988; Pedersen 2009) becomes a major threat to the running water biodiversity (Kendle 1970; Brooker 1985; Poff and Ward 1989; Johansson 2013; Hartson et al. 2014). The absence of areas of deep, slow water alternating with areas of shallow, swift water in channelized rivers (Leopold and Langbein 1966) makes it less habitable for most of the aquatic organisms except a few which prefer fast flowing waters (Hartson et al. 2014). Less number of chutes and sloughs in the river channel make the channelized streams less suitable for spawning and nursing (Kendle 1970), as a result fishes migrate. During low flows, natural sinuous streams have more water storage than a channelized stream (Zimmer 1976). In a channelized stream the total drift of invertebrates is comparatively low (decrease in the standing crop) (Dewson et al. 2007; Kairo et al. 2017), thus the amount of food availability decreases resulting in competition for the available food among fishes. A site located just below the channelized reach also experiences a huge disturbance in types of sediment deposition and overall in-stream dynamics. Thus the complete downstream reaches get affected in an unpredictable manner. Channelizing a river stream also isolates it from the surrounding riparian areas (Humphries et al. 1999; Baattrup-Pederson et al. 2005; Kennedy and Turner 2011).

This paper makes a preliminary assessment of the loss of river processes and ecosystems under changed hydraulic regimes post riverfront development project. It argues that, due to loss of river-banks, reduced channel width from the 16 m deep diaphragm walls and other related morphometric changes, there would be decline in freshwater species and water quality, lowering of groundwater tables in the city reach resulting from diminishing base flow and flooding of

the downstream areas. The river maintains a variable flow with a very lean flow during the summer season. The reduction in flow, in the absence of water augmentation measures, will further impact the minimum environmental flows required to maintain the healthy ecosystems in the river. The paper suggests that the riverfront development projects need to be more sensitive to the river corridors—the channel and the immediate local environment, to optimise the conservation and restoration potential of the fluvial habitats.

About the study area

The River Gomti, an alluvial river of the Indo-Gangetic Plain, originates from the lower Himalayas from a lake—‘Fulhaar Jheel’ in Madhotanda, about 30 km east of the Pilibhit town in Uttar Pradesh (UP), is rain and groundwater-fed and hence does not receive any snowmelt water (Fig. 1).

It joins the main stem of the Ganga River downstream at Kaithi, in Varanasi (UP), after traversing 960 km in south, south-east direction and contributes 7.39 billion cu m of water per year to Ganga. The total area of Gomti River basin has been estimated to be 30,437 km² (Dutta et al. 2011, 2015). River Gomti maintains a multi-thread morphology with a complex mosaic of bars, channels, islands, wetlands and floodplain environments. The basin has a gentle slope, low surface relief, low surface run-off, high infiltration rate, and low water storage capacity which indicates the mature stage of topographic evolution and erosion and so reworks the pre-existing sediments of the Ganga Plain. The climate of the basin is semi-arid to sub-humid tropical, with average annual rainfall at different locations varying between 850 and 1100 mm. About 75% of total annual rainfall is received between June to September due to the South-West Monsoon (Rai et al. 2010). The Gomti River has an average flow of



Fig. 1 a Location of the study area. b Gomti River in Lucknow city with its tributaries

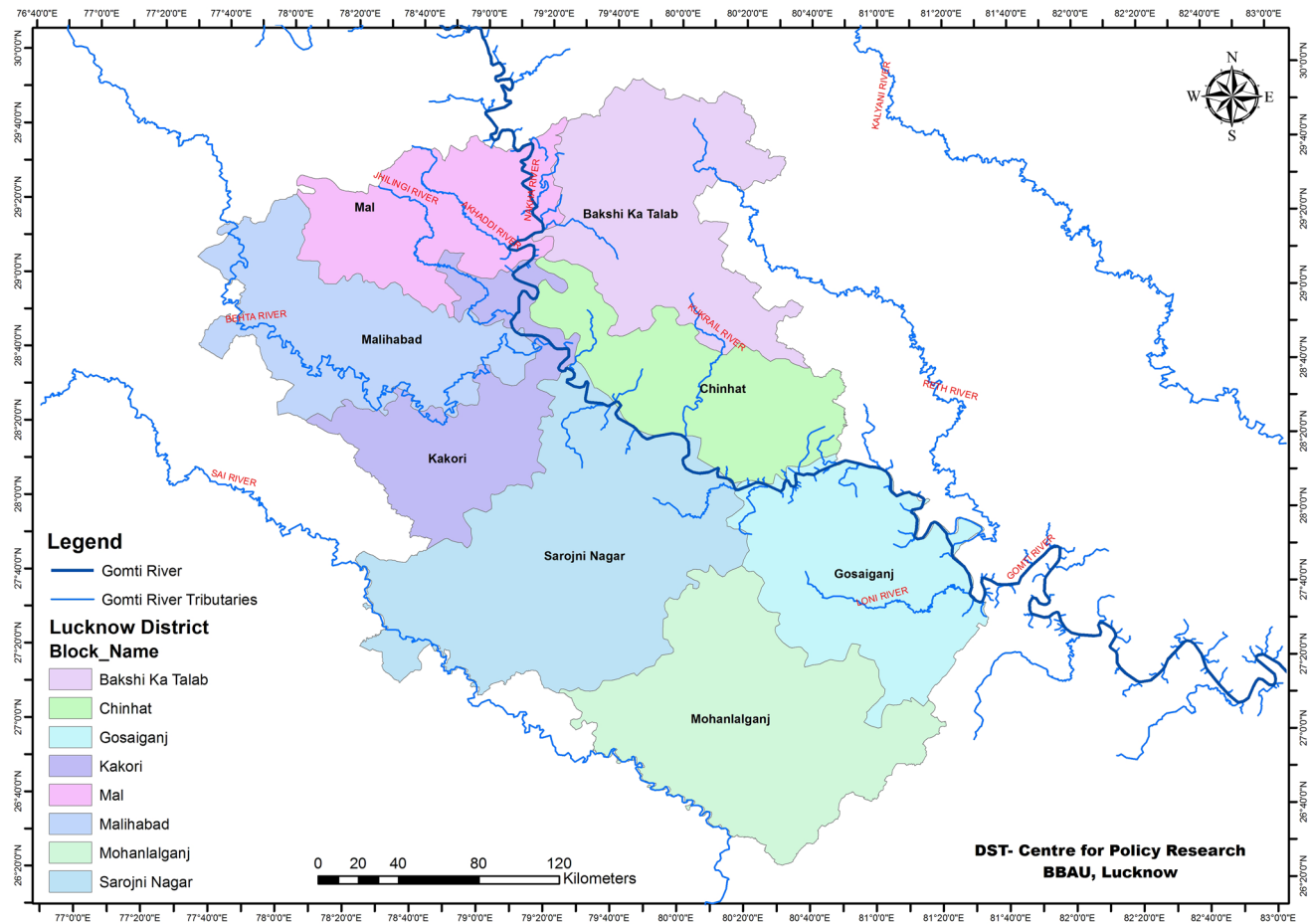


Fig. 1 (continued)

1500 million per day (MLD), varying from 500 MLD in low dry season to 45,000 MLD in peak monsoon flows at Lucknow. The 75% dependable flow in September has been recorded as 125 cumec at Hanuman Setu in Lucknow city and 450 cumec at Maighat after Sai-Gomti confluence in Jaunpur. The average lean flow recorded for the month of April, has been 15 and 25 cumec respectively for these locations. The active flood plain is characterized by active channel, dry channels, channel bars, bank bars, point bars, scroll bars, abandoned channels and cut off meanders.

The River is an important source of water supply to cities of Lucknow, Jaunpur, and other habitations downstream. A number of tube-wells have also been bored near the river-bed to exploit groundwater in the basin which also forms significant water supply source for agriculture, drinking and industrial needs. The river and its tributaries are important source of aquifer recharges in the basin for sustainable yield of groundwater (Fig. 1b). The contribution of shallow groundwater is 15–20% of the average annual yield of the entire basin (Dutta et al. 2011). However, the baseflow contribution during non-monsoon period is predominant. River

Gomti passes through the mid of the Lucknow city, dividing it into two parts and also connects the major traffic routs. The Gomti barrage, constructed to maintain water levels for water abstraction in the city's upstream, is located in the middle of the city.

Gomti River when flooded rises up by 6–7 m along various observation points, breaching the flood embankments along the river of widths between 250 and 450 m. Due to flooding events in the past, high embankments were made to save habitation from inundation. Consequent to the ever maximum flood in Gomti River in 1960, embankments were constructed along both the banks of the river up to 7 km upstream of the barrage. The distance between these two embankments varies from 250 to 450 m.

The Irrigation and Water Resources Department of Government of Uttar Pradesh undertook an ambitious project of riverfront development during April 2015 to March 2017 in the capital city of the Lucknow, on Gomti River (Fig. 2). Under this project, straightening and shortening of the river channel was done by controlling its width, shape and river-bed through constructing a heavily reinforced diaphragm

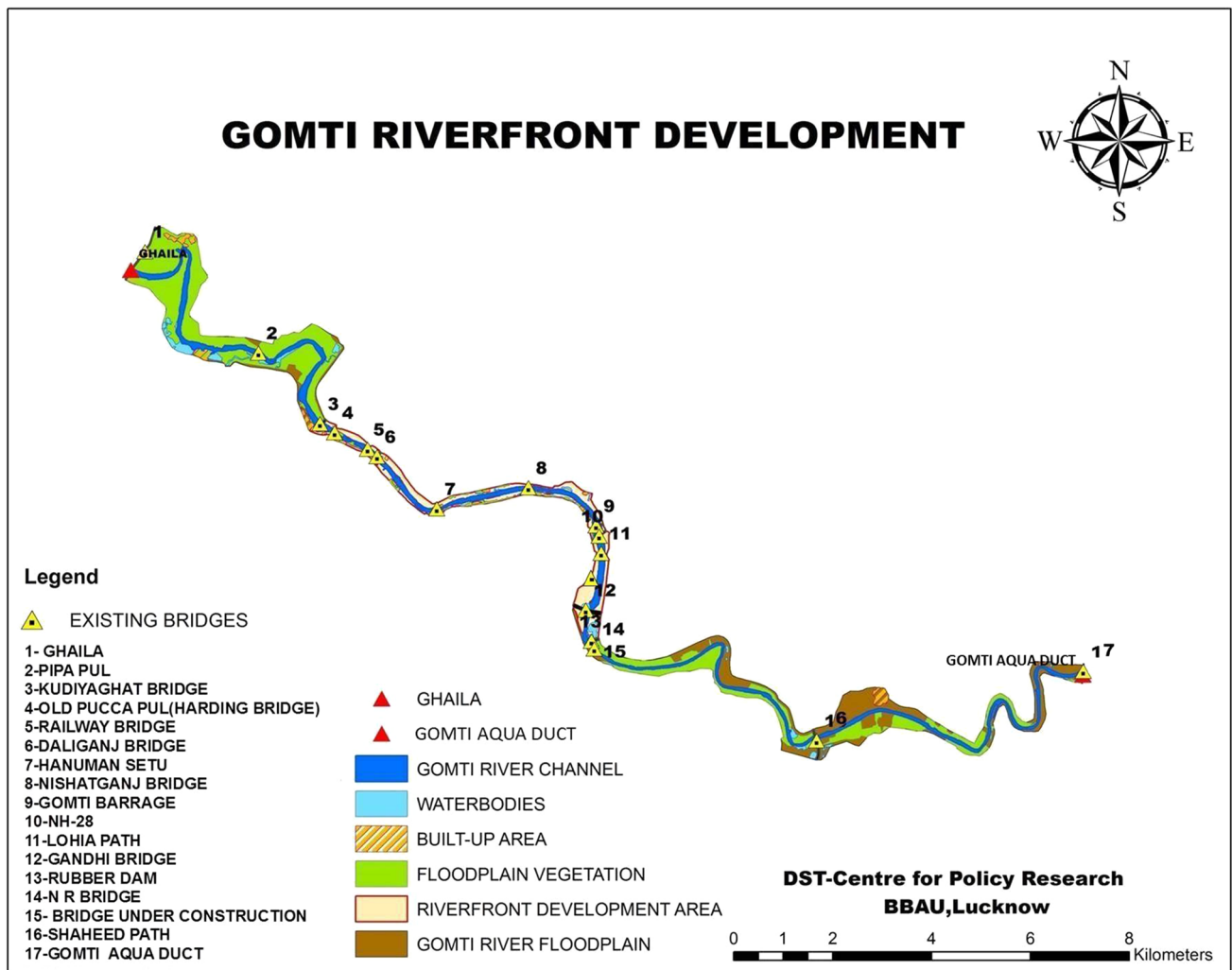


Fig. 2 Stretch of the Gomti River in Lucknow with areas demarcated for riverfront development

wall on both banks on a 8.1 km stretch. River floodplain width was restricted to 240 m out of 450 m and clear waterway to 100–125 m from existing 250 m to reclaim about 200 ha of land upstream and downstream of Gomti barrage in the city (Fig. 3).

Materials and methods

The methodology included estimation of wetted perimeter of the river, estimation of environmental flows, water quality assessment and fishing experiments. They are briefly explained in the following sub-sections:

Estimation of wetted perimeter of the river

To quantify the effect of the riverfront development on river morphology, long term flow data, channel cross-sections,

records of high flood levels at different locations were obtained from the Central Water Commission. Each cross-section was divided into main channel and floodplain. The return period for the flood in the Gomti River for the riverfront development has been taken 100 years as per guidelines of IS 12094:2000. According to this guideline, a flood of 25 years frequency in case of predominantly agricultural area is considered for the design of flood embankments, while 100 years flood is taken if the concerned embankments are to protect townships, industrial areas or other places of strategic and vital importance. Lacey’s perimeter using Lacey’s Regime Theory was used to propose minimum width and the required wetted perimeter of the river at its HFL (high flood level). According to this theory, in an alluvial river channel to carry a certain discharge, the bottom width, depth and bed slope of the channel will undergo modifications by silting and scouring till equilibrium is attained. The channel is now said to be a regime channel.

Fig. 3 Channel straightening and construction of diaphragm walls across the Gomti River banks



A regime channel is defined as a stable channel whose bed width, depth and side slopes have undergone modifications by silting and scouring and are so adjusted that equilibrium is attained. A minimum width of river equal to Lacey's perimeter is generally provided to an alluvial river to attain its regime conditions. In this study, it was proposed to provide a width of river equal to the Lacey's perimeter to avoid the morphological changes of river from its regime condition. The available particle size gradation of bed materials of Gomti river from 0.5 to 2.5 m depths and at various locations such as Kudiaghat, Nishatganj bridge, Bhaisakund, and Hanuman Setu have been analyzed. Based on the average size of bed material, silt factor was calculated.

Estimation of environmental flows

Flow Duration Curves (FDC) are prepared for different stretches of the river based on long-term flow data. For Gomti river cross section at Hanuman Setu, water level and discharge relationship is developed based on 1969–2011 peak flow values and correcting for outliers. Flow duration curves were calculated using the FDC 2.1 software package developed by hydro-office. Long term flow duration curves for the flow percentages were calculated and prepared at 0.50–0.95 percentiles. The base flow index for different sites was calculated using the BFI+ 3.0 software developed by hydro-office. The method implied

for the analysis is sliding interval method by Sloto and Crouse (1996).

Water quality assessment

The water quality parameters were analyzed using standard sampling procedures (APHA 1998). Four samplings across 4 months were conducted at seven sites along the river stretch as listed in Table 1. Eighteen water quality parameters, including pH, electrical conductivity (EC), total dissolved solids (TDS), dissolved oxygen (DO), biochemical oxygen demand (BOD), chemical oxygen demand (COD), alkalinity (Alk), hardness (Hard), chloride (Cl^-), nitrate (NO_3^-), nitrite (NO_2^-), ammonia (NH_4^+), phosphate (PO_4^{3-}), sulphate (SO_4^{2-}) and heavy metals (Pb, As, Cd, Cr) were measured to calculate the water quality index (WQI) (Lumb et al. 2011).

Fish sampling

Water quality and fish diversity was measured based on standard quality assessment and experimental fishing spanning for 2 years, before and after the river channelization and riverfront development project. Samples were collected at three sites covering pre rain and post rain at daytime during September 2013 to February 2014, and during the winter season spanning the months of October 2017 to January 2018. The earlier available data on fish diversity was also compared with the observed data during the sampling. Experimental fishing was carried out by

using the expertise of local fishermen from four sampling sites. Fishes were collected with gill nets of different sizes (mesh size 1.3×1.3 cm, 2.2×2.2 cm, 3.5×3.5 cm and 4.8×4.8 cm and $L \times B$ was 30.48×0.76 m) and cast net (sized 5.8 m diameter, mesh size 2.2×2.2 cm). At each site gill nets were deployed overnight and during day time sampling was done using cast net in the channel and near the shoreline. At each site five gill nets and 10 cast nets were deployed. Gill nets were placed approximately 2 cm below the water surface for a period of 14 h. Nets were placed at different points to get the maximum number of fish catch from different river habitat samples. Captured fishes were released after recording of data except for a few individuals which needed to confirm species identifications in the laboratory. Catch per unit of fishing effort (CPUE) i.e. total catch divided by the total amount of effort used to harvest the catch was calculated for each sampling sites following as per method described by Biswas (1993). The various diversity indices were calculated in each selected sampling sites using the PAST (PAleontological STatistics) software VERSION 3.20 (Hammer et al. 2001) that included: Species richness, Shannon index, Simpson index, Berger parker dominance index, and evenness. The habitat categorization method was followed as per Bain and Stevenson (1999) with some modifications. Fish sampling was done in channel and near shoreline as per Knight and Bain (1996). The local fishermen were also contacted at the sampling sites, to monitor and look for the presence of any species which were not obtained during experimental fishing.

Table 1 Physiochemical parameters of the sampling sites (results are mean of four replicates \pm standard deviation)

	Ghaila Pul	Pakka Pul	KGMC	Hanuman Setu	Birbal Sahani	Lohia Path	Shaheed Path
pH	8.17 \pm 0.51	7.76 \pm 0.58	7.08 \pm 0.61	7.70 \pm 0.15	7.84 \pm 0.52	7.57 \pm 0.41	7.44 \pm 0.48
EC (μs)	264 \pm 23.76	525.75 \pm 218.10	662.25 \pm 163.15	640 \pm 103.68	691 \pm 122.86	467.25 \pm 140.28	468.5 \pm 138.64
TDS	132 \pm 11.88	262.87 \pm 109.05	331.12 \pm 81.57	320 \pm 51.84	345.5 \pm 61.43	233.62 \pm 70.14	234.25 \pm 69.32
NO_3^-	0.50 \pm 0.55	0.71 \pm 0.147	0.17 \pm 0.18	0.24 \pm 0.31	0.19 \pm 0.21	0.33 \pm 0.15	0.31 \pm 0.28
NO_2^-	0.52 \pm 0.186	2.08 \pm 0.51	0.81 \pm 1.01	0.88 \pm 0.77	2.85 \pm 1.49	2.15 \pm 0.72	0.99 \pm 1.17
NH_4^+	1.66 \pm 0.98	0.33 \pm 0.18	5.44 \pm 3.99	13.57 \pm 26.20	35.80 \pm 46.73	18.05 \pm 34.34	22.05 \pm 41.19
PO_4^{3-}	2.15 \pm 2.155	4.64 \pm 2.71	4.25 \pm 3.21	3.95 \pm 3.14	6.32 \pm 6.61	4.79 \pm 3.22	4.87 \pm 3.62
SO_4^{2-}	1.89 \pm 0.99	3.81 \pm 1.75	3.25 \pm 2.21	4.32 \pm 4.82	5.31 \pm 2.92	4.25 \pm 3.38	4.49 \pm 2.80
Alk	241.25 \pm 19.61	247.5 \pm 14.10	181.58 \pm 16.37	228.25 \pm 14.88	253.16 \pm 65.23	242 \pm 30.27	237.75 \pm 16.26
Hard	25.5 \pm 9.71	37 \pm 10.03	38.25 \pm 15.84	48 \pm 13.46	58 \pm 12.19	48 \pm 8.67	29.75 \pm 7.41
Cl^-	14.05 \pm 10.69	22.71 \pm 8.96	23.21 \pm 10.23	19.60 \pm 17.47	26.19 \pm 22.07	20.48 \pm 12.06	31.11 \pm 2.75
DO	6.64 \pm 0.65	6.31 \pm 2.78	5.34 \pm 0.63	4.2 \pm 2.03	5.45 \pm 2.13	5.32 \pm 0.67	4.96 \pm 1.87
BOD	3.74 \pm 1.96	5.44 \pm 4.47	2.89 \pm 3.55	3.59 \pm 4.56	3.9 \pm 4.37	4.10 \pm 5.59	3.65 \pm 3.40
COD	16.47 \pm 5.41	20.13 \pm 3.84	20.39 \pm 4.96	22.93 \pm 8.30	23.40 \pm 6.27	17.76 \pm 4.30	18.72 \pm 6.79
Pb	0.31 \pm 0.26	0.23 \pm 0.17	0.23 \pm 0.14	0.30 \pm 0.29	0.24 \pm 0.23	0.11 \pm 0.06	0.20 \pm 0.26
As	0.078 \pm 0.039	0.084 \pm 0.02	0.078 \pm 0.04	0.065 \pm 0.027	0.0837 \pm 0.03	0.079 \pm 0.038	0.045 \pm 0.03
Cd	0.031 \pm 0.016	0.056 \pm 0.033	0.084 \pm 0.08	0.073 \pm 0.085	0.058 \pm 0.04	0.08 \pm 0.10	0.054 \pm 0.04
Cr	0.035 \pm 0.015	0.085 \pm 0.05	0.075 \pm 0.07	0.034 \pm 0.033	0.37 \pm 0.68	0.084 \pm 0.061	0.031 \pm 0.01

Results and discussion

Channel engineering for straightening the river channel under the riverfront development project has fixed the Gomti River into an artificial course for about 8.1 km. Land should have been reclaimed only at certain locations along the river, not continuously all along the river. The current pattern of channelization depicts profound exercises of control dominated by engineering an otherwise fragile ecosystem. The riverfront development project has deprived the Gomti River of its catchment, resulting in loss of river banks for aquatic species like turtles requiring sandbars on banks for their basking, and the river water interaction with groundwater of connected catchments in the 16 km stretch. Parallel to diaphragm walls on both banks, intercepting drains have been constructed to prevent sewage entering into the river. In doing so, many historic public ghats (riverbanks), that gave the natural riverfront of Gomti its unique identity and direct access to river water to the people, were erased resulting in loss of place-based collective memories. The main findings of the study are outlined below:

Estimation of water quality index

The present class of water indicates a threatened water quality index due to frequent discharge of waste effluents from various anthropogenic sources in the river. From the given Table 1, it is observed that as the river enters the city, it has fair WQI but as it passes through the city and reaches Pakka Pul, KGMC, Hanuman Setu and Birbal Sahani sites, the WQI deteriorates to marginal. It is evident that site Birbal Sahani had a WQI value of 59.23 which gives an idea that this place is more polluted than the other sites (Table 2). It holds true as the number of waste inlets at site Birbal Sahani is more as it is in the mid of the city. So the number of domestic as well as municipal and industrial discharge effluents is concentrated here. But as the water goes downstream near Lohia Path and Shaheed Path, we observe that the WQI improves to fair

Table 2 WQI of Gomti river stretch in Lucknow city

Sites	WQI (%)
Ghaila Pul	65.26
Pakka Pul	62.81
KGMC	61.87
Hanuman Setu	60.80
Birbal Sahani	59.23
Lohia Path	65.44
Shaheed Path	66.64

as the water replenishes itself while moving away from these polluting sources.

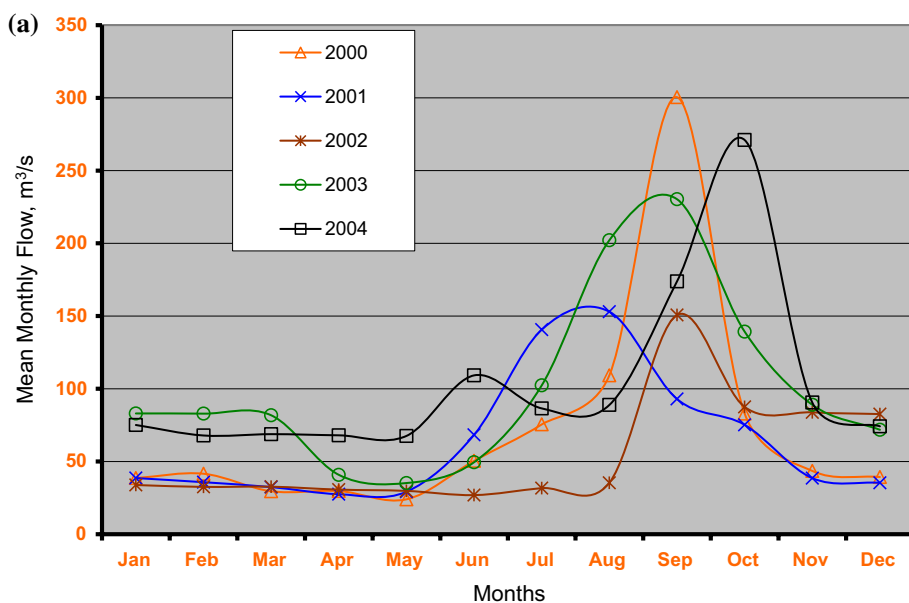
Estimation of environmental flows

Quick environmental flow assessed is $15.84 \text{ m}^3/\text{s}$ against MAF availability $79.22 \text{ m}^3/\text{s}$ whereas the mean monthly minimum flow is $6 \text{ m}^3/\text{s}$. This means river flow augmentation is needed (as it enters Lucknow) from Sarda canal system and for Gomti barrage downstream reach from Sarda Sahayak canal system or by increasing the catchment contribution for good health of the river.

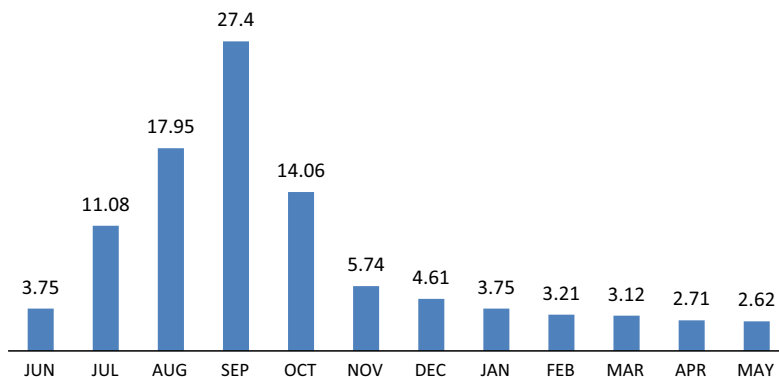
The mean monthly peak flow in Gomti river at Lucknow is varying from August to October over years 2000–2004 (Fig. 4a). Average monthly flows in Gomti are plotted for Lucknow as percentage of Mean Annual Runoff (MAR) and are shown in Fig. 4b. Monthly flows as % MAR during 2011–2012 at Lucknow are shown in Fig. 4c. The maximum 551 cumec and minimum 6 cumec discharge is reported based on daily discharge in Gomti River at Lucknow (Fig. 5a). Flow Duration Curve gives discharge of 100 and $79.22 \text{ m}^3/\text{s}$ at 60 and 75% dependability respectively (Fig. 5b). The river flow characteristics have been summarized in Table 3. Analyzing present day flows in Gomti River at Lucknow, it is strongly recommended to augment the river flow either from Sarda Canal system or from river catchment management conserving water in ponds and wetlands distributed in the upper reach of Gomti basin. This is also required for sustainability after the riverfront development project and maintenance of good health of the river Gomti.

Base flow index of Gomti River in Lucknow stretch showing the contribution of baseflow is shown in Fig. 6 based on 1975–2014 data. Since the river gets a substantial amount of water from the aquifers, the baseflow contribution is very high. For Gomti river cross section at Hanuman Setu, water level and discharge relationship is developed based on 1969–2011 peak flow values and correcting for outliers. This plot is shown in Fig. 7a. Perusal of Fig. 7b suggests that up to $1000 \text{ m}^3/\text{s}$ flow, G–D relationship is almost linear for river main channel whereas for upper values the relationship shows another slope due to floodplain compound section when water depth increases less as compared to width of the river involved. Historically, annual maximum recorded flood at Hanuman Setu is given in Fig. 7b. The wet year peak flows were $3085 \text{ m}^3/\text{s}$ on 11th September 1971, $2106.54 \text{ m}^3/\text{s}$ on 20th September 1985 and after that during recent years less than $1000 \text{ m}^3/\text{s}$ peak flows have been recorded. The minimum peak flow has been recorded $83.72, 129.06 \text{ m}^3/\text{s}$ in drought year of 1993 and 1979 respectively. Mean peak flows (averaged over 43 years) comes to $595.32 \text{ m}^3/\text{s}$ only and average water level of 106.565 m. The analysis of daily discharge data of a limited period (5 years, 2000–2004) also gives peak flow as $551.41 \text{ m}^3/\text{s}$.

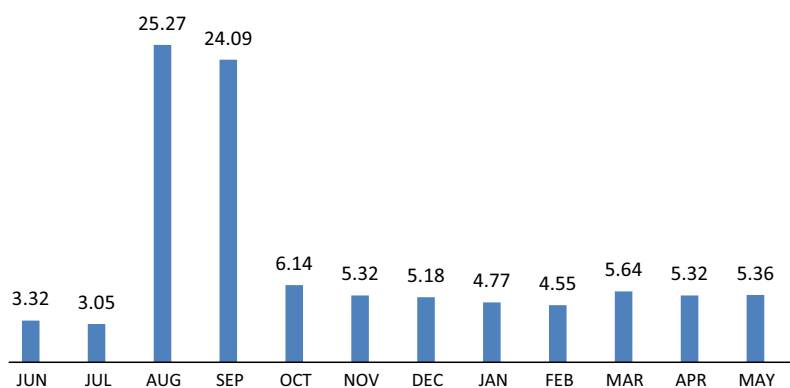
Fig. 4 a Mean monthly flow (in m^3/s) in Gomti River at Gomtinagar, Lucknow (2000–2004). **b** Flows variability during the last four decades in River Gomti at Lucknow (1970–2011). **c** Monthly Flows as % MAR during 2011–2012 at Lucknow. (Data source: CWC)



(b) Average Monthly Flows in Gomti at Lucknow (1970–2011) as % of MAR



(c) Monthly Flows in Gomti at Lucknow (2011–12) as % MAR



Disturbances in the continuum of natural habitats

Morphology of a river channel is formed by thousands of years of natural events that govern the movement of water and sediment in relation to the material locally available in the river bed and banks. Hydraulic and morphological

variability through space and time determine the various habitats found both within the river and in the adjacent riparian and floodplain zones. The expansion and development of urbanization and riverfront infrastructural developments, such as the construction of dams and weirs, has broken the continuum of natural habitats of Gomti River into small

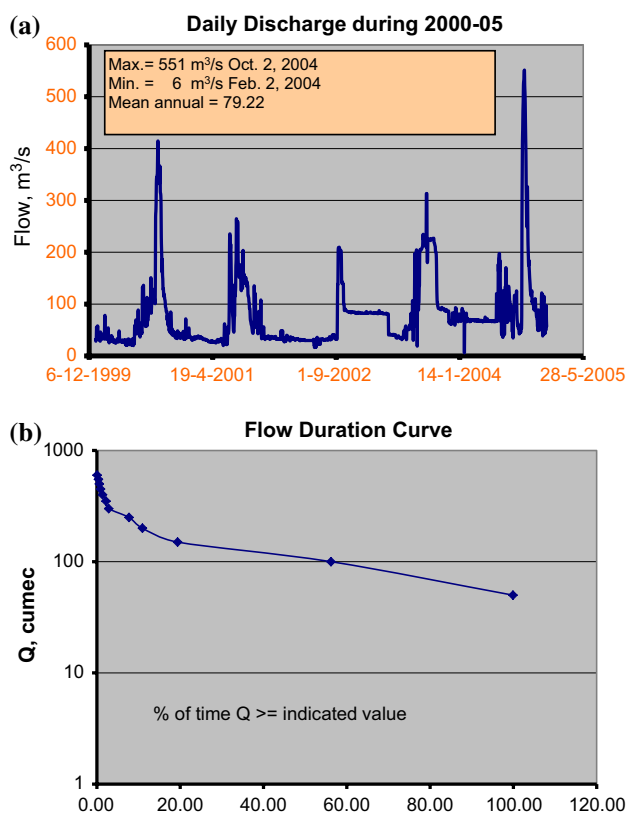


Fig. 5 a Daily discharge in Gomti River at Lucknow. b Flow duration curve

Table 3 Flow characteristics in m³/s. Source: Based on Gominagar gauge data for Gomti River, Uttar Pradesh Irrigation Department

Highest flood (1971)	3085.00
Lowest flood (1993)	83.72
Maximum monthly flow (Oct, 2004)	551.41
Minimum monthly flow (Feb, 2004)	6.00
Long term (1970–2011) mean monthly max. flow (Sep)	191.66
Long term (1970–2011) mean monthly min. flow (May)	37.36
Mean annual flow	79.22

fragments and these patches of fragmented habitat may be too small to support a breeding group of aquatic plants and animals (Khan et al. 2014; Nawab 2007). It is of note that area sensitive species have a low dispersal capacity, and are often unable to re-colonize such patches following extinction (Collinge 1998, 2009).

Reductions in the channel width and loss of floodplain corridors

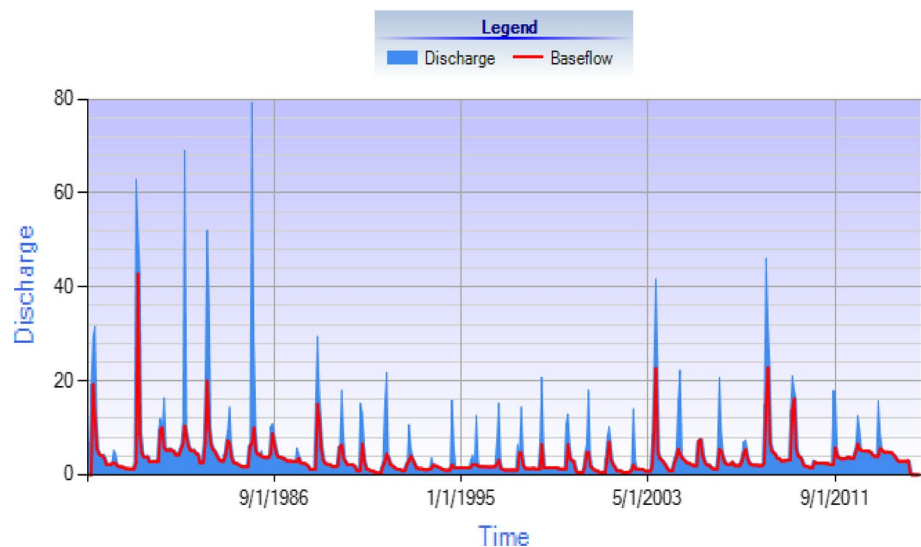
Stream channelization due to riverfront development is a common form of anthropogenic disturbance to urban river systems. The Gomti riverfront development project was

designed to construct public recreational facilities and beautification of the surroundings. However, limited use has been made of catchment ecology and geomorphic understandings to guide river management applications. Based on the long-term flow data and the existing section of the Gomti River in the study reach, it was proposed to keep minimum width of the river at its high-flood level equal to 250 m, however, in the riverfront development project the channel width was kept between 100 and 130 m. Heterogeneous habitat patches with sand bars and river pool during year 2011 is shown in Fig. 8a and loss of channel width and channel connected pool during the channelization project in 2015 is shown in Fig. 8b. Due to heavily reinforced 16 m deep diaphragm walls on both the banks, river health has been adversely affected as evident from the decline in water quality and fish diversity; however, the long term ecological impacts may be visible only after few years. The physical habitat variables play a leading role in the distribution of fishes in River Gomti and the habitat alteration brought about by channelization contribute significantly to the endangerment of freshwaters species. The modified channel is devoid of typical pool-riffle sequences and without vegetation resulting in loss of the river channel habitat which may further inhibit the reestablishment of native species across multiple trophic levels.

Loss of heterogeneous habitat types

The Gomti River maintained a mosaic of vegetation patches which is related to the rejuvenation of the successions associated with channel erosion and deposition (Table 4). Pools and riffles that resulted from interactions of flowing water and mobile sediments have been removed due to dredging and channelization. Pools, riffles and bars are composed of different bedload materials which provide environments for a variety of benthic organisms including fishes. Species richness and the structure of fish assemblages depend mainly on the spawning places and potential nurseries available (Jura jda 1995). Natural channels support higher densities, greater biomass and more species, and any recovery is usually slow (Brooker 1985). Loss of river channel habitat resulting from straightening can be substantial (Hansen 1971). In a channelized river, due to absence of areas with lentic backwaters and side-arms with aquatic vegetation, the fish could only use the stabilized stony banks or shallow-slope gravel shorelines. However, the vertical diaphragm walls for Gomti riverfront development project do not have stony banks or shallow-slope shorelines eliminating the potential fish habitat in the stretch. Habitats sampled in the Gomti River were common for floodplain river channels of the Ganga River basin. Based on the present study, eight major types of fish habitat were identified as shown in the Table 4. We observed all the eight types of habitat in the undisturbed segments of

Fig. 6 Base flow index of Gomti River in Lucknow stretch showing the contribution of baseflow (based on 1975–2014 data)



the Gomti River, while only two major habitat types were present in the channelized segments.

The riverfront projects and associated land use conversion of the heterogeneous habitats may cause future habitat homogenization followed by a fish-fauna homogenization on a regional scale, resulting in overall decline in fish diversity. It is widely accepted globally that in-stream habitat complexity has a major role in fish diversity. Functioning of the hydrological systems defines the habitat types in the catchment, and heterogeneous habitat types are preferred for restoring fish diversity. Fish assemblage structure follows stream habitat configurations. All the eight types of habitat are present in the undisturbed stretch of the river, while only two major habitat types are present in the channelized section (Table 4).

The design of diaphragm walls on both sides shows that the architects behind the riverfront development scheme lacked firm understanding of the physical, biological and chemical processes that drive river ecosystems. It is notable that a change in discharge, channel width and sediment load rarely produces an immediate response, but it leads to sequence of changes which may extend over a long period of time. A natural channel is neither straight nor uniform—but the architects of Gomti riverfront development project have not only straightened the channel but also reduced the width substantially though an earlier study cautioned them to not reduce to channel width to less than 250 m (IITR 2013). Straightening, dredging, and river bed re-alignment have altered the depth, slope and velocity of flow which directly produce bank erosion and sediment transport. The low fish production of the major fish groups in the river Gomti is the recruitment failure of the young ones due to degradation of the natural spawning habitat resulting from decreased flow volumes, changes in flow patterns, and high discharge of untreated wastewater.

Loss of fish biota

Around 20 species of fishes were found in Gomti River in the upstream of Lucknow at Ghaila, 7 species at Hanuman Setu and 8 species at Pipraghat during 2013–2014 which was un-channelized stretch (Table 5). In the downstream of the riverfront site, eight species were found during 2014; however, this site reported only one species with substantial reduction in catch per unit after riverfront development project. Distribution pattern of fishes in river Gomti at Lucknow region showed variation among different sites. Out of 19 species, 16 species were spotted in upper reach i.e. Ghaila Pul and 2, 6 and 1 species were reported at sites 2, 3, and 4 respectively (Table 6). It may be due to unstable environment caused by extensive riverbed dredging and loss of banks sides, and also from the fluctuating water levels. The distribution pattern of fishes showed major shift from the previously reported studies of Gupta (2011), Lakra (2010), Sarkar et al. (2013). Gupta (2011) reported 12 species in the Lucknow region but in the present study only 4 species were found out of those 12 species reported earlier. There are also possible threats to the indigenous fish fauna, as a result of the invasion and proliferation of some exotic species (Sarkar et al. 2012). Two species *Oreochromis niloticus* (Tilapia) and *Puntius chola* were also reported in the region. In the channelized section, the fish diversity reduced drastically with only six species reported after the riverfront project. The total fish biomass in the downstream site (sites 3 and 4) was about 85% less than in the natural channel in the upstream. We also found principally juvenile and smaller species, compared to the undisturbed channel in the upstream. It may be due to unstable environment caused by extensive riverbed dredging and loss of banks sides, and also from the fluctuating water levels. Studies have indicated in the past that the rate of recovery of fish population from

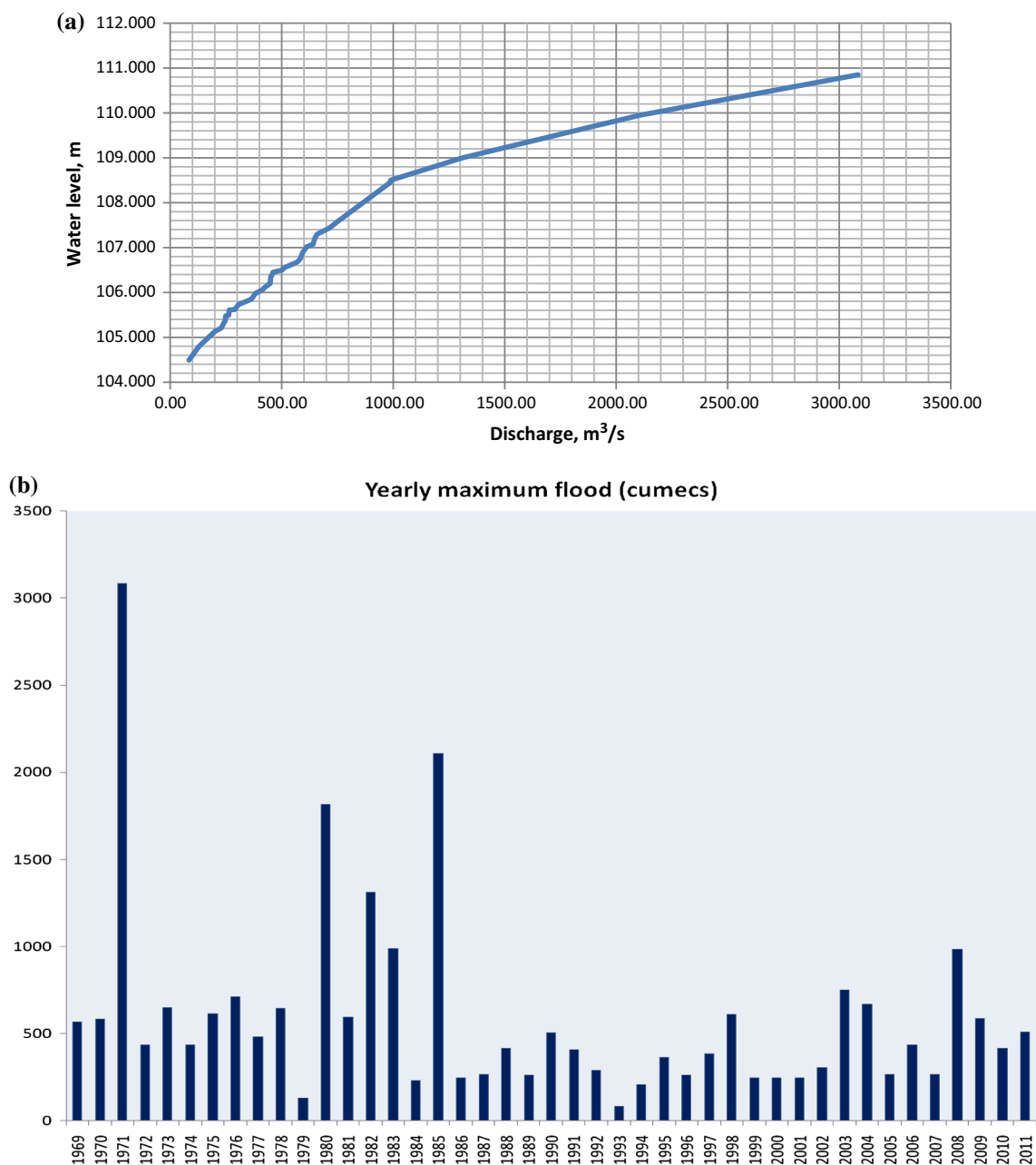


Fig. 7 **a** Guage-discharge relationship at Hanuman Setu cross section-Pre riverfront development project (author's elaboration based on CWC data). **b** Annual maximum recorded flood (in m³/s) at Hanuman Setu between year 1969–2011. (Credit: CWC 2012)

the effects of channelization is extremely slow, with some stretches showing no sign of significant recovery even after 30–40 years (Niemi et al. 1990; Detenbeck et al. 1992).

The species richness in four sampling sites showed considerable variation and higher richness was recorded in the upstream of channelization region. Maximum species richness was recorded in site 1 (16 species) i.e. Ghalia Pul, while lowest at the site 4 (1 species). At sites 2 and 3 species richness was also low; 2 and 6 species respectively. Due to river channelization project, a lot of dredging was carried

out by stopping the flow of the river which resulted in loss of habitat and the diversity in the downstream stretch. The Shannon fish diversity index of different sites ranged from 0 to 1.45. The maximum fish diversity index was recorded at site 3 as compared to other sites. The comparatively low diversity index may be due to the occurrence of a few abundant species and many other lesser relative abundance. The Simpson diversity indexes in different sites varied from 0.48 to 0.72. Highest was recorded at site 3 i.e. Rubber Dam. In general, the value of D ranges between 0 and 1, with



Fig. 8 **a** Heterogeneous habitat patches with sand bars and river pool during year 2011. **b** Loss of channel width and channel connected pool during the channelization project in 2015

high score indicating high diversity. The values of species dominance (Berger-Parker Dominance index) ranged from 0.40 to 0.56. The highest dominancy was reported at site 2 (Pakka Pul), even though higher richness was recorded in the upstream of channelization region. Evenness for the study area ranged from 0.26 to 0.98 (Table 7).

The freshwater resources of Ganga Basin are currently experiencing an alarming decline in fish biodiversity due to various anthropogenic activities. Destructive fishing methods, entry of exotic species, habitat alteration, water diversion, poor vegetation cover in the river banks, siltation, water abstraction, and low water velocity have affected the overall fish diversity to large extent. In the study area, fragmentation and changes in the hydrology of river due to riverfront development project, dredging and artificial barriers are major threat to the fishes in the Gomti River apart from water quality degradation due to sewage pollution.

Riverfront development projects based on hard-engineered approaches require expensive long-term maintenance and repair and may deteriorate river conditions by negatively impacting the natural ability of a healthy river system to cleanse pollutants and moderate flow variability. The built landscape within the active floodplain cause external perturbations which may challenge river's self-sustaining capacity

and resilience requiring costly follow-up maintenance of both water quality and fluvial habitat. The lack of connectivity between the river channel and floodplain through the affected site means that floodplain habitat and breeding ground is essentially absent, as all riverbanks have been subject to the construction of deep vertical diaphragm walls. The river is highly fragmented into pools due to earthen dam, barrage and a weir in the downstream within a span of 10 km. The diaphragm walls have also created disturbances on sediment transport due to flow in a confined channel. Since the affected area falls in the middle part of the basin with suitable habitats of turtles and native fishes, the project would impact their diversity in the future, as evidenced by reduced fish richness after the riverfront project. Reduction in fish diversity is a serious concern in the long-term protection of freshwater ecosystems.

Restoration of riverine habitats has been carried out in United Kingdom, United States and Europe by a number of researchers (Friberg et al. 1994; Trexler 1995; Muotka et al. 2002; Helfield et al. 2007; Newson 2010; Raven et al. 2010). The important lessons are: these programs are long term, technically robust, use river stretches with special conservation designations for wildlife as a 'springboard for a strategic approach to river restoration' and rely on separate funding for habitat modifications (Philip and Paul 2012). Restoration programs also target geomorphic structure, function and evolutionary trajectory of a river system (Brierley et al. 2010). There is need of putting in place a restoration plan which is scientifically and technically robust, large-scale, long-term and economically viable for Gomti River. Several conservation measures can be used to design urban rivers to maximize their geomorphic and ecologic diversity (Neave and Rayburg 2016) with improved understanding of ecology-physical habitat relationships (Vaughan et al. 2009; Covarrubia et al. 2016). River banks and channel connectivity can be restored in a phased manner by removing the diaphragm wall and stabilizing the bank vegetation in the long run. As channelization reduces river's geomorphic complexity with concrete channels providing little or no geomorphic complexity or diversity, effort should be on restoring immediate river corridors such as wetlands and seasonal ditches that can improve base flows to the river. There is also a greater need to consider whole catchments and river landscape in the development of eco-hydromorphic research (Eyre et al. 2002; Vaughan and Ormerod 2010). The water quality in the channelized stretch can be substantially improved by controlling point and non-point sources of river pollution, many of which are scaled to the catchment via the runoff/sediment system (Newson 2010). The land-use and land-management planning system must be activated to conserve and restore river ecosystem integrity (Dutta 2012).

Table 4 Habitat matrix and species preference and their status in channelized and unchannelised sections of the Gomti River. Source: Authors' own elaboration

Habitat types	Characteristic	Species preference	Unchan-nelized sections	Chan-nelized sections
1. Open river	River without channel confluences and pools	Mixed assemblage of fishes	Present	Present
2. Deep pools	Deep pools with high turbidity, and coarse substrate	Species such as Chitala, Wallago, Ompok, Clarias, Channa inhabit this habitat	Present	Present
3. Backwater and shallow pools	Medium-sized pools with low water flow	Notopterus, Cirrhinus, Rita, Labeo prefer this habitat	Present	Absent
4. Scour pools	Channel-spanning pools	Pool holds juvenile fish, used for spawning, preferred by fishes sensitive to extended low-flow periods	Present	Absent
5. Channel confluence	Junction of two rivers	Ideal place for fish habitat	Present	Absent, tapped by parallel drains
6. Wetlands-connected ditches	Medium-sized to small ditches connected to riverside wetlands	Small natural ditches host many habitat specialist fish species	Present	Absent
7. Grassed banks	Stabilizes stream banks	Grassed banks support more individuals and more fish species	Present	Absent
8. Well-vegetated banks	Well-vegetated banks maintain the stream temperature	Assemblage composition of fishes improves with vegetated banks, fishes move to those places where there is considerable vegetation	Present	Absent

Table 5 Diversity of fishes in Gomti River, Lucknow before the channelization project in 2013–2014

Species	Family	Local name	Ghaila Pul (Upstream)	Hanuman (Mid-stream)	Pipraghat (Down-stream)
<i>Clarias magur</i>	Clariidae	Magur	+	+	+
<i>Mystus cavasius</i>	Bagridae	Tengan	+	+	+
<i>Channa punctatus</i>	Channidae	Girai	+	+	+
<i>Rita rita</i>	Bagridae	Rita	+	–	+
<i>Heteropneustes fossilis</i>	Heteropneustidae	Singhi	+	–	+
<i>Mastacembelus armatus</i>	Mastacembelidae	Bam	+	–	–
<i>Notopterus notopterus</i>	Notopteridae	Patra	+	–	–
<i>Labeo rohita</i>	Cyprinidae	Rohu	+	–	+
<i>Catla catla</i>	Cyprinidae	Bhukur	+	–	–
<i>Cirrhinus mrigala</i>	Cyprinidae	Nain	+		–
<i>Chitala chitala</i>	Notopteridae	Moi	+	–	–
<i>Ompok pabda</i>	Siluridae	Pabda	+	–	–
<i>Ompak bimaculatus</i>	Siluridae	Pabda	+		
<i>Labeo bata</i>	Cyprinidae	Bata	+		+
<i>Labeo calbasu</i>	Cyprinidae	Karonch	+		
<i>Cirrhinus reba</i>	Cyprinidae	Reba	+	+	+
<i>Channa marulius</i>	Channidae	Sol	+	+	–
<i>Bagarius bagarius</i>	Sisoridae	Goonch	+	–	–
<i>Clupisoma garua</i>	Schilbeidae	Bachwa	+	+	–
<i>Puntius ticto</i>	Cyprinidae	Puthia	+	+	–
<i>Catch per unit effort (Kg/man/h)</i>			0.970	0.785	0.865

Table 6 Diversity of fishes in Gomti River, Lucknow after the channelization project in 2017–2018

Genus Species	Family	Ghaila Pul (Site 1)	Pakka Pul (Site 2)	Downstream of Rubber Dam (Site 3)	Pipraghat (Site 4)
<i>Chanda nama</i>	Ambassidae	+	–	–	–
<i>Anabas testudineus</i>	Anabantidae	+	–	–	–
<i>Mystus vittatus</i>	Bagrifidae	+	–	–	–
<i>Rita rita</i>	Bagrifidae	+	–	–	–
<i>Colisa fasciatus</i>	Anabantidae	+	–	–	–
<i>Channa striatus</i>	Channidae	–	–	+	–
<i>Oreochromis niloticus</i>	Cichlidae	–	–	–	+
<i>Clarias magur</i>	Clariidae	–	–	+	–
<i>Amblypharyngodon mola</i>	Cyprinidae	+	+	+	–
<i>Labeo calbasu</i>	Cyprinidae	+	–	–	–
<i>Osteobrama cotio</i>	Cyprinidae	+	–	–	–
<i>Puntius chola</i>	Cyprinidae	+	+	+	–
<i>Puntius sophore</i>	Cyprinidae	+	–	–	–
<i>Puntius ticto</i>	Cyprinidae	+	–	+	–
<i>Glossogobius guiris</i>	Gobiidae	+	–	–	–
<i>Heteropneustes fossilis</i>	Heteropneustidae	+	–	–	–
<i>Macrognathus pancalus</i>	Mastacembelidae	+	–	–	–
<i>Nandus nandus</i>	Nandidae	+	–	–	–
<i>Notopterus notopterus</i>	Notopteridae	+	–	+	–
<i>Catch per unit effort (Kg/man/h)</i>		0.394	0.392	0.155	0.068

Table 7 Table showing the diversity index Species richness, Shannon index, Simpson index, Berger parker dominance index and Evenness

Location	Species richness (S)	Simpson index (D)	Shannon (H)	Berger Parker Dominance Index	Evenness (e ^H /S)
Ghaila Pul	16	0.64	1.42	0.54	0.26
Pakka Pul	2	0.49	0.68	0.56	0.98
Rubber Dam	6	0.72	1.45	0.40	0.71
Pipraghat	1	n.a.	n.a.	n.a.	n.a.

n.a. not applicable

Conclusions

The design of riverfront projects should be based on sound ecological principles so that health of the river is measurably improved. Any riverfront project should consider wide ranging aspects of habitat degradation including the potential role of protected areas and fish sanctuaries, habitat management and life history traits of prioritized species. Species diversity and habitat heterogeneity is necessary for the long term maintenance of stable, complex freshwater ecosystem. Therefore, the conservation policy should promote the management practices that maintain integrity of aquatic ecosystem through adopting ecohydrological approaches. The study advocates a need to identify critical fish habitats in both the upstream and downstream of affected areas to

declare them as conservation reserves. In all such projects, both pre- and post-assessment must be completed and data made publicly available. Further, river engineers need to understand that biological and ecological sciences are fundamental to their tasks of riverfront development and should avoid hard engineering approach in developing riverfronts. The declaration of fish conservation areas along with landscape level conservation plan, proper Environment Impact Assessment for any riverfront development activities in the basin, habitat restoration schemes, and time-bound species recovery plan for threatened species in the study area may help the restoration possibilities of the native fish diversity. The restoration of disturbed channel streams is a time-taking process and needs to be monitored with a long-term restoration plan.

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