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Linking weir imprints with riverine water chemistry, microhabitat alterations, fish assemblages, chlorophyll-nutrient dynamics, and ecological health assessments

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ABSTRACT

The weir construction in larger rivers has displayed harmful impacts due to unpredicted modifications in hydrology and microhabitats. This study illustrated the impacts of three massive weirs installed in the mainstream Geum River, South Korea. We used the modified multimetric index of biotic integrity (mmIBI) and water pollution index (mmWPI) to understand the imapcts of weir installations on riverine water chemistry and fish assemblages. The results divulged seasonal and spatial heterogeneities by indicating the gradual degradation of water quality. Phosphorus and sediments displayed an excessive influence of seasonal rainfall patterns. The nutrients (N, P) showed week relationships at weir (GW: $R^2 = 0.21$, SW: $R^2 = 0.12$, BW: $R^2 = 0.25$), but stronger links in the upstream river ($R^2 = 0.74$) sites. The mmWPI revealed the weir sites and riverine zones into 'fair to very poor' water quality status, while mmIBI specified the sites in 'fair to poor' ecological health. Overall, 60 fish species sampled as 64,637 individuals were observed, indicating 81.24% of individuals at the weir sites. Squalidus japonicus coreanus (18.47% RA) and Hemibarbus labeo (9.25% RA) were relatively the most abundant fish species in this investigation. The total number of fish species and individuals gradually declined along the river gradient. The principal component analysis (PCA) grouped the dominant factors by distinct riverine zones, with a percent cumulative variance of 81.80%. The tolerant and omnivorous fish species were established in aggregations in downstream, with increased insectivorous species. In conclusion, the impacts of weir installation were assiduously manifested and indicted an exceedingly deteriorating water chemistry that could have caused a decline in sensitive species, favored the tolerant species, and overall reduced the habitat quality suitable as natural breeding and feeding grounds. Furthermore, the declining fish assemblages and their distribution, perturbed microhabitat conditions, and inclusively deteriorating ecological health status were linked to the weir imprints.

1. Introduction

Freshwater ecologists have shown consensus that the natural processes of the lotic ecosystems and biological communities are often dictated by the dynamics and nature of disruption regimes that primarily reflect upon spatial and seasonal fluctuations of streamflow (Karr 1981; Ahn et al., 2014; Poff et al., 2007). Out of the most severe challenges to the natural streamflow, is the serial installations of weirs in larger rivers (Shewit et al., 2017). As a favored tool of robust modifications in the natural flow regime, a weir could potentially degrade and modify the characteristic community differences at river and watershed scales by imposing ecological homogeneity (Miranda et al., 2005; Cha et al., 2015). With a potential to modify the habitat and flow regime, weirs are widely prevalent in Canada (Hatry et al., 2016), USA (Salant et al., 2012), Australia (Keller et al., 2012), Asia (Cha et al., 2015; Yang et al., 2012), Europe (Głowacki and Penczak 2000; Miranda et al., 2005), United Kingdom (Lothian et al., 2019) and Africa (Shewit et al., 2017).

Weirs have displayed wide-ranging impacts on the riverine ecosystems. To enumerate a few are the disrupted stream connectivity and habitat simplification (Baek et al., 2015), water chemistry modifications (Park et al., 2017), declining biological assemblages with interrupted spawning or forced seasonal migrations (Gauld et al., 2013; Baumgartner et al., 2014), limited access to food resources and preferred habitats (Maceda-Veiga et al., 2017). The other impacts cover subdued genetic flow (Moon et al., 2020; Bae et al., 2020), enhanced susceptibility to predation and diseases by aggregations (Moon et al., 2015), fragmented communities with hampered mobility (Shewit et al.,

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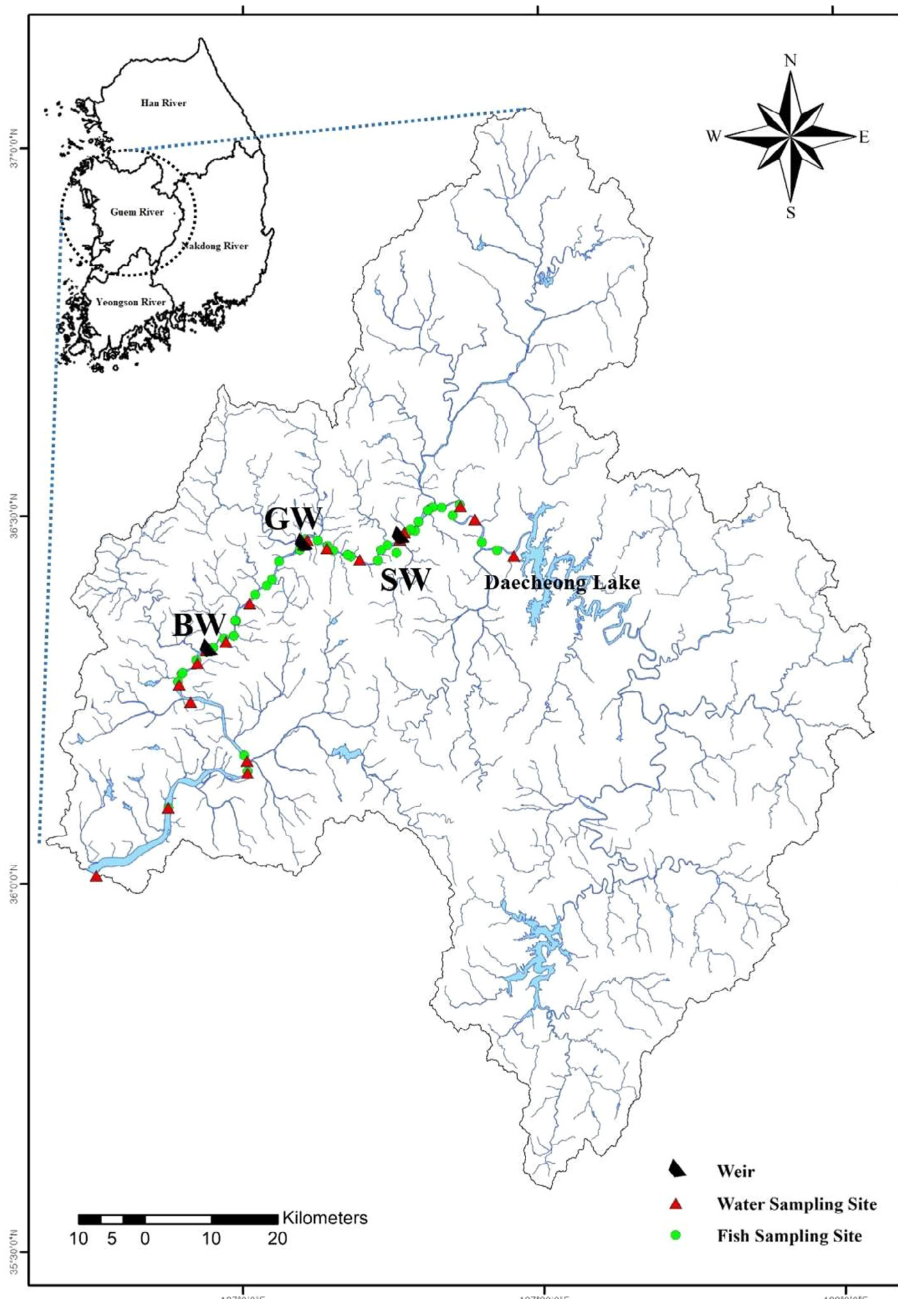

Fig. 1. Study area map showing the arrangement of study sites for water sampling, fish sampling, and weir placements. *SW = Sejong Weir, GW = Gongju Weir, BW = Baekje Weir.*

2017), occasional flooding of streamside vegetation and toxic algal blooms (Yu et al., 2015).

The eccentrically distributed seasonal rainfall pattern necessitates the construction of weirs and dams for irrigation, drinking, flood damage control (Atique and An, 2019a,b), and drought management in the monsoon dominated climate regions (Lah et al., 2015; Lee and An 2014). It further implicates the ecosystem functioning by greater hydrological and ecological modification (Han, 2015; Choi et al., 2017). The physical and biological alterations of microhabitat and fish communities further aggravate the essential ecological processes and provide suitable grounds for exotic species (Yang et al., 2012; Kim et al., 2019; Atique et al., 2019). Since weir construction remodels the stream channel and morphology (Landemaine et al., 2015), such modifications of physical habitat and hydrological regime strongly influence the trophic, tolerance, and habitat guilds leading to abrupt shifts in fish communities (Atique and An 2018; Kim et al., 2019).

The industrial urbanization and agricultural intensification are inducing higher inflows of nutrient and pollutant enriched sediments, a variety of pollutants, and organic matter into the broad rivers (Atique et al., 2020; HaRa et al., 2020; Saeed et al., 2020). Due to the widespread anthropogenic activities at the watershed-scale and the various land-use patterns are adversely affecting the ecological health and biodiversity (Egler et al., 2012; Extence et al., 2013; Mueller et al., 2013; Atique and An, 2019b; Atique and An, 2020). In the adverse situation, affluent sediment deposit as layers in the river bed and prevent oxygen and explicit water supply to the spawned eggs and fry pushing them to hyporheic zones that culminates into the decline of overall fish populations (Lange et al., 2014; Sternecker et al., 2014; Saeed et al., 2020).

Therefore, it is pertinent to claim that persistence and stability are considered essential for temporal and seasonal settlement of aquatic assemblages. Researches on persistence and stability of fish assemblages are central to our understanding of the very structure and function of ecosystems (Meffe and Berra, 1988). The classic theory of serial discontinuity (Ward and Stanford, 1979) also declares that the installation of massive weirs and dams could lead to discontinuous ecological processes in river zones (upstream, midstream, and downstream), thereby influencing environmental structure, functions, persistence, and stability.

Based on the above aspects, we endeavoured to test the hypothesis that the serial installations of weirs can cause potentially significant changes to the water chemistry, microhabitat conditions, chlorophyll-nutrient dynamics, and fish assemblages in Geum River, South Korea. With established and multiple detrimental impacts on riverine ecosystems, notably disrupted continuum, a watershed-scale investigation targeting the symptomatic repercussions of weir installation is lacking. Therefore, the goals of this investigation included the understanding of watershed-scale change in water chemistry under the influence of intensive monsoon rainfall at weir sites and Geum River zones. We also identified the links between nutrient contributing factors (TN, TP), TN:TP ambient ratios, and Chl-a at weirs and river zones. Further, we studied the dynamic patterns of various fish assemblages, ecological health assessment by employing the index of biotic integrity (IBI), relative abundance, spatial water quality dynamics, and relationships between trophic and tolerance guilds of fish species. We also illustrated the water quality status by the multimetric water pollution index (mmWPI).

2. Materials and methods

2.1. Watershed and weirs

This research targeted Geum River Watershed, which is positioned in South Korea between the longitude and latitude of 126°41′–128°25′ and 35°35′–37°05′, respectively. It is the third-largest river watershed spanning an area of 9896.7 km^2 while the main river channel total length is 395.9 km. This river is a classic example of human-controlled natural river flow. The mainstream river flow is actively controlled by two large reservoirs viz. Daecheong (1981) and Yongdam (2001). Geum River watershed receives 1240 mm of average annual rainfall, with 12,800,000,000 m^3/year of the total volume of natural runoff (Ministry of Land, Infrastructure, and Transport, 2016). The rain is intensive during monsoon season (July-August), whereas the nethermost precipitation occurs during January – February. Being largescale water supply resources to the major cities, the riverine flows are continuously fluctuating. Therefore, to maintain environmental flow, the Korean Government installed sixteen weirs in the four major rivers (Han, Geum, Yeongsan, and Nakdong) under the famous 'Four Major Rivers Restoration Project' during 2009–2011. This project included flood control, coping with water security and drought, improvement of water quality, ecological restoration, and waterfront development objectives (Ahn et al., 2014). Three out of these sixteen weirs were built in the Geum River. The study area map is showing the watershed topography, settings of the three weirs viz. Sejong Weir (SW), Gongju Weir (GW), and Baekje Weir (BW), and location of water quality and fish sites in Fig. 1. The hydro-morphological aspects and physiognomic details are specified in table 1.

2.2. Study plan

This study spanned from 2010 to 2017, and we investigated water quality at 21 sites while fish sampling held at 26 locations. We divided the Geum River into three zones viz. Geum River Upstream (GRU), Geum River Midstream (GRM), and Geum River Downstream (GRD). All the study sites categorized under the 6th stream order according to Strahler's (1957) classification of stream orders. It is essential to declare

Table 1
Hydrological, morphological and geographical summary of weirs installed in Geum River.

Weir (W)	Stream Order	Geographical Location		Height (m)	Average Depth (m)	High Water Level (EL.m)	Low Water Level (EL.m)	Storage Capacity ($10^6 m^3$)	River Width (m)	Surface Area ($10^6 m^2$)
		Longitude	*Latitude*							
Sejong Weir (SW)	6	127.2617	36.47163	4	2.1	11.8	10.7	1.3	72	3
Gongju Weir (GW)	6	127.0987	36.46241	7	4.2	8.75	3.28	10.4	78	4.7
Baekje Weir (BW)	6	126.9391	36.31879	7	4.6	4.2	2.34	18.1	131	6.8

Table 2
Summary statistics of the water chemistry parameters grouped by weirs and regions of Geum River during 2010–2017.

Area	Stat. Att.	pH	DO	WT	BOD	COD	TSS	EC	TOC	TCB	FCB	TN	TDN	NH_4-N	NO_3-N	TP	TDP	PO_4-P	TN:TP	Chl-a
GongjuWeir	Min	6.8	5	1.1	0.7	4.3	2.2	106	2.5	12	0	1.86	1.62	0	0.99	30	0	0	5.24	1.2
(GW)	Max	9.2	16.4	30.3	5.7	11.4	212.8	700	8.6	24,540	8040	8.91	8.05	2.87	4.41	493	0.18	0.17	135.66	117.2
	Mean	8.11	10.84	15.09	2.62	6.79	18.80	341.7	4.36	1704	234	3.59	3.35	0.47	2.30	93.7	0.04	0.03	49.66	34.90
	S. dev.	0.39	2.07	8.37	1.10	1.35	23.25	110.3	1.10	3088	685	1.21	1.20	0.63	0.70	58.2	0.03	0.03	29.02	26.90
SejongWeir	Min	6.9	3.2	2.3	0.9	1.62	0.98	171	2.6	24	0	0.01	1.58	0.04	0.91	20	0.02	0.01	14.43	19.1
(SW)	Max	8.9	15.7	27.6	5.9	9.8	58.5	690	6.9	12,950	455	7.40	4.85	0.68	3.53	287	0.11	0.09	154.21	95
	Mean	7.92	9.15	14.99	2.3	5.26	6.53	343.1	4.22	1330	55	2.30	2.96	0.21	2.13	65.9	0.03	0.01	63.06	47.32
	S. dev	0.34	3.55	7.05	1.05	1.97	7.05	110.4	0.86	2545	102	1.99	1.00	0.18	0.84	33.2	0.02	0.02	28.94	18.44
BaekjeWeir	Min	6.9	5.1	0	0.8	4.2	2.3	105	2.4	19	0	1.78	1.58	0.01	0.06	26	0	0	6.61	1.7
(BW)	Max	9.3	18.6	33	5.5	13.1	167.5	649	7.6	41,675	12,303	6.82	6.30	2.68	4.23	427	0.15	0.13	139.27	95
	Mean	8.11	10.93	15.45	2.59	6.80	17.28	331.8	4.29	1267	209	3.35	3.13	0.39	2.18	84.1	0.04	0.02	50.45	34.62
	S. dev	0.35	2.34	8.72	0.88	1.23	17.91	102.9	0.94	3223	1002	1.09	1.07	0.51	0.70	48.1	0.02	0.02	30.09	19.55
GRUp-Stream	Min	6.7	5.9	1.5	0.4	1.8	0.5	66	1.8	9	0	1.01	0.94	0	0.05	4	0	0	5.23	0.3
(GRU)	Max	9.1	40.9	27.3	5.3	9.7	136.1	690	8.6	260,000	23,245	10.32	8.44	3.24	5.65	363	0.23	0.1	305.85	137.1
	Mean	7.80	10.87	13.99	1.74	5.53	9.82	265.2	3.84	7147	1553	3.14	2.95	0.30	2.11	72.7	0.04	0.01	72.85	15.93
	S. dev	0.35	2.61	6.91	1.05	1.50	14.43	123.1	1.08	19,568	3511	1.61	1.48	0.51	0.94	62.3	0.04	0.02	54.30	22.05
GRMid-Stream	Min	6.8	4.1	0.5	0.7	0.01	0.003	112	2.5	29	0	0.8	1.62	0.01	0.99	32	0	0	6.73	1.3
(GRM)	Max	9.2	25.20	30.10	6.6	12	216.5	661	9.50	51,375	15,150	80.7	7.15	2.80	5.49	391	0.20	0.18	138.68	117.7
	Mean	8.02	11.93	15.21	2.73	6.32	14.63	354.2	4.48	2550	470	4.69	3.37	0.44	2.39	90.8	0.04	0.02	51.26	39.07
	S. dev	0.48	3.09	8.19	0.9	2.31	18.02	108.8	1.02	4915	1395	6.33	1.20	0.57	0.78	52.4	0.02	0.02	29.69	27.81
GRDown-	Min	6	3.6	0	0.9	4.4	2.7	86	2.1	0	0	0.78	0.41	0.001	0.15	24	0	0	5.16	1.9
Stream	Max	9.8	21.7	32.9	9.7	20.2	260.3	1240	11	71,000	16,000	8.85	7.28	3.19	4.72	365	0.17	0.13	140.62	199.5
(GRD)	Mean	8.13	10.91	15.84	2.87	7.40	21.29	320.3	4.49	1560	208	3.19	2.94	0.32	2.02	90.5	0.04	0.02	44.23	38.97
	Stand. dev	0.50	2.73	8.82	1.06	1.85	22.51	110.8	1.14	5967	957	1.16	1.06	0.45	0.75	48.7	0.03	0.02	25.42	30.84

GR: Geum River, Stat. Att.: Statistical attributes, Min: Minimum, Max: Maximum, S. dev.: Standard deviation, DO (Dissolved oxygen, mg/L), BOD (Biological oxygen demand, mg/L), COD (Chemical oxygen demand, mg/L). TSS (total suspended solids, mg/L), TN (Total nitrogen, mg/L), TP (Total phosphorus, μg/L), TOC (Total organic carbon, mg/L), WT (Water temperature, °C), EC (Electrical conductivity, μS/cm), TCB (Total coliform bacteria), TDN (Total dissolved nitrogen, mg/L), NH_4-N (Ammonia-nitrogen, mg/L), NO_3-N (Nitrate-nitrogen, mg/L), TDP (Total dissolved phosphorus, mg/L), PO_4-P (Phosphate-phosphorus, mg/L), Chl-a (Chlorophyll-a, μg/L), FCB (Fecal coliforms bacteria).

that all of these study sites are part of the long-term national-level ecological monitoring by the Korean Ministry of Environment. Geum River catchment area has numerous point-sources, for instance, wastewater treatment plants (WWTP), industrial zones, and sewage treatment plants, as well as non-point sources (e.g., agricultural runoff) of pollution.

2.3. Water quality analyses

In total, 19 chemical water quality parameters were studied, and the full names and measuring units of the parameters are presented in table 2. The water quality data procured every month and the factors included pH, dissolved oxygen (DO), biological oxygen demand (BOD), chemical oxygen demand (COD), total suspended solids (TSS), total nitrogen (TN), total phosphorus (TP), ambient ratios of TN and TP, total organic carbon (TOC), water temperature (WT), electrical conductivity (EC), total coliform bacteria (TCB), total dissolved nitrogen (TDN), ammonia nitrogen (NH_4-N), nitrate-nitrogen (NO_3-N), *ortho*-phosphorus (PO_4-P), chlorophyll-a (Chl-a) and faecal coliform bacteria (FCB). At the time of sample procurement, the water sample amounting to one litre was stored in pre-rinsed polyethene containers for detailed chemical analyses. The pH, WT, EC, DO, TSS and Chl-a were recorded at the spot by using the multi-parameter Sonde sensor (YSI Sonde 6600, Environmental monitoring system, Yellow Springs, OH, USA). TN was estimated by the second derivative method, followed by digestion in a persulfate solution (Crumpton et al., 1992). The NH_4-N and NO_3-N were investigated by phenate and ion chromatography methods, respectively, then filtered through GF/C filters (Whatman, Maidstone, UK) to obtain an extract of source sample. The TP and PO_4-P were measured by the ascorbic acid method followed by the persulfate oxidation (Prepas and Rigler 1982; APHA 2005). BOD, COD, TOC, TCB, FCB, and TSS were estimated by the standard methods (APHA 2005). Nutrients (TN, TP, and their allied species) analyses were completed in triplicates to warrant rationality, while BOD and COD were performed in duplicates (MOE, 2000; APHA 2005).

2.4. Multi-metric water pollution index (mmWPI)

The mmWPI helps in designating the water pollution status of a water resource based on salient water quality parameters. For this purpose, we used a modified multimetric WPI adopted from nutrient pollution index (NPI) by Dodds et al., (1998) and Atique and An (2019a). Crucially important seven water chemistry parameters constitute its metrics (M): nutrient regime (M_1: TN, mg/L; M_2: TP, μg/L; M_3: TN:TP ambient ratios), Organic matter (M_4: BOD, mg/L), ionic and solid content (M_5: TSS, mg/L; M_6: EC, μS/cm) and primary production indicator (M_7: Chl-a (μg/L). The basis for the ascribed scoring criteria to each mmWPI metric is established on the limits set by the one-third of the observed distribution of acquired values. Subsequently, the assigned scoring criteria for each of the parameters are 5, 3, and 1, with five signifying functional water quality status and one as degraded water quality. The accumulative score appraised the judgment of the water pollution status at each study site. The final score established the specific categorization of all study sites between excellent (31–35), good (25–29), fair (19–23), poor (13–17) to very poor (07–11).

2.5. Fish sampling and gears

We conducted fish data collection twice per year at all the study sites during 2010–2017. Each year, first sampling was accomplished during pre-monsoon (May–June) months, while second sampling events were held during post-monsoon (September–October) months. Sampling days were chosen at times, and places of relatively stable hydrological flows to minimize sampling error. Due to the occurrence of > 60% of the total annual rainfall during monsoon months, hydrological flow fluctuates abruptly. Consequently, higher would be the chances of frequent disarrangements of microhabitats and disrupted fish communities. Each of the fish sampling events spanned between 50 and 60 min and included the upstream and downstream stretches of the sampling station. We targeted each type of microhabitat, including pools, riffles, and run to minimize the sampling error and maximize the chances of covering all kinds of fish species. The sampling method used in this study is termed as the wading method that is modified after the protocols of the US EPA (Barbour et al., 1999) and South Korea (An and Choi, 2003). Two types of fishing gears were used in the river, including cast net (mesh size 5 × 5 mm) and kick net (mesh size 4 × 4 mm), while fyke nets were used in the weir sites by employing boats. The fish identification key used is compiled by Kim and Park (2002) that relates the salient identification features based on morphological characteristics of the Korean fish species. Besides, Nelson's (2006) systematic classifications method was followed for scientific categorization. Also, each of the tested fish individuals was attentively examined for any morphological abnormalities such as deformities (D), erosion(s) (E), lesions (L), and tumours (T), that is also recognized as DELT and provides detailed insights into the physical health of each fish individual (Sanders et al., 1999).

2.6. Index of biotic integrity (IBI)

The tendencies in the fish assemblages and riverine ecological health assessment were examined by using IBI with fish sampling datasets. The development of IBI at the regional-scale based on the identification of various environmental degradations in the target study sites linked to biological and community analyses (Karr, 1981). IBI is modelled with the combination of eight metrics further classified into three main categories viz. species richness and composition, trophic and tolerance guild compositions, and the fish abundance along with an insight to the physical well-being of fish individuals. Further itemization of these groups discloses that the first group (M_1–M_4) reflects upon the component features of species while the second group (M_5–M_6) unveils the composition of trophic characteristics of fish, and the third category (M_7–M_8) represents fish abundance and individual well-being. All details on mmIBI are followed from Atique and An, 2018. Each of the selected IBI metrics is ascribed scores of 5, 3, or 1 consistent with the described standard and habitat conditions. These ratings attributed to selected parameters were cautiously assigned as per the MSRL (maximum species richness line) concept (Rankin and Yoder, 1999) that is based on the stream order links with fish community abundance. The given scoring criteria indicated the extent of ecological health in comparison with pristine environments, either approximated (5 points), moderately deviated (3 points) or critically degraded (1 point). The final scores were obtained by the aggregate of all the allotted scores directed to the absolute IBI value indicating overall ecological health status. The conclusive environmental health ranks characterized based on final IBI scores were excellent (36–40), good (28–34), fair (20–26), poor (14–18), and very poor (8–13).

2.7. Trophic, tolerance and habitat guilds analyses

Trophic and tolerance guild features help establish our opinion on the vital fish assemblages. For allotment of legitimate score corresponding to each metric, each variety of fish assemblages is required to be designated to various trophic, tolerance and, habitat guilds. The trophic guild consisted of omnivorous, carnivorous, herbivorous, or insectivorous fish species, while tolerance guild comprised sensitive, tolerant, or intermediate species. According to the habitat preference (water column or riffle benthic), habitat guild is allotted to each species. It is meaningful to consider that the majority of fish species are water column while a few are riffle-benthic loving. The apportionment of each fish species into the relevant trophic, tolerance and habitat guilds was arranged in consistence with the established methodologies by Karr (1981) and An and Choi (2003). The region-specific analysis and origin (endemic or exotic) of the fish species were charted from previously established categories (Kim, 1997; An et al., 2001). Furthermore, this approach was developed in the view that the proliferation of native and sensitive species (SS) symbolizes robust ecological health status. In contrast, an abundance of omnivorous, tolerant, and exotic species reflects eco-biological deterioration (Choi et al., 2011).

2.8. Statistical analyses

All the datasets used in this study were subjected to normality check by Kolmogorov-Smirnov test before executing the log-transformations. The seasonal and spatial dynamics of water quality in the riverine zones and three weirs examined. Further, we used the box-plot method to analyze the fish assemblage patterns. Regression analyses on the nutrient contributing factors (TN, TP), primary production indicator (Chl-a), and ambient nutrient ratios (TN:TP) were also plotted. The water pollution status and ecological health assessments were established according to standard methods by employing IBI and mmWPI, respectively. Principal component analysis (PCA) was performed on normalized datasets with the help of PAST software. The principal component analysis (PCA) successfully displayed the settlement of water quality and fish assemblage indicators in three riverine zones. It also presented the correlation between water chemistry and fish assemblages. The loading values obtained from PCA reflected the strength of variation and relationships between water quality factors and fish assemblages. These relationships were rated either as strong ($r > 70$), moderately strong ($r < 70– > 50$), and weak relationship ($r > 30 – \langle 50$). We used the Sigma Plot version 14 (Systat. Software Inc., San Jose, CA, USA) and PAST software for preparing the illustrations and data analyses.

3. Results and discussion

3.1. Dynamics of water quality in weirs and river zones

The river water chemistry at the weir stations (SW, GW, BW) and river zones (GRU, GRM, and GRD) exposed spatial, and weir linked heterogeneities in 19 water quality determinants that flagrantly reflected the variety of characteristics affecting the Geum River ecosystem during 2010 – 2017 (Table 2). Most of the parameters symbolized water quality degradation from upstream to downstream river zones. Furthermore, weir sites manifested gradient-wise water quality deteriorations when compared between the upstream and downstream zones. The pH, DO, WT, allied nitrogen species (NO_3-N, NH_4-N), and orthophosphate (PO_4-P) did not reveal any exceptional discrepancies at the weir sites. However, a few indicated a slight degradation from upstream to downstream zones. To provide a snapshot, BOD was higher at the downstream weir BW (2.59 ± 0.88) approximating with that of GRD (2.87 ± 1.06). COD showed a gradual increase from upstream (SW: 5.26 ± 1.97; GRU: 5.53 ± 1.5) to downstream (BW: 6.80 ± 1.23; GRD: 7.40 ± 1.85) in weirs and river zones, indicating no impact of weir installations. However, weir sites pointed a three-fold accretion in TSS from the upstream weir (SW: 6.53 ± 7.05) to the downstream weirs (GW: 18.80 ± 23.25; BW: 17.28 ± 17.91). The riverine zones, however, displayed a gradual and spatial increase in TSS from GRU to GRD. The foremost reason for intensified sediments level at the weirs could be linked with higher water residence time (WRT). Such an intensification in river turbidity could be hazardous to the aquatic fauna and flora, mainly fish, as the higher buildup of solids at the weir sites could be highly detrimental to the aggregating fish individuals. This may induce and worsen the gill-clogging problem, and ultimately resulting in respiratory failure, a concomitant decline in foraging efficiency, and troubled spawning (Gray et al., 2012; Kimbell and Morrell 2015). Further, this could be supported by the mounting levels of organic matter downstream zones, indicating whereby no or insignificant influence of weirs on the organic matter flow down the river stretches (An et al., 2013).

In the case of nutrients in riverine zones, the concentrations of TN, TP, and allied chemical species did not display any distinct pattern variabilities; however, TN:TP ambient ratios indicated a gradual decline from the upstream to downstream river zones. The total coliform bacteria (TCB) and faecal coliform bacteria (FCB) illustrated a declining trend from the upstream to downstream zones. The higher bacterial burdens upstream informed about the existence and straight influence of anthropogenic activities and domestic effluents as well as extensive livestock farming. The sequence of sestonic Chl-a concentration in weirs and river zones revealed that SW (47.32 ± 18.44) embraced a higher while BW (34.62 ± 19.55) and GW (34.90 ± 26.90) reported levels of Chl-a, while mean Chl-a levels explicated a consistent increase from the GRU to GRD. It is pertinent to consider that the whole Geum River watershed, including the riverine zones and weir sites, alluded to a P-limitation scenario (Ahn et al., 2014). At all the riverine zones and weir areas, pre-eminent water chemistry determinants (TN, TP, BOD, TN:TP ambient ratios, and Chl-a) appeared to be strongly influenced by the intensive monsoon precipitation regime (An and Choi 2003; Schinegger et al., 2016). Good water quality is crucial to sustaining the physiological, feeding activities, very existence in the ambient aquatic ecosystems, and controlled cultures (Iqbal et al., 2017; Mehboob et al., 2017; Batool et al., 2018). The impacts of these critically vital water quality characteristics are intimately relatable to the fish communities in lotic ecosystems (Khanom et al., 2020; Iqbal et al., 2020). Furthermore, installations of weirs enhanced their roles and significance even more critical to the constant instream movements. The variety of the factors impacting riverine water chemistry are intensive livestock farming, untreated metropolitan sewage, fertilizer and pesticide-based agriculture, and various land uses activities (Miserendino et al., 2011; Kim and An 2015; Kim et al., 2019).

3.2. Monsoon linked seasonal dynamics of water chemistry

The monsoon dominated precipitation design elucidated seasonal and spatial fluctuations in oxygen demanding regime (BOD, COD), solids (TSS), nutrients (TN, TP, and their ambient ratios), organic matter (TOC), ionic contents (EC), bacterial loads (TCB) and primary production indicator (Chl-a) in the weir localities and river zones. The intensive rainfall, mainly concentrated during the monsoon months (July-August), manifested substantial influence on seasonal water chemistry factors revealing parameter-specific trends (Fig. 2). Under the critically manoeuvring control, the water quality parameters either approximated, deviated, or speckled contrastingly against the seasonal rainfall curve in the river watershed. In a specific breakdown, BOD pointed higher tendencies at weir sites and river regions during pre-monsoon rainfall and declined during post-monsoon. At the same time, COD indicated approximations with monsoon peaks at riverine and weir sites (Fig. 2a, b). TN, TN:TP ambient ratios and EC varied oppositely while TSS and TP went well along with the seasonal precipitation patterns at the weirs and river zones. TOC and sestonic Chl-a, however, displayed a haphazard plot at the weir sites and river zones and appeared to be changing irrespective of the influence of the intensive rainfall or dry periods. Such assorted fluctuations in the vital water chemistry factors influenced by the extreme monsoon regime indicated that water quality is gradually degrading at the weir and river zones. TN and TP conspicuously deviated and approximated with the seasonal rainfall pattern, respectively. It further alluded to the runoff currents delivering loads of phosphorus, especially from the adjacent agricultural pastures and livestock farming units.

Similarly, coliform bacteria were introduced into the upstream stretches of the Geum river when the intensive rainfall became a connecting tool between the weirs and river zones, transporting the anthropogenic and domestic products to the river. In the case of TN and ionic contents, however, the same monsoon precipitation worked as a dilution factor. Those mentioned above spatial and seasonal heterogeneities in water chemistry features in weirs and river zones are distinct and substantial in the context of longitudinal gradient and richly supported by previous studies (Choi et al., 2011; Ahn et al., 2014; Cha et al., 2015).

3.3. Empirical links between Nutrients, ambient Rations, and Chlorophyll

We performed linear regression examinations on the nutrients (TN, TP) and their ambient proportions (TN:TP) at the weir sites and riverine zones of the Geum River. Relationship of TP on TN symbolized weak links at the weirs (GW: R^2 = 0.21, SW: R^2 = 0.12, BW: R^2 = 0.25), while displayed strong positive connections in GRU (R^2 = 0.74). GRM and GRD exhibited almost no relationship between TN and TP (Fig. 3). The regression analyses on TP and ambient ratios of TN:TP presented extreme negative (R^2 > 0.70) links indicating the highest settlements in the GRU and weir sites. However, in the case of TN, links with ambient ratios of N and P displayed moderately strong positive (R^2 > 0.50 < 0.70) connection at the GW and SW while strong positive relationship at BW (R^2 > 0.70). In the Geum River regions, TN and TN:TP showed weak negative (R^2 < 0.50) relationship in the GRU, while in the GRM and GRD, the relationship was moderately strong positive (R^2 > 0.50 < 0.70). These conclusions meant that TP is the limiting factor in the Geum River watershed irrespective of the hydromorphological modifications by installed weirs. However, in the GRU, moderately negative links between TN and ambient ratios indicated lower nitrogen inputs as compared to the TP inflows from the upstream region of the Geum River watershed.

On the same model, we attempted to figure out the influence of powerful nutrient contributing factors in the production of Chl-a at the weir sites and river zones, and their illustrations are shown in Figs. 4 and 5. Chl-a datasets symbolized no associations with nutrients at the SW. At the same time, it displayed weak negative links with TN at BW and almost no relations to TP and ambient ratios (Fig. 4). At the GW, however, Chl-a exhibited negative approximation with TN and a very week positive connection with TP. However, we observed heterogenic interactions in the Geum River zones. For illustration, in GRU, weak positive (R^2 = 0.23) 0.50 < 0.70) while at GRM, weak negative (R^2 = 0.19) links between TN and Chl-a. In the GRU, Chl-a linked weak positively with TN:TP (R^2 = 0.36) while no significant relations at GRM and GRD.

On the other hand, Chl-a revealed a negative association with ambient ratios in three zones of the Geum River (Fig. 5). In an established P-limitation waterbody, the role of phosphorus loadings becomes exceptionally vital in the primary production regime. Our linear modelling approach further strengthened formerly reported results on TN, TP, and ambient ratios as well as the nutrient limitation benchmarks at the local and global scales. As a result, this established the crucial significance of TP for sustainable primary support to the production of sestonic Chl-a (An et al., 2013). The limiting nutrients could further be impacted by the variety of factors, for instance, turbidity, physical location, and land use pattern as well as the installed infrastructures (weirs) that could enhance the water residence time (WRT) and disrupt the light availability, hence all conjointly impact primary production (Adams et al., 1999; Schinegger et al., 2016; Atique et al., 2019).

3.4. Assessment of water pollution status

We applied a modified multimetric water pollution index (mmWPI) to characterize the chemical pollution status of the three weir sites and riverine zones. The computed scores helped to ascribe and conclude the overall chemical fitness of the flowing water at weir sites and river zones during 2010–2017 (Table 3). Composed of three principal categories (mmWPI), the nutrient regime (TN, TP, and TN:TP ambient ratios) was the most critical element of river water chemistry status that plays an essential role in the estimation of impending eutrophication events. According to the criteria of nitrogen, except SW (mesotrophic; TN = 1.5–3 mg/L), GW and BW classified as eutrophic (TN > 3 mg/L) while all riverine zones exhibited eutrophic state. Respectively, the TP level displayed all three weir sites and river zones in mesotrophic (TP = 30–100 μg/L) state, although TP manifested a gradual increment along the downstream regions. It is pertinent to mention that

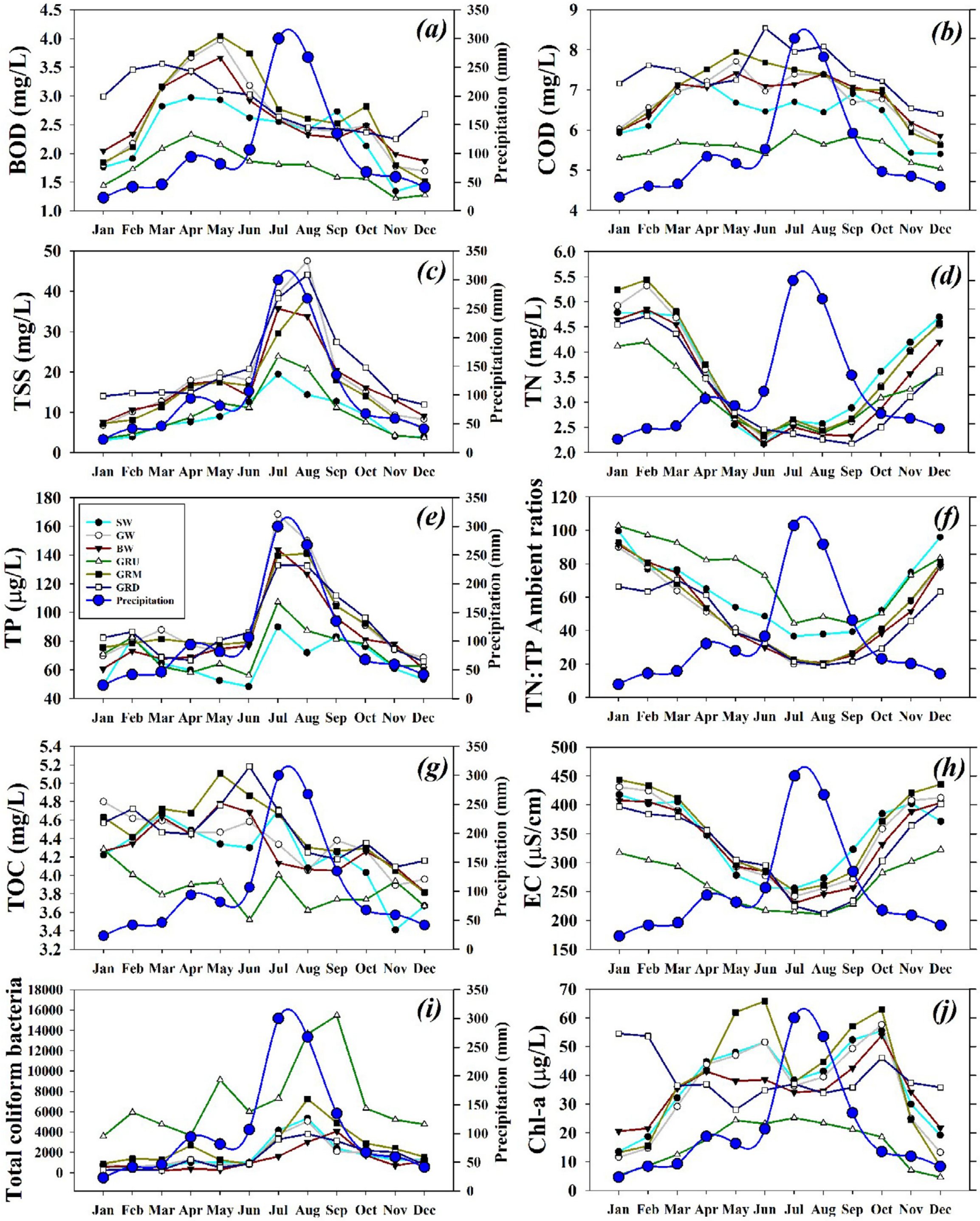

Fig. 2. Seasonal trends and comparative heterogeneities of significant physicochemical and nutrient contributing factors in relation to weir sites and riverine zones in Geum River and impact of monsoon precipitation 2010–2017. Figure legends are shown in figure (e) i.e. TP. *GW = Gongju Weir, SW = Sejong Weir, BW = Baekje Weir, GRU = Geum River Upstream, GRM = Geum River Midstream, GRD = Geum River Downstream.*

substantially comparable TP levels reflected the activity of wastewater treatment plants (WWTPs). Except for GW and GRD (mesotrophic), TN:TP ambient ratios presented mesotrophic state while other river zones and weir sites were in oligotrophic state based on TN:TP ambient ratios criteria of mmWPI. TN:TP ambient ratios periphrastically point out nutrient limitation scenarios of inland water bodies (Fujimoto and Sudo 1997; Kim and An, 2015). Therefore, declining ambient ratios allude to a higher nutrient pollution level. The organic matter, on the other hand, represented by BOD levels, revealed mild to severe chemical degradations due to the increasing inflow of biodegradable elements into the river waters. The ionic contents (TSS, EC) displayed slight deterioration in the GRU and SW. There could be several factors that could potentially manoeuvre the riverine water pollution, with the leading ones as longer WRT and abrupt water currents causing internal erosions. Both elements yet again allude to the critical role of weir installations along with the regular river flows that have shown tremendous potential to impact the water quality status and the sedimentation process. The primary production indicator, i.e., the mean

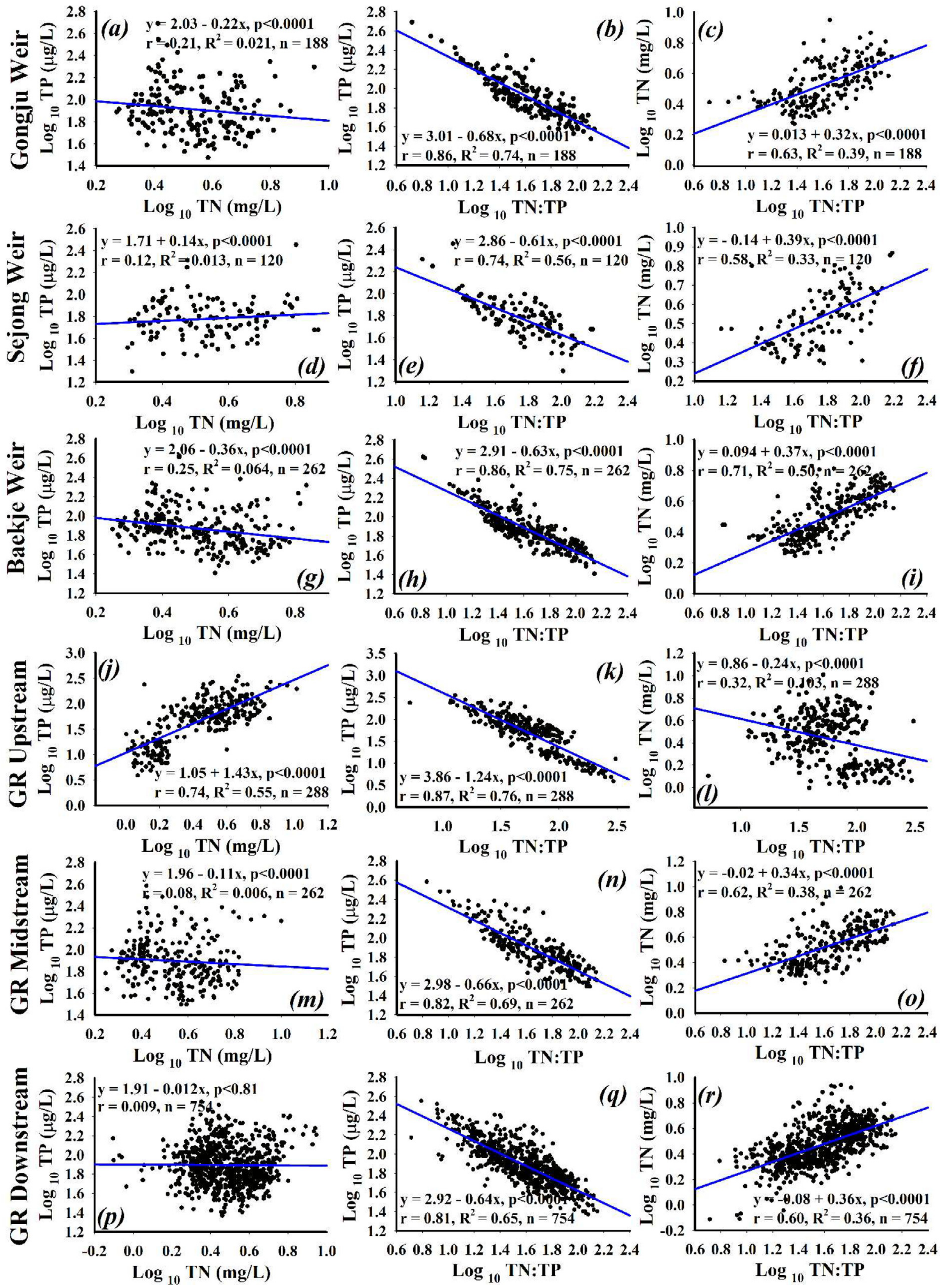

Fig. 3. Spatial regression analyses on TN, TP and their ambient ratios (TN:TP) at the weir sites and riverine zones in Geum River during 2010–2017.

sestonic Chl-a, indicated the imminent eutrophication at the weir sites and downstream riverine zones. After summation of the assigned mmWPI metric scores, the final categorization of the weir sites displayed SW in 'fair' (19), while BW (13) and GW (11) in the 'poor' and 'very poor' chemical health status, respectively. Furthermore, the GRU displayed as 'fair' (19), GRM as 'poor' (13), while GRD as 'very poor' (11) chemical health status. These findings are in approximation with the results of water chemistry analyses at the weir

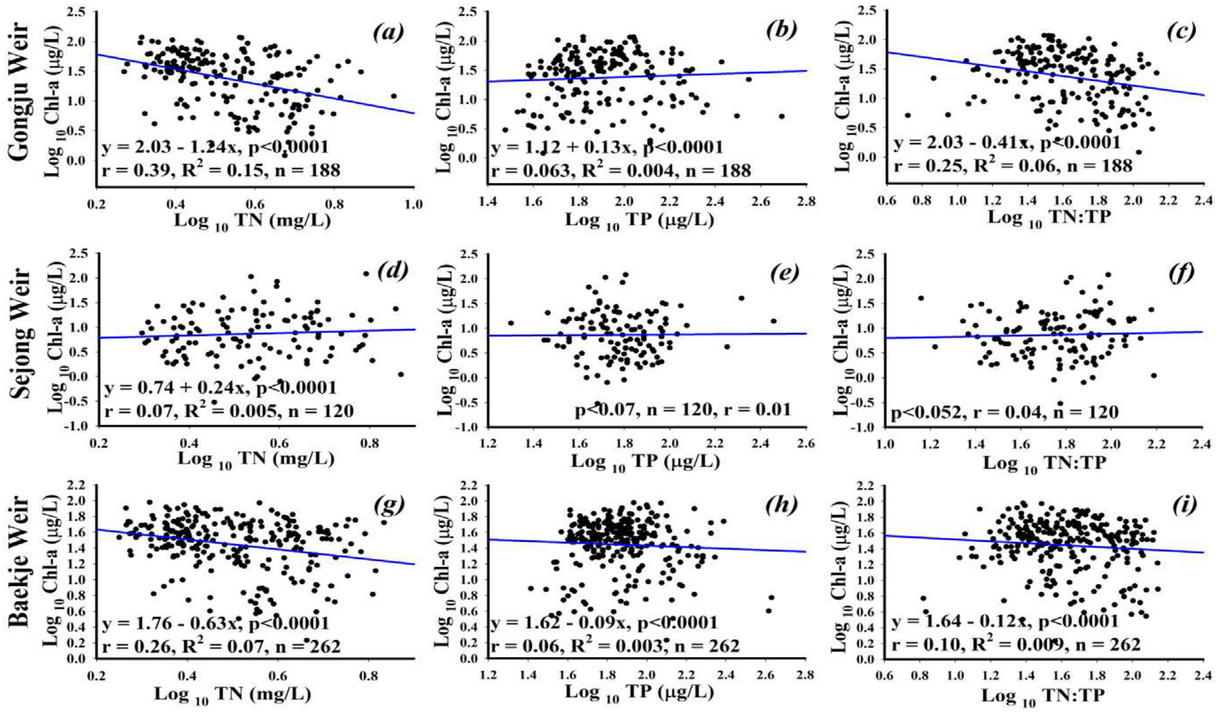

Fig. 4. Regression relationship between Chl-a, nutrients and their ambient ratios at weir sites during 2010–2017.

sites and river zones. Our conclusions bolster efficient and prudent management of the riverine water quality, primarily of those of critical importance in the modelling of mmWPI. The most significant water chemistry factors include the nutrient regime indicators, oxygen demanding chemical inflows, sedimentation, and riverbed erosion factors, as well as equally crucial, the primary productivity parameters (Sternecker et al., 2014; Lah et al., 2015; Ko et al., 2016).

3.5. Ecological health evaluation based on IBI

Site-based ecological health evaluations at each weir site and in the riverine zones revealed the preponderance of weir sites in a 'fair' - ecological health status (Fig. 6a). In the case of river study sites, the situation was akin to that of weir sites health status (Fig. 6b). The GW displayed all sites mean IBI score as 24 (fair) with middle section showing the one-time occurrence of excellent health status. The SW,

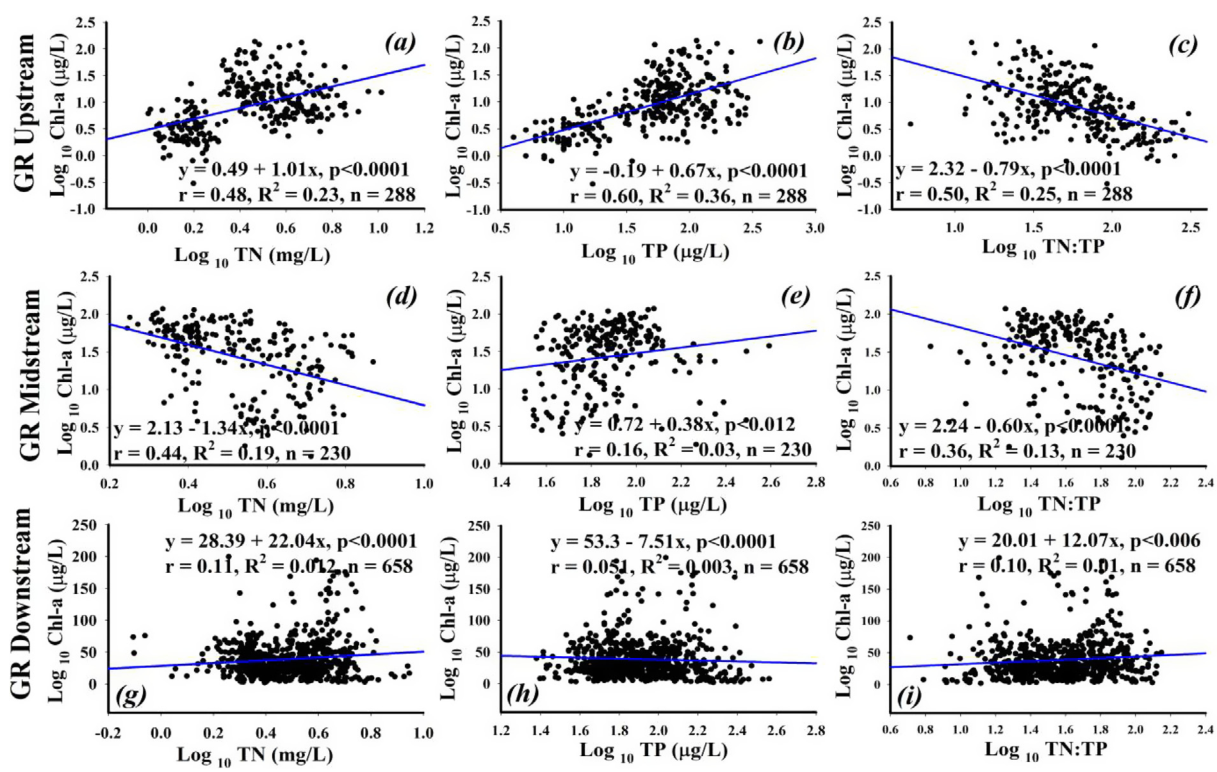

Fig. 5. Regression relationship between Chl-a, nutrients and their ambient ratios in river zones during 2010–2017.

Table 3
Water quality assessment based on modified-multimetric water pollution index (mmWPI) applied on Weirs and Geum River zones during 2010–2017. The WPI scores ascribed are shown in parenthesis.

Category	Model Metrics (M)	Weirs Gongju Weir	Sejong Weir	Baekje Weir	Geum River (GR) Upstream	Midstream	Downstream
Nutrient Regime	Total Nitrogen (mg/L)	(3.59 ± 1.21 (1)	2.30 ± 1.99 (3)	3.35 ± 1.09 (1)	3.14 ± 1.61 (1)	4.69 ± 6.33 (1)	3.19 ± 1.16 (1)
	Total Phosphorus (μg/L)	93.73 ± 58.23 (3)	65.93 ± 33.25 (3)	84.06 ± 48.06 (3)	72.73 ± 62.32 (3)	90.84 ± 52.38 (3)	90.46 ± 48.70 (3)
	TN:TP Ambient Ratios	49.66 ± 29.02 (3)	63.06 ± 28.94 (5)	50.45 ± 30.09 (5)	72.85 ± 54.30 (5)	51.26 ± 29.69 (5)	44.23 ± 25.42 (3)
Organic Matter	Biological Oxygen Demand (mg/L)	2.62 ± 1.10 (1)	2.30 ± 1.05 (3)	2.59 ± 0.88 (1)	1.74 ± 1.05 (3)	2.73 ± 0.90 (1)	2.87 ± 1.06 (1)
Ionic Content and Solids	Total Suspended Solids (mg/L)	18.80 ± 23.25 (1)	6.53 ± 7.05 (3)	17.28 ± 17.91 (1)	9.82 ± 14.43 (3)	14.63 ± 18.02 (1)	21.29 ± 22.51 (1)
	Electrical Conductivity (μS/cm)	341.71 ± 110.29 (1)	343.01 ± 110.43 (1)	331.77 ± 102.97 (1)	265.18 ± 123.14 (3)	354.24 ± 108.78 (1)	320.31 ± 110.83 (1)
Primary Production Indicator	Sestonic Chl-a (μg/L)	34.90 ± 26.90 (1)	47.32 ± 18.44 (1)	34.62 ± 19.55 (1)	15.93 ± 22.05 (1)	39.07 ± 27.81 (1)	38.97 ± 30.84 (1)
Total Score		11	19	13	19	13	11
WPI Criteria		Very Poor	Fair	Poor	Fair	Poor	Very Poor

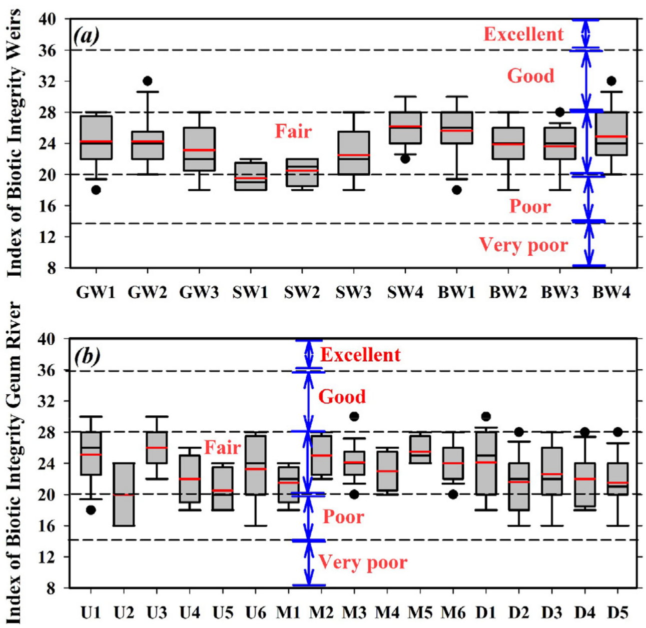

Fig. 6. Site-based ecological health assessments ascribed after the calculation of IBI scores at each site. (a) shows weir sites and (b) shows the river sites arranged in the order of upstream (U), midstream (M) and downstream (D) during 2010–2017. Redline denotes mean and dotted lines indicate the boundaries of biological health categories according to the criteria of IBI. The dots indicate outliers.

however, demonstrated 'poor to fair' ecological health from the upstream to downstream direction, indicating thereby aggregations of fish species in the downstream sites due to difficulty in crossing at the weir infrastructures. This is equivalent to the disruption of the potamodromous migration patterns in fish assemblages that are mostly for breeding and feeding purposes. The BW displayed mean IBI health scores around 'fair' (24) as well, with most of the GRD sites infrequent occurrence of excellent (32) ecological health status. Such an out of proportion environmental health outcomes indicated the accumulation of estuarine fish species as well because the estuarine region is the endpoint of the GRD. The mainstream GRU study sites showed the tendency of 'poor to fair' health status with discontinuous bearings of 'good' health status. In approximation with the weir sites, GRM sites indicated increasing IBI values along the riverine gradient. The GRD, although the mean score was in the range of 'fair' category, the trend, however, reported a decline in the ecological health along with the distant downstream sites. The 'poor to fair' ecological health prominence demands a serious consideration of all zones of Geum River as well as installed weirs.

Our findings provide useful insights into the absence of pristine inland ecosystems with a clear-cut indication of quick ecological degradation. The environmental health status revealed after the application of IBI redirected the impacts of rigorously deteriorating chemical health status at the weir sites and river zones corroborating to each other. The leading reasons of the declining ecological health status could be the substantial drop in the overall total number of native fish species (TNNFS), the total number of native individuals (TNNI) and reduction in sensitive species (SS). All these biological factors positively reflect upon an improving ecological health status (Dodds et al., 1998; Kim and An 2015; Kim et al., 2019). On the other hand, the trophic guild displayed alarming situation due to the affluence of omnivores and the increasing proportion of native insectivores that all over again reinforced the declining ecological health status (Konrad and Booth 2002; Baumgartner et al., 2014; Atique and An 2018).

3.6. Spatial dynamics of fish assemblages

We plotted all IBI metrics to take portraiture of the spatial variations of fish assemblages at weir sites and riverine zones (Fig. 7). The sensitive species (SS) and DELT metrics are not shown owing to the absence of SS in most of the study sites, while DELT characteristics were not observed in the sampled fish species. The total number of individuals (TNI) displayed spatial shifts at the weir sites, and river zones, with GW, mean TNI (458.15) as the highest while BW (357.97) and SW (211.5) in the next order. Among the river zones, GRM (86.08) displayed the highest TNI, while GRU (77.84) and the lowest in GRD (46.37). It is unambiguous to declare that TNI showed a gradual decline along the river gradient. However, at GW, the highest number of TNI in one sampling even reached 2081 fish individuals, while in a similar context at GRU, the first sampling event accounted for only 345 fish individuals (Fig. 7a). Such disparities provide an insight into the role of weir installation and impact on the aggregation of fishes near the weir sites.

One of the critical reasons for this vast accumulation of fish individuals could be the obstruction to the potamodromous migration of fish species and the disruption in the river continuum. Being a parallel measure, the total number of species (TNS) approximated the pattern of TNI at the weir sites and river zones. TNS exhibited a gradual decline along the river gradient (Fig. 7b). Riffle-benthic species (RBS) occurrence remained very low throughout the study duration, with SW as the

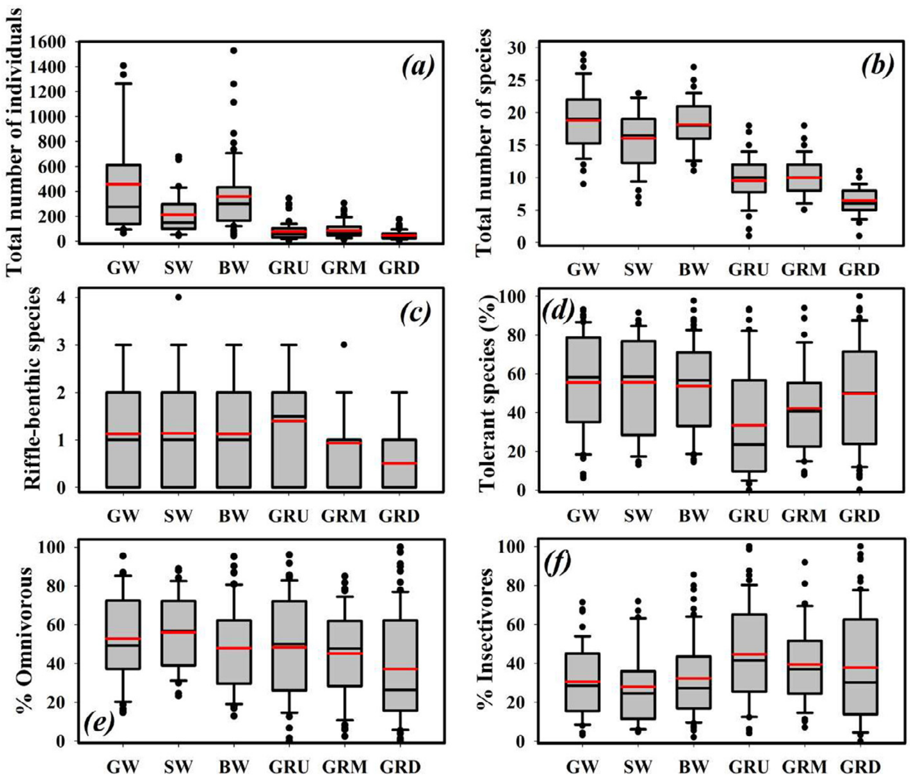

Fig. 7. Box plot depicts the spatial dynamics of fish assemblages extracted from the metrics of IBI at the weir sites and riverine zones of Geum River during 2010–2017. Redline denotes mean while dots indicate outliers. *GW = Gongju Weir, SW = Sejong Weir, BW = Baekje Weir, GRU = Geum River Upstream, GRM = Geum River Midstream, GRD = Geum River Downstream.*

most populated concerning RBS. In the tolerance guild (TS and SS), with nominal or no presence of SS, TS dynamics displayed an exciting picture. TS persisted almost the same proportion at the three weir sites indicating their preference to the installed infrastructures (Choi et al., 2011). At the same time, they manifested an increase from GRU to GRD in a balanced manner. Similar outcomes displayed by the deteriorating water quality from the upstream to downstream, indicating conceivable connections between TS and water quality degradations. The trophic guild revealed the highest percentage of omnivores (% O) in SW while a gradual decline in the mean rate of omnivores along the rover zones. The percent insectivores (% I) displayed a gradual decrease in the river zones while increased from the upstream weir sites to the downstream weirs. The absence of SS provided a piece of evidence that the Geum River water quality is subjected to advanced deterioration, as SS prefer to thrive relatively in the pristine waters (Extence et al., 2013). However, the intensity of water quality degradation is not inflicting any DELT abnormalities in fish individuals.

3.7. Fish composition and abundance analyses

We examined the fish composition and relative abundance of the sampled fish fauna at the weir sites and river zones, and the results based on each weir and river zone are presented in Table 4. The fish species are classified based on tolerance guild, feeding mode (trophic guild), and habitat preferences and shows the total number of individuals (TNI) and relative abundance (RA %). In total, 60 fish species (i.e. TNS) and 64,637 total fish individuals (i.e. TNI) were sampled during the whole study duration in the Geum River zones and weir sites. Detailed analysis based on each weir explicated that the highest number of fish species (55) and TNI (22907) were recorded at the BW followed by GW (TNS: 47; TNI: 21991) and SW (TNS: 43; TNI: 7614). On the contrary, the TNS and TNI dynamics in riverine zones exhibited a gradual decline along the river gradient, i.e. GRU to GRD. TNS and TNI at GRU were recorded as 47 and 4515, respectively, while at GRU, TNS and TNI samplings revealed 31 species and 3478 fish individuals. Squalidus japonicus coreanus is a tolerant fish species and is omnivorous, which was caught in the highest number with TNI 11,936 and 18.47% RA. Hemibarbus labeo and Erythroculter erythropterus appeared in 5981 and 5867 times (TNI) with RA % 9.25 and 9.08, respectively. Squalidus japonicus coreanus was the most abundant fish species at GW (TNI = 5912), BW (TNI = 4443), while Hemibarbus labeo was the most abundant fish species at SW (TNI = 964). In the case of Geum River zones, the most abundant fish species at GRU and GRM was Zacco platypus with TNI equal to 987 and 577, respectively, followed by Acheilognathus lanceolatus with TNI similar to 541 and Hemibarbus labeo with TNI of 431. In case if GRD, however, the highest TNI (568) was that of Microphysogobio jeoni followed by that of Opsarichthys uncirostris amurensis with the total individuals of 532. Interestingly, in all the weirs and riverine zones, the dominant fish assemblages in tolerance guild were TS followed by intermediate species (IS) while in the trophic guild were the omnivores (O) and insectivores (I). Out of the total 60 fish species observed, 23 fish species percent RA was < 0.1%, which indicated that these species are in the vulnerable state. In comparison, three out of these 23 fish species were sampled only one fish individual during the whole study duration. Therefore, these fish species may be likely to disappear from the Geum River watershed.

Another significant aspect revealed during this study convinced that extraordinarily higher abundance of some fish species at the weir sites revealed their affiliation with the installed weirs as well as disrupted river continuum. Other mentionable reasons could be the troubled habitat conditions and the deteriorating water quality that might have promoted specific new fish species recruitments from the surrounding areas. In contrast, some of the native fish fauna would have been forced to relocate from their preferred habitat after weir installations. Similarly, invasive and hazardous fish species Lepomis macrochirus (Bluegill) and Micropterus salmoides (Largemouth bass) were observed in higher numbers at the weir sites as compared to river zones (Kim et al., 2019). Such disturbance in fish assemblages are directly linked with alterations in streamflow, disturbed and modified feeding, spawning and shelter grounds, remodelling of instream covers, and microhabitat creation or shifts. All such transformations collectively

Table 4
Records of each fish species with details of about various guilds, total number of individuals, total number of species and relative abundance observed at the weir sites and riverine zones during 2010–2017.

Fish Species	Tol. G.	Tro. G.	Hab. G.	GW	SW	BW	GRU	GRM	GRD	TNI	RA (%)
Squalidus japonicus coreanus	TS	O		5912	780	4443	130	294	377	11,936	18.47
Hemibarbus labeo	TS	I		2593	964	1352	401	431	240	5981	9.25
Erythroculter erythropterus	TS	C		1756	767	3084	22	35	203	5867	9.08
Opsarichthys uncirostris amurensis	TS	C		2320	355	1674	121	416	532	5418	8.38
Zacco platypus	TS	O		1492	727	662	987	577	196	4641	7.18
Microphysogobio jeoni	IS	I		662	5	2888	2	333	568	4458	6.89
Pseudogobio esocinus	IS	I		947	590	1313	483	404	390	4127	6.38
Squalidus chankaensis tsuchigae	IS	O		853	210	1469	13	273	41	2859	4.42
Squalidus gracilis majimae	SS	O		1281	563	539	58	58	3	2502	3.87
Carassius auratus	TS	O		472	684	682	386	102	57	2383	3.69
Acheilognathus lanceolatus	IS	O		446	160	594	541	171	57	1969	3.05
Acanthorhodeus macropterus	IS	O		780	365	699	50	30	13	1937	2.99
Hemiculter eigenmanni	TS	O		179	65	1031	39	64	79	1457	2.25
Acanthorhodeus gracilis	IS	O		396	240	422	65	18	8	1149	1.78
Rhinogobius brunneus	IS	I	RB	105	101	385	159	180	138	1068	1.65
Squaliobarbus curriculus	IS	O		90	40	288	15	86	289	808	1.25
Pseudorasbora parva	TS	O		233	262	85	141	56	30	807	1.25
Micropterus salmoides	TS	C		128	61	127	97	189	97	699	1.08
Hemibarbus longirostris	IS	I		167	132	193	82	45	9	628	0.97
Tridentiger brevispinis	TS	I	RB	59	44	119	127	22	101	472	0.73
Lepomis macrochirus	TS	I		124	38	54	24	169	8	417	0.65
Sarcocheilichthys nigripinnis	IS	I		159	47	87	13	16	1	323	0.49
Microphysogobio yaluensis	IS	O	RB	165	65	56	16	9	5	316	0.49
Acheilognathus rhombeus	IS	O		109	85	54	11	5	0	264	0.41
Pungtungia herzi	IS	I		32	40	12	111	7	0	202	0.31
Carassius cuvieri	TS	O		84	31	63	5	3	0	186	0.29
Hypomesus nipponensis	IS	I		0	0	0	177	1	0	178	0.28
Sarcocheilichthys variegatus wakiyae	SS	I		70	9	62	8	13	0	162	0.25
Cyprinus carpio	TS	O		52	23	31	20	24	7	157	0.24
Abbottina rivularis	TS	O		43	45	42	1	9	0	140	0.22
Rhinogobius giurinus	TS	O		57	9	53	2	0	11	132	0.20
Gnathopogon strigatus	IS	I		16	40	9	53	10	0	128	0.19
Coilia nasus	IS	C		0	0	121	0	0	0	121	0.19
Acheilognathus yamatsutae	IS	O		13	0	13	52	4	0	82	0.13
Leiocassis nitidus	TS	I		21	2	49	0	0	0	72	0.11
Odontobutis interrupta	IS	C		30	15	23	0	0	0	68	0.11
Rhodeus notatus	IS	O		4	0	15	16	31	0	66	0.10
Silurus asotus	TS	C		38	11	5	4	0	0	58	0.09
Pseudobagrus fulvidraco	TS	I		7	7	22	2	3	5	46	0.07
Misgurnus mizolepis	TS	O		20	6	2	13	3	1	45	0.07
Channa argus	TS	C		7	5	28	2	1	0	43	0.07
Sniperca scherzeri	SS	C		17	3	11	7	3	0	41	0.06
Leiocassis ussuriensis	IS	I		22	6	10	0	0	1	39	0.06
Misgurnus anguillicaudatus	TS	O		10	3	4	18	3	1	39	0.06
Rhynchocypris oxycephalus	SS	I		0	0	1	0	21	0	22	0.03
Pseudobagrus koreanus	SS	I	RB	2	4	2	10	1	0	19	0.03
Oryzias sinensis	TS	O		0	3	9	2	0	1	15	0.02
Mugil cephalus	TS	H		0	0	5	0	0	9	14	0.02
Rhodeus uyekii	IS	O		7	0	6	0	1	0	14	0.02
Abbottina springeri	TS	O		6	2	2	1	0	0	11	0.02
Odontobutis platycephala	SS	C		2	0	1	7	1	0	11	0.02
Zacco koreanus	SS	I		0	0	0	11	0	0	11	0.02
Rhodeus ocellatus	IS	O		0	0	0	0	9	0	9	0.01
Coreoleuciscus splendidus	SS	I	RB	0	0	0	8	0	0	8	0.01
Gobiobotia nakdongensis	SS	I	RB	3	0	1	0	1	0	5	0.007
Cobitis lutheri	IS	I		0	0	2	0	0	0	2	0.003
Iksookimia choii	SS	I		0	0	0	2	0	0	2	0.003
Acheilognathus koreensis	IS	O		0	0	1	0	0	0	1	0.001
Coreoperca herzi	SS	C		0	0	1	0	0	0	1	0.001
Monopterus albus	TS	C		0	0	1	0	0	0	1	0.001
Total Number of Species (TNS)	47	43	55	47	44	31	60				
Total Number of Individuals (TNI)	21,991	7614	22,907	4515	4132	3478	64,637				

Tol. G. = Tolerance guild (TS = Tolerant species, IS = Intermediate species, SS = Sensitive species), Tro.G. = Trophic guild (O = Omnivore, I = Insectivore, C = Carnivore, H = Herbivore), Hab.G. = Habitat guild (RB = Riffle-benthic), TNI = Total number of individuals, RA (%) = Percent relative abundance, TNS = Total number of species, GW = Gongju Weir, SW = Sejong Weir, BW = Baekje Weir, GRU = Geum River Upstream, GRM = Geum River Midstream, GRD = Geum River Downstream,

cater to the needs of new species and compel exodus of the endemics (Paller et al., 2000; Richardson et al., 2011; Lee and An 2014; Kim et al., 2019).

3.8. Relationships between water chemistry and fish assemblages

Principal component analysis (PCA) yielded the water chemistry datasets, indices applied (mmWPI and mmIBI), and fish assemblages unfolding potential links among them at the weir sites and river zones

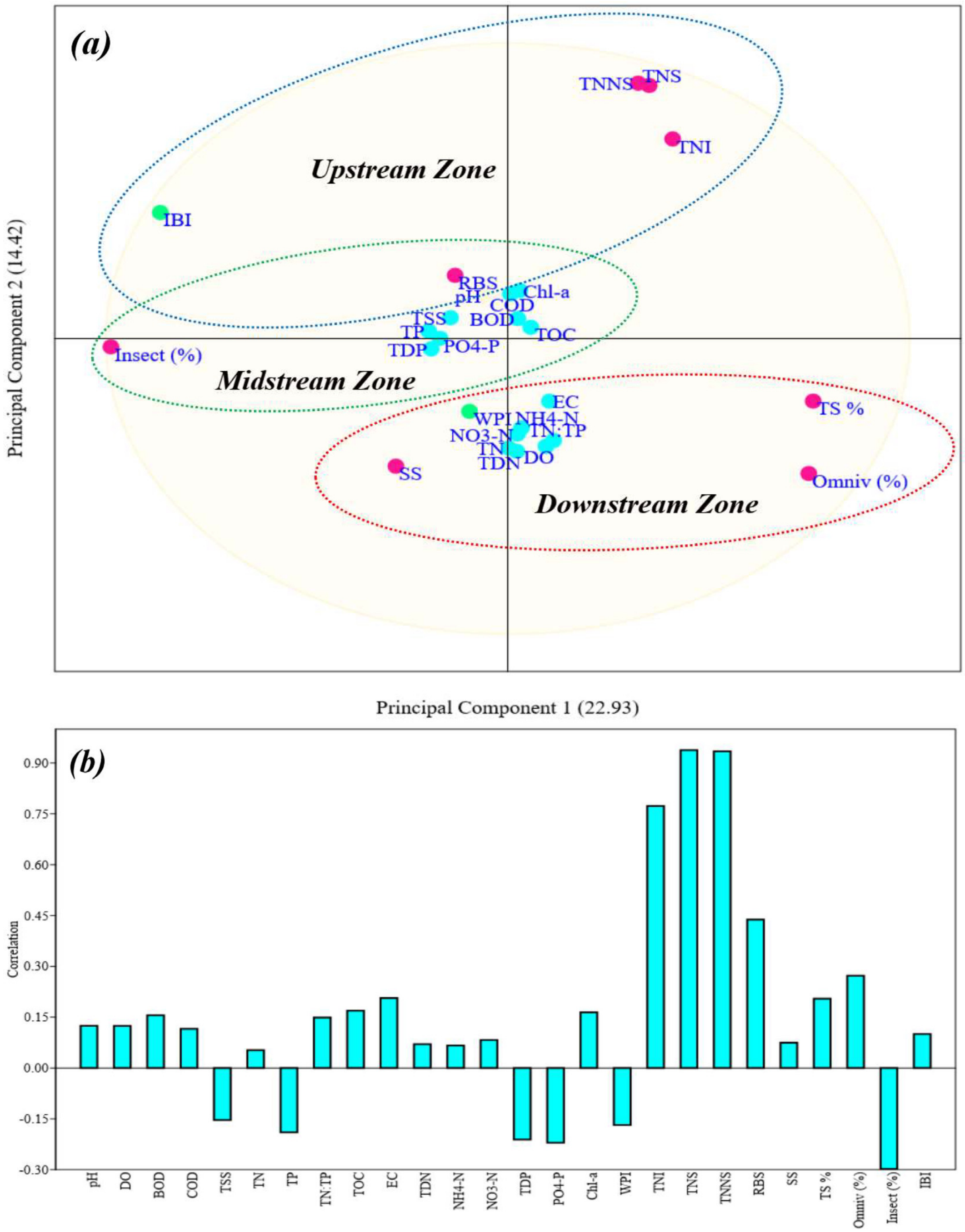

Fig. 8. PCA showing the settlement of water chemistry factors and fish assemblage indicators in three compartments of Geum River during 2010–2017. (a) shows the big plot, and (b) shows the Pearson's correlation. DO (Dissolved oxygen, mg/L), BOD (Biological oxygen demand, mg/L), COD (Chemical oxygen demand, mg/L). TSS (total suspended solids, mg/L), TN (Total nitrogen, mg/L), TP (Total phosphorus, μg/L), TOC (Total organic carbon, mg/L), EC (Electrical conductivity, μS/cm), TDN (Total dissolved nitrogen, mg/L), NH_4-N (Ammonia-nitrogen, mg/L), NO_3-N (Nitrate-nitrogen, mg/L), TDP (Total dissolved phosphorus, mg/L), PO_4-P (Phosphate-phosphorus, mg/L), Chl-a (Chlorophyll-a, μg/L), WPI (Water pollution index), TNI = Total number of individuals, TNS = Total number of species, TNNS = Total number of native species, RBS = Riffle-benthic species, SS = Sensitive species, TS % = Percent of tolerant species, Omniv % = Percent omnivores, Inset % = Percent insectivores, IBI = Index of biotic integrity.

(Fig. 8a, Table 5). Seven components of PCA yielded 81.80% of the cumulative variance in the data during 2010–2017, with 37.35% variance in the first two principal components (PC). We also showed the Pearson's correlation between the water chemistry factors and fish assemblages in PCA and the relationships illustrated in Fig. 8b. We used PCA to classify the tendencies and persistence among water quality parameters and fish communities at weirs and river zones, and the PCA displayed distinct zones of upstream, midstream, and downstream by classifying the settlement of dominant parameters along the river gradient. The arrangements of three riverine compartments in relation to the studied zones of river reflected the upstream zones dominated by the higher number of invidious (TNI) and species (TNS) along with the dominance of riffle-benthic species (RBS).

The midstream component was characterized by the negatively increasing percent insectivore species as well as adversely increasing TP, allied species of phosphorus, and TSS while positively settling Chl-a, BOD, COD, and TOC. The downstream zones, however, revealed the considerable influence of nitrogen yielding fertilizers from the

Table 5
PCA loading plot showing the first seven principal components while the used parameters are grouped on this basis of water chemistry and fish assemblages.

Categories	Parameters	PC 1	PC 2	PC 3	PC 4	PC 5	PC 6	PC 7
Water Chemistry	pH	0.12	0.13	0.06	−0.48	−0.30	0.03	0.14
	DO	0.12	−0.19	0.84	0.13	0.13	0.03	−0.04
	BOD	0.16	−0.02	0.16	−0.55	−0.34	0.09	0.34
	COD	0.12	0.00	−0.16	−0.58	−0.42	0.21	0.42
	TSS	−0.15	0.15	−0.65	0.25	0.06	0.19	0.11
	TN	0.05	−0.07	0.75	0.25	0.30	0.20	0.31
	TP	−0.19	0.22	−0.56	0.30	0.19	0.29	0.36
	TN:TP	0.15	−0.21	0.89	0.05	0.10	−0.08	−0.12
	TOC	0.17	−0.08	0.16	−0.50	−0.26	0.20	0.38
	EC	0.21	−0.16	0.75	−0.26	−0.07	0.05	0.06
	TDN	0.07	−0.10	0.78	0.26	0.30	0.18	0.27
	NH4-N	0.07	−0.11	0.53	0.24	0.21	0.24	0.30
	NO3-N	0.08	−0.08	0.71	0.24	0.31	0.04	0.06
	TDP	−0.21	0.19	−0.47	0.36	0.26	0.25	0.37
	PO4-P	−0.22	0.16	−0.60	0.34	0.18	0.18	0.25
	Chl-a	0.16	−0.01	0.01	−0.68	−0.48	0.02	0.26
	WPI	−0.17	0.04	−0.02	0.68	0.49	0.03	−0.16
Fish Assemblages	TNI	0.77	0.01	−0.03	−0.22	0.23	0.16	0.15
	TNS	0.94	0.16	−0.14	0.08	0.13	−0.02	0.00
	TNNS	0.93	0.19	−0.14	0.10	0.12	−0.04	0.00
	RBS	0.44	0.38	0.10	0.19	−0.44	−0.22	−0.34
	SS	0.07	0.32	0.12	0.32	−0.45	0.71	−0.16
	TS %	0.20	−0.65	−0.16	−0.36	0.28	0.29	−0.38
	Omniv. (%)	0.27	−0.60	−0.03	0.46	−0.37	−0.22	0.28
	Insect. (%)	−0.30	0.85	0.14	−0.19	0.12	−0.04	−0.03
	IBI	0.10	0.94	0.06	−0.04	0.12	−0.09	0.10
Summary	**Eigenvalue**	**36.79**	**23.14**	**20.66**	**17.46**	**14.58**	**9.71**	**8.88**
	% Variance	**22.93**	**14.42**	**12.88**	**10.88**	**9.09**	**6.05**	**5.54**
	% CV	**22.93**	**37.35**	**50.24**	**61.12**	**70.21**	**76.26**	**81.80**

DO (Dissolved oxygen, mg/L), BOD (Biological oxygen demand, mg/L), COD (Chemical oxygen demand, mg/L). TSS (total suspended solids, mg/L), TN (Total nitrogen, mg/L), TP (Total phosphorus, μg/L), TOC (Total organic carbon, mg/L), EC (Electrical conductivity, μS/cm), TDN (Total dissolved nitrogen, mg/L), NH_4-N (Ammonia-nitrogen, mg/L), NO_3-N (Nitrate-nitrogen, mg/L), TDP (Total dissolved phosphorus, mg/L), PO_4-P (Phosphate-phosphorus, mg/L), Chl-a (Chlorophyll-a, μg/L), WPI (Water pollution index), TNI = Total number of individuals, TNS = Total number of species, TNNS = Total number of native species, RBS = Riffle-benthic species, SS = Sensitive species, TS % = Percent of tolerant species, Omniv % = Percent omnivores, Inset % = Percent insectivores, IBI = Index of biotic integrity

agriculture pastures. It was further characterized by negatively increasing percent omnivorous and percent TS along with ionic contents. The mmWPI displayed a weak negative correlation with the majority of water quality factors except for TP and TSS, while it showed a weak negative relationship with IBI. Percent of insectivore fish species displayed negative links with abundance, TS, and percent omnivore species while showed a positive relationship with RBS. Evidently, from the settlement of water quality factors and fish assemblages, the ecological health of Geum River underwent drastic deteriorations from upstream to downstream with the leading reason of water quality degradation reinforced by weir installations by severely damaging the feeding, spawning and microhabitat grounds. The adverse abundance of TS and percent omnivores showed further worsening ecological health status (Ko et al., 2016).

3.9. Overall impacts of weir installation

Finally, we present a conceptual framework stipulating the unfavourable influences of weir installation on the riverine habitat, water quality, flow regime and fish assemblages (Fig. 9). The leading coincidental impacts of weirs and human restorations could be the improvised riffle, run and pool microhabitats, along with restricted or lost gravel substrates. Nevertheless, the unintended consequences of weir installations and restoration efforts are the resultant riffle and run microhabitats, as well as modified or diminished gravel substrates that are home to habitat-specific fish communities (Salant et al., 2012). On the reverse side, limited and local erosions at the incised plugs in streams may disturb the physical heterogeneity by inflated downstream fish abundance and diversity (Shields and Hoover, 1991). In some circumstances, however, enlarged pool area, as well as higher water volume, may not improve habitat diversity, or too many pools could lead to the loss of other varieties of microhabitat, i.e., riffles and run (Shields et al., 1998). Similarly, frequently occurring deeper pools might become detrimental to the ecosystem, if, the pools restore the disappearing riffles or run microhabitats, as those are significant for instream primary productivity (Shields et al., 1998).

Furthermore, the high-velocity water flow zones with free gravel substrates are more favourable to certain fish species for spawning purposes (Muhlfeld, 2002; Salant et al., 2012; Maceda-Veiga et al., 2017. Most of the Korean rivers, similar to the ones in other countries, are a mosaic of succeeding weir installations in short geographic ranges from the upstream to downstream zones. Therefore, it is imperative to specify the impacts of weir establishments on the riverine fish assemblages, habitat, water chemistry, and flow regime. For instance, the serial installation of weirs in the Geum River resulted in the decline of SS, RBS, TNS, endangered species, and overall value of the riverine fisheries. On the other hand, TNI, TS, IS, omnivorous species, predation and invasive species illustrated an increase. Similarly, flow regime and water quality were negatively impacted that concomitantly affected the fish assemblages mentioned above. Various modifications in the habitat quality eventually transform the riverine fish assemblages as well.

4. Conclusions and further studies

We presented the relationships between water chemistry, fish assemblages, index of biotic integrity (IBI), and modified multimetric water pollution index (mmWPI) at the weir sites and riverine zones in the Geum River watershed during 2010–2017. The long term data set used attested our hypothesis that the prominent water quality parameters indicated spatial and seasonal heterogeneities and indicated

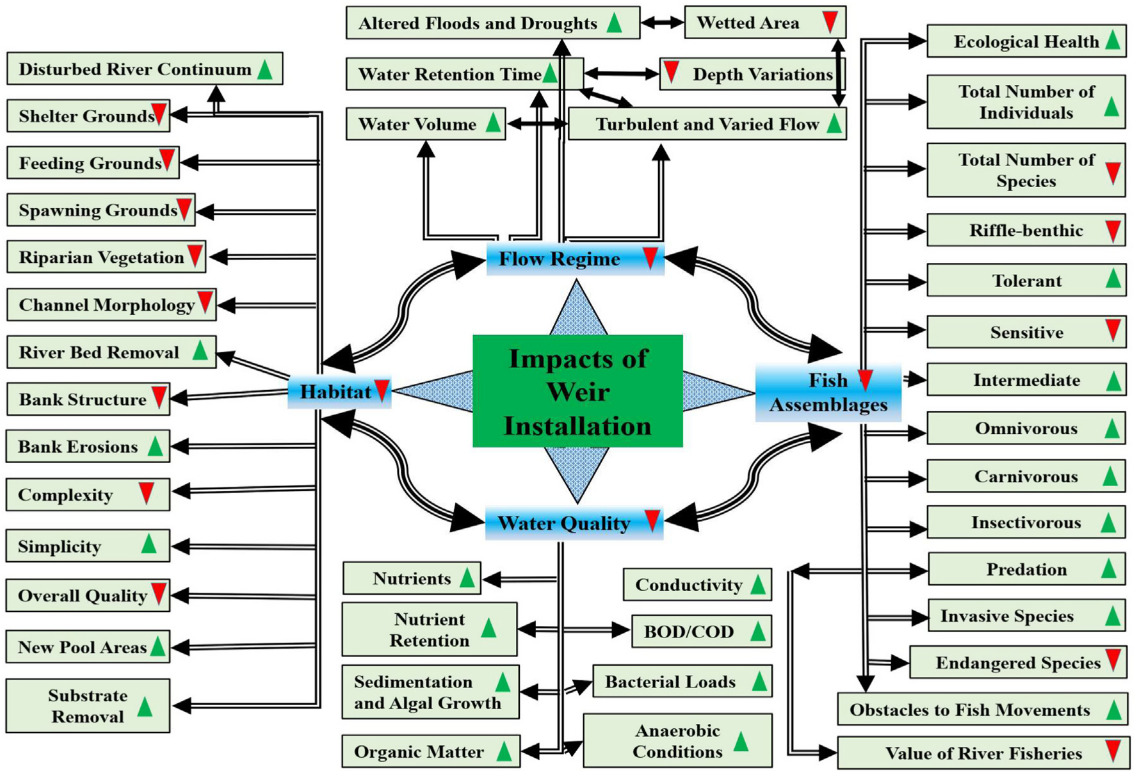

Fig. 9. Conceptual framework specifying the impacts of weir installation on riverine flow regime, habitat, water quality and fish assemblages. This is important to mention that most of these factors are strongly impacted by each other however, the links cannot be designated in a single framework. *The green triangle (upwards) indicate increase while red triangle (downwards) alludes to the decline in the respective ecological parameters.*

severely deteriorating water quality status from the upstream to downstream zones. The regression assessment further symbolized TP as the limiting nutrient for primary production. The mmWPI categorized the weir sites and riverine zones according to water pollution stats and displayed the weirs, and river zones were in 'fair to very poor' status. Significant water quality parameters (TP and TSS) approximated with the seasonal rainfall patterns. Most of the weir and river sites exhibited 'fair to poor' ecological health situation calculated after IBI. The total number of individuals, total number of species, and percent omnivorous species showed a gradual decline along the river gradient. The weir sites illustrated a profuse aggregation of fish species, especially tolerance and insectivorous species that indicated deteriorating habitat conditions and a disrupted river continuum. Squalidus japonicus coreanus and Hemibarbus labeo were the most abundant fish species sampled during the study duration.

Further, the set of data analyses used in this study could be successfully used in the future to study the impacts of weir installations on water chemistry and fish assemblages. However, future applications of disturbance theories to understand the implications of ecological disturbances on riverine ecosystems by using the low flows and drought dynamics may provide some useful insights. The river flow management in the context of human demands and climate variability and their impacts on aquatic biota may unveil some novel ecological perspectives in the future.

CRediT authorship contribution statement

Usman Atique: Conceptualization, Methodology, Formal analysis, Investigation, Data curation, Writing - original draft, Visualization, Writing - review & editing. **Seokcheol Kwon:** Formal analysis, Resources, Data curation. **Kwang-Guk An:** Methodology, Validation, Resources, Supervision, Project administration, Funding acquisition.

Declaration of Competing Interest

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

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