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Assessing the Impact of In-Stream Structures on Riverine Geomorphology and Biological Integrity

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Abstract: *Effect of in-stream grey infrastructures mainly through the dams, weirs, barrages, culvert and bridges has been explored for river system of Lower Ganga River basin using applied geospatial technology, field based geomorphological measurements to reveal the hydro-geomorphological changes and corresponding possible effect on the river ecology. The study finds installation of 96 large over the focused area have been trapped about 1,06,400 million cubic metres (MCM) of water with an average capacity of ~1100 MCM. The installation of undersized stream crossings is also significantly changing the channel form by increased depth, reducing width-depth ratio in the downstream direction of the crossing sites.*

Keywords: Grey Infrastructre, Dams, Stream Crossings, Channel Geomorphology, River Ecology

1. Introduction

Rivers are essential to maintaining terrestrial ecosystems because they support around 10% of all known species, including about 30% of vertebrate species, such as fish, amphibians, and reptiles, as well as countless invertebrates and microorganisms (Reid et al., 2019; Dudgeon et al. 2006). The preservation of natural hydro-geomorphological continuity makes such forms of biological integrity feasible (Wohl, 2004). Leopold and Maddock (1953), Vannote et al. (1980), and Montgomery (1999) have employed their models of 'Downstream Continuum' (DC), 'River Continuum Concept' (RCC), and 'Process Domain Concept' (PDC) to investigate the existence of longitudinal continuity in channel morphology, hydrology, and ecosystem. However, expanding human-induced interventions such as in-stream construction of dams, weirs, barrages, culverts, and bridges significantly compromise the natural continuity and integrity of geomorphology and biology, respectively (Nilsson et al., 2005; Ward and Stanford, 1995). These in-stream structures are profoundly altering the natural regime of sediment and water of the concerned river system and consequently disturbed the entire river ecosystem (Wohl, 2004; Graf, 2006; Kondolf et al., 2014). In particular, by disturbing the sediment flow to the downstream those interventions could significantly influence the riverine integrity by obstructing the formation of habitats and other required physical conditions for aquatic and riparian species (Kondolf, 1997; Wohl, 2004). Because sediments help to formation of different fluvio-geomorphological features in riverbed, banks and floodplain, which are acting as spawning grounds, habitat for benthic invertebrates (Karr, 1981). The dam-induced sediment trapping creates the effect of 'hungry water' (Kondolf, 1997) by disconnecting the downstream riverine floodplain from the main channel to exchange matters and energy through intensive erosion of the channel bed (Wohl, 2019).

The study of river health, which is a combine monitoring of the four main elements of the fluvial system—hydrology, geomorphology, water quality, and the biotic profile of the concerned river—could be used to evaluate the integrity of the river ecosystem (Modi et al. 2021). The concept of river health was legally first introduced by the U.S. in 1972 through Clean Water Act (CWA). All countries are now focussing on managing such an essential natural resource since rivers and streams are now one of the most vulnerable ecosystems in the world. For instance, the Government of India's Ministry of Jal Shakti launched the "National Mission for Clean Ganga" (NMCG) in June 2014 in partnership with IITs, the UNDP, and foreign partners. The NMCG aims to revitalise the River Ganga by reducing pollution, conserving biodiversity, reforesting large areas, treating sewers, developing riverfronts, raising public awareness, and closely monitoring industrial effluent. As the most populous region in the world and for India as well, it is crucial to investigate the nature of the Ganga River ecosystem's vulnerability as a result of various anthropogenic activities. In-stream constructions are the main focus of the current study because they pose a risk to the hydro-geomorphological and ecological features of the Lower Ganga Basin (LGB). Thus, the main goal of the current study is to determine how dams affect the hydrological regime, how bridge and curvet building affects the channel geomorphology of headwater streams specifically, and whether these changes have an impact on the river community.

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2. Study Area

The selected Lower Ganga Basin (LGB) encompasses 25% of the total Ganga Basin (~1,080,000 km2) within the three important East Indian states, i.e., Bihar, Jharkhand, and West Bengal (Figure 1). With major urban centres like Kolkata (~4.5 million), Patna (~1.68 million), Asansol (0.56 million), and Durgapur (~0.57 million), the region is home to roughly 35% of the basin's population. However, due to their increasing socioeconomic demands and disruption of ecological behaviour, the region is under a lot of anthropogenic pressure. For example, the Damodar River, which was formerly known as the "Sorrow of Bengal" because of its frequent catastrophic flood conditions, today experiences decreased flow and ecological deterioration as a result of significant regulation of water for industrial use. Due to the regional climate, which has an average annual rainfall of 100 to 150 cm, the tributaries of this big river in LGB—Gandak, Kosi, and Jalangi on the right bank, and Sone, Falgu, Damodar, Mayurakshi, Ajay, and Dwarkeswar on the left—are primarily monsoon-fed. Quaternary alluvium covers most of the area of LGB with few patches of Archaean-Proterozoic formations in its southwestern regions. The predominant land use in the basin area is agriculture (~59%) and built-up area (~16%), which are generally motivated for deforestation, development of urban sprawl and disturbing the ecological integrity of the region.

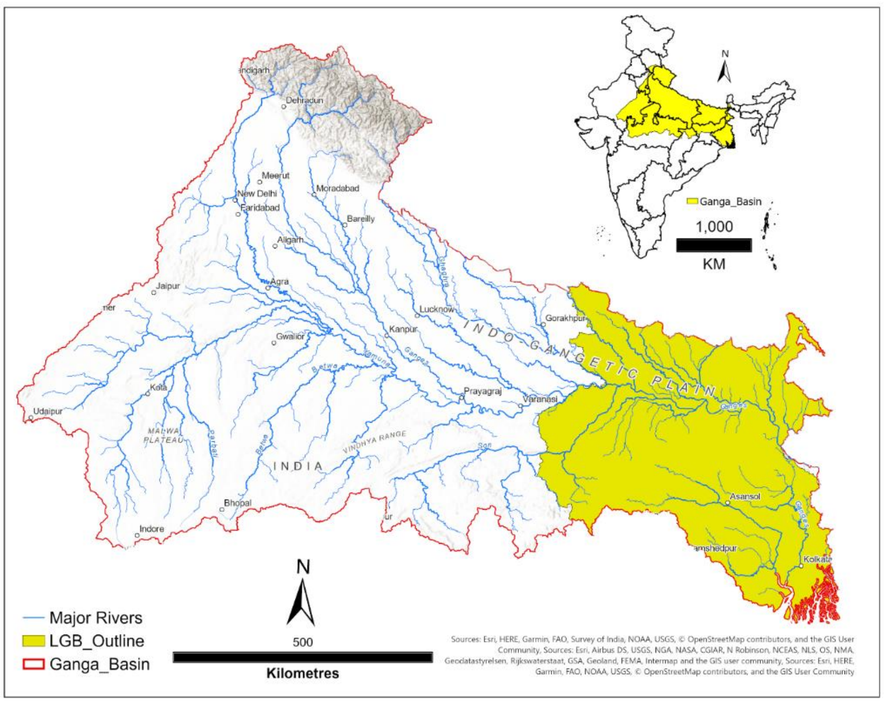

Figure 1: Location of Lower Gangetic Basin (LGB) inside the Ganga Basin of India

3. Methods and Database

Geospatial technology has been intensively used to prepared the database required to interpreted the effects of dams and barrages on the flow regime of the study area. In particular, the location of dams, together with information about their height and water-holding capacity, has been obtained from the Central Water Commission's (CWC) National Register of Large Dams in India. Location and length of the major barrages have been extracted manually from the Google Earth Image. Using an Auto level (Sokkia C410, with a standard deviation of 2.5 mm for a one-kilometre double run levelling) and other surveying tools, an extensive geomorphic field survey has also been conducted at several locations throughout the Kunur River Basin (Figure 2), a tributary of the Ajay Rive Basin, to get required fluviometric indicators of the survey streams. Specifically, ten cross profiles and a longitudinal profile have been examined at ten distinct road-stream crossing locations between 50 m upstream and 50 m downstream. For each crossing site, cross-sections were obtained at intervals of 1 m, 5 m, 10 m, 20 m, and 50 m in both upstream and downstream directions.

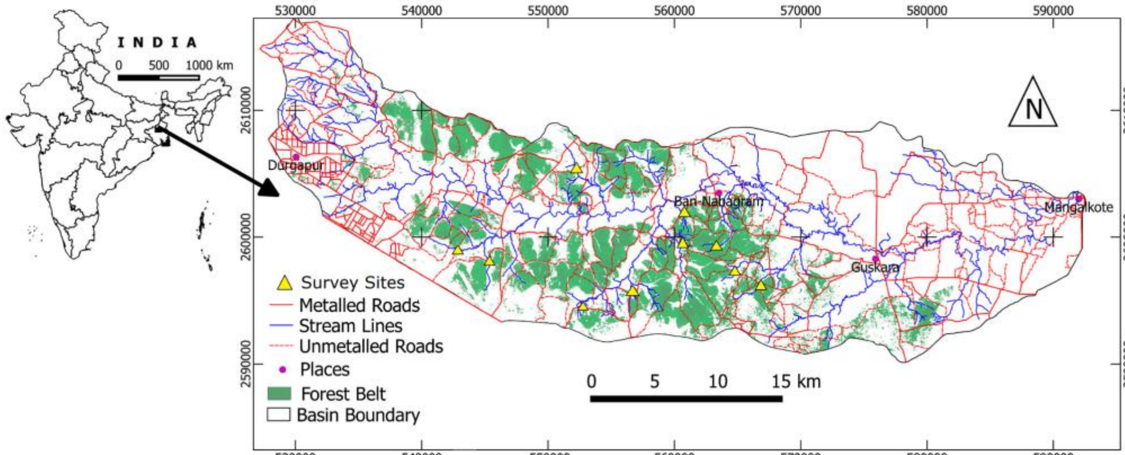

Figure 2: Kunur River Basin, a sample survey basin to study the effect of stream crossings on fluvial geomorphology

4. Results and Discussion

4.1 *Effect of Dams and Barrages on Flow Discontinuity*

Dams and barrages are typically built to control flooding and increase river water use for various needs, including irrigation, hydropower production, industrial use, and other household uses. However, these barriers have severely disrupted the channels' longitudinal continuity, which significantly impacts the integrity of the ecology and geomorphology along the channel (Ward and Stanford, 1995; Yang et al. 2019). According to the National Register of Large Dams (NRLD) of the Government of India,currently 411 major dam projects under construction and 5334 completed projects in the nation (CWC, 2019). A 'large dam' is defined by the International Commission on Large Dams (ICOLD, 2018) as "a dam that is 15 meters or higher from lowest foundation to crest or a dam that is between 5 and 15 meters in height and impounds more than 3 million cubic meters." Specifically, the LGB witnessed the construction of 96 large dams, of which 39 are in Jharkhand, 26 are in Bihar, and 31 are in West Bengal (Figure 3a). The major concentration of these dams has been observed over the plateau region on the south-western part of LGB, whereas, the plain region of LGB is featured with numbers of large barrages including the longest Farraka Barrage (~2300 m) across the Ganga River in Murshidabad district of West Bengal (Figure 3b). Within the LGB a total of 21 major barrages (length >100 m) have been identified on different major rivers like Ganga, Son, Kosi, Damodar, Mayurakshi, Gandak, Falgu etc. with an average length of about 500 m. In addition, the longitudinal continuity of small to medium rivers also affected by installation of numerous check dams to accumulate upstream water.

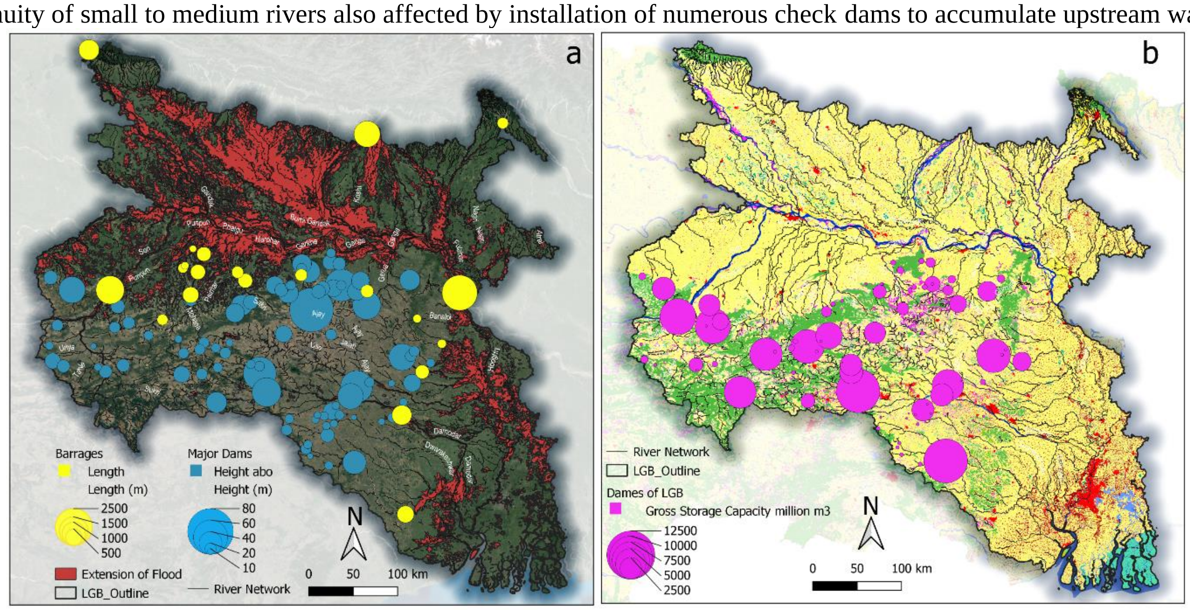

Figure 3: (a) Distribution of major dams and barrages across the LGB including the proportional circles based on their height and length, respectively, with the maximum spatial extent of the flood-affected area; (b) Variation of gross water storage capacity (in million m3) of the respective dams of LGB

The structural details of these dams show among the 96 dams of LGB the Barnar Dam on Barnar River near Jamui, Bihar is the highest dam with 76.75 m of height (from the lowest foundation to the crest of the dam), followed by the North Koel (67.86m), Konar (57.60m), Badua (56.66m) and Maithon (56.08m) dams. The lowest and mean dam height in the LGB region is ~10 m and ~25 m, respectively. Kangsabati Dam (WB) is the longest dam of this region with a length of 10.40 km followed by the Panchet (6.77 km), Tenughat (6.50 km), Burhi (5.76 km), whereas the average length of all dams is 1.28 km. The dams of LGB are cumulatively holds ~1,06,400 million cubic metre (MCM) of water with an average capacity of ~1100 MCM. The maximum capacity of gross storage has been observed at Kangsabati Dam (~10,360 MCM) followed by Tenughat (~10,209 MCM), North Kole (~7020 MCM), Batane (~6787 MCM), and Massanjore (~6170 MCM). The correlation values show the gross storage capacity of a dam is more associated (positively) with the height of a dam (r = 0.67) than the length of a dam (r = 0.46). The effect of selected dams of LGB have been highlighted significant changes in the hydro-geomorphological characteristics of downstream river systems of the respective dams (Table 1).

Table 1: Effect of selected dams on the hydro-geomorphological alteration of different rivers in LGB (West Bengal)

Name of the Dam	Location	Post-Dam/Reservoir/Barrage Changes		Source (s)
		Hydrological Changes	**Geomorphological Changes**	
KOMARDANGA DAM (Bangladesh)	**River**: Dhepa River (in Bangladesh) of Punarbhaba River Basin **Year**: 1992 **Lat/Long**: 25°51’46” N/88°39’52” E	Reducing in the average water level of pre-monsoon and post-monsoon by 52.24% and 32.34%, respectively	Reducing of floodplain area by squeezing the river corridor and about 40% reduction in flood water extension over the basin; Disconnection between active channel, floodplain, and wetlands. Water crisis for the wetland habitats	Talukdar and Pal (2017)
MASSANJORE DAM (Jharkhand, India) and TILPARA RESERVIOR (WB)	**River**: Mayurakshi River (Jharkhand) and Kushkarni River (WB) **Year:** 1955 and 1976 **Lat/long:** 24°06'25"N / 87°18'31"E and 23°56’46’’N/87°31’30’’E	Decreasing monsoon and pre-monsoon water level and about 34% (7.73mg/l to 4.96mg/l) reduction in suspended sediment load below the dam and reservoir	Reducing the carrying capacity of upstream channels e.g., 26% for Kushkarni River and declining the longitudinal bed slope and velocity Experience of river bank erosion	Pal (2016a)
MOHANPUR DAM and RESERVIOR (Bangladesh)	**River**: Atreyee **Year:** 2012 **Lat/long:** 25°32'23.28"N/88°45'35.39"E	Reducing of seasonal discharge by 30.97%, 66.86% and 64.01% during pre-monsoon, monsoon and post monsoon periods and bbout 18.26% negative change in base flow, immediate after the dam construction		Pal (2016b)
FARAKKA BARRAGE (WB)	**River**: Ganga **Year:** 1975 **Lat/long:** 24°48'16.76"N/ 87°55'50.73"E	**On Padma**: At Hardinge bridge station (Bangladesh), the average dry-season (Jan-may) discharge 2340 $m^3 s^{-1}$ of pre-Farakka (1934–1975) reduced to 1236 $m^3 s^{-1}$ during post-Farakka (1975–1995). In particular, the maximum, average and minimum discharges have been reduced around 22, 48 and 72%, respectively, in dry-season; About 13% increase in peak-discharge during post-Farakka Period. The salinity of the Padma in Bangladesh also increased from 380 μΩ/cm during the pre-diversion period in 1974 to about 29,500 μΩ/cm in 1992.	Huge sediment load has been trapped from the upstream of the Ganga Basin and about 87 million cubic metres of water was impounded and the effect exhibit through changing course and severe bank erosion in Malda district (WB); **On Bhagirathi-Hugli**: Increasing the formation rate of cut offs and ox box lakes;	Rudra (2014, 2016, 2018); Rahaman and Rahaman (2018)

MAITHON and PANCHET DAMS (JHARKHAND) AND DURGAPUR BARRAGE (WB)	**River**: Damodar **Year:** 1957, 1959, 1955 **Lat/long:** 23° 47 ' 7"E/ 86° 48 ' 43" N; 23° 40 ' 51"E/ 86° 44 ' 50" N; 23°28'35.95"N/ 87°18'5.16"E	The monsoon discharge of 6081–10,676 $m^3 s^{-1}$ is reduced up to 2574–4470 $m^3 s^{-1}$ due to reservoir storage and diversion of flow through canals; Forwarding the period of peak flood	The dominance of aggradational landforms, braiding, avulsion, high width–depth ratio, breaching of right bank, and valley widening up to 82 km from Durgapur Barrage then phenomena of bank erosion, confined sinuosity, low width–depth ratio, and narrowness are more pronounced up to the confluence.	Ghosh and Guchhait (2014)
KANGSABATI DAM (WB)	**River**: Kangsabati Kumari **Year:** 1965 **Lat/long:** 86°47'20.14"E / 22°57'49.90"N	Significant reduction in peak flow and total annual discharge; non-monsoonal low flow increasing due to irrigational water supply; The frequency of low flood (2 – 10 years return period) reduce and large flood (>10years) has been eliminated	Changes in river bed elevation by huge sedimentation and loss of habitat	Mittal et al. (2014)

4.2 *Effect of Culverts and Bridges on Stream Geomorphology*

Culverts and bridges are helping to accommodate road traffic over surface waterways and facilitate rapid movement of material across the rivers and other drainages. However, undersized and architecturally poor crossings have significant negative impact on the hydrology, geomorphology and ecology of rivers (Merril & Gregory, 2007; Hancock, 2002; Blanton and Marcus, 2009, 2014; Bouska et al., 2010). Such effects could be categorised into two sections i.e., immediate effects and delay effects (Table 2).

Table 2: Short-term and long-term effects of in-stream highway, bridge and/or culverts construction on river geomorphology and hydraulics (after FHWA, 1990)

Immediate Effects	Delay Effects
• **Increased Flow Velocity;** • **Contraction;** • **Local Scour Development;** • **Sediment Remove from upstream and deposition in the immediate downstream;** • **Backwater Effect;** • **Increase sediment yield in river water.**	• Become straight planform of the channel in the downstream; • River Incision or Low Entrenchment ratio; • Increase of the stream gradient; • Lowering of water level in the main channel, and negative change in the local base level of erosion of the tributary streams, increased channel bed gradient and erosional activities in the tributaries and start to degradation of local area; • Instability of River Bank and Bridge/ Culvert

As shown in figure 4 and table 3, the survey results demonstrate the significant impacts of crossing structures on stream morphometry clearly evident. Along with the type of crossings, the channel form values have changed from upstream to downstream. Three different crossing types—box culverts, pipe culverts, and small bridges—have been seen among the ten crossing sites. Although no significant change has been observed for channel width, however, significant adjustment has been observed in case of mean depth and maximum death of the channel. In particular, at D1, D5, and D10 channel depths are significantly ($p < 0.01$) increased at the rate of 9%, 20%, and 19% respectively in comparison with their counterparts U1, U5, and U10. However, 7% and 9% decreases have been observed at D20 and D50 respectively (Figure 4). Significant ($p < 0.001$) differences in width – depth ratio (w/d) between upstream and downstream reaches has also been observed. In the immediate downstream (D1), ~12% decrease in w/d ratio has been observed for pipe culvert but in case of bridge and box culvert, the values have been increased at the rate of 60% and 96% respectively, followed by its counterpart (U1) (Table 3). The cross-sectional area of the 100 cross-sections calculated from ten crossing sites ranges from 0.13 m^2 to 8.23 m^2. The mean cross-sectional area below the crossing structure increased significantly ($p < 0.05$), as seen in Figures 4e and table 3. The immediate upstream (U1: 40%) and downstream (D1: 68%) of the crossing constructions have seen the largest increases in cross-sectional area when compared to the U50 (the natural stream segment considered to be least affected). The values of Flow Velocity (v), Stream Power (ω) and Froude Number (Fr) are immediately decreased at D1 and thereafter increased towards downstream. In compare to U50, at D1 *v* and Fr have been decreased at the rate of 19% and 20% respectively; whereas 120% increase of ω has been observed here. Crossing type wise variation shows ω and *v* are significantly increased in downstream for pipe culvert, whereas for bridge both are decreased in the downstream. The longitudinal profile of those studied channel also shows notable change in the pool – riffle sequence along the river, which can disturb the movement of river community and habitat.

Table 3: Crossing type wise differences in the mean values of channel parameters between upstream and downstream reaches

Crossing Type	Reach	a (m^2)	w (m)	d (m)	D (m)	w/d	ω ($W\ m^{-2}$)	*v* (m^3/s)	Fr
Box	Upstream	0.73	2.87	0.26	0.45	11.51	190.50	3.23	0.81
	Downstream	0.92	3.18	0.26	0.47	11.99	209.61	3.18	0.81
Bridge	Upstream	2.38	5.21	0.42	0.66	15.83	327.65	2.37	0.61
	Downstream	2.76	5.96	0.41	0.69	16.16	259.49	2.22	0.60
Pipe	Upstream	1.07	4.67	0.20	0.38	23.15	79.30	1.96	0.58
	Downstream	1.17	4.29	0.22	0.40	21.39	273.50	2.59	0.75

a = cross-section area; w = width of the channel; d = mean depth of channel; D = maximum depth of the channel; ω = stream power; *v* = flow velocity, and Fr = Froude number

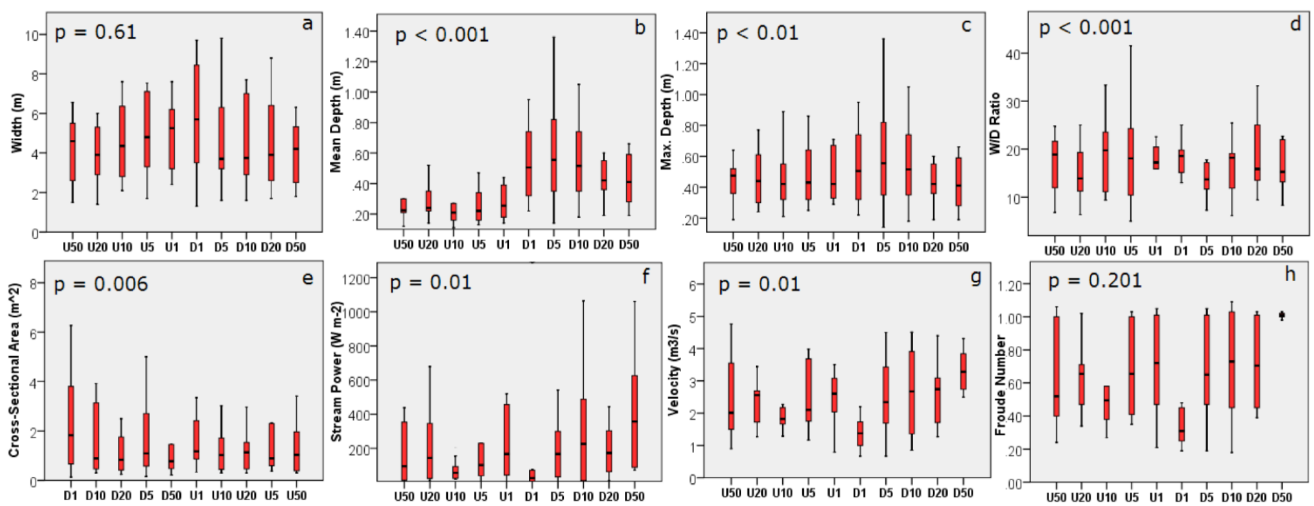

Figure 4 (a – h): Box plots of eight channel parameters for ten different reaches (U50 to D50) are showing the range differs in absolute values between upstream and downstream, where p-value indicates the level of significance in these differences (Source: Field Survey)

5. Conclusions

The study reveals a clear relationship between in-stream structures—primarily dams, weirs, barrages, culverts, and bridges—and the change in flow regime and channel geomorphology from big rivers to headwater streams, respectively. Major identified immediate hydro-geomorphological changes by dam construction are reducing average water level as well as discharge during pre and post monsoon season of all trunk rivers, reducing of floodplain area by squeezing the river corridor, disconnection between active channel, floodplain, and wetlands, water crisis for the wetland habitats, reducing the carrying capacity of upstream channels, dominance of aggradational landforms, braiding, avulsion, high width–depth ratio, breaching of right bank, and valley widening etc. The undersized culvert and bridges are also significant alter the change geomorphology with severe change in the immediate upstream and downstream of crossing structure. Among the culvert types, pipe culvert makes more alternation followed by box culvert and bridges. All such alternation in geomorphology could also significantly disturbed the channel ecology by acting as barrier for the free movement of river biota along the channels, by changing the habitat of riverine community, by change the pool – riffle sequence in the channel. .

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