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Original article

Spatio-temporal characterization of nutrient and organic pollution along with nutrient-chlorophyll-a dynamics in the Geum River

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ABSTRACT

River water pollution is one of the biggest environmental challenges in the world. Therefore, it is imperative to assess the spatial and temporal variability of surface water quality to manage water resources from pollution. This study aimed to identify spatio-temporal variations of Geum River surface water quality and the factors that influence it. Summer monsoon, land-use land-cover (LULC), and weirs are dominant factors determining the dynamics of river water quality. Empirical analysis showed that total phosphorus (TP), total nitrogen (TN), biological oxygen demand (BOD), and chemical oxygen demand (COD) had positive linear functional relations with the agricultural and built-up cover but negative linear relations with forest cover. The results showed that the total suspended solids (TSS), chlorophyll-a (CHL-a), TP, and COD levels were higher in the summer than in any other season. On the other hand, total nitrogen (TN) and electrical conductivity (EC) levels were lower during summer in the river due to the dilution effect. Pollutant-transport theory shows that TSS acts as a TP carrier (R^2 = 0.83, $p < 0.001$). The empirical model suggested that TP (R^2 = 0.76, $p < 0.001$) was the better predictor for CHL-a compared to TN (R^2 = 0.13, $p < 0.001$) as well as showed strong P-limitation based on TN:TP ratios. The high average WQI values of the Geum River (except for S01 and S02) show a higher pollution level, indicating its unsuitability for drinking, irrigation, and industrial usage. Our results suggest that industrial and domestic sewage treatment and agricultural diffuse pollution control could improve the Geum river water quality.

1. Introduction

Rivers provide fresh water for agriculture, industry, and drinking supplies, aid in navigation and hydropower, and offer various habitats for aquatic plants and animals (Liu et al., 2016; Varol et al., 2012). However, natural factors (climate and topography) and anthropogenic activities can affect river water quality. Anthropogenic activities such as channelization, damming, and discharging industrial waste can affect the river ecosystems in structural and functional dimensions that conciliate its benefits and ecosystem services (Lopez-Lopez and Sedeno-Dıaz, 2015). As a result, rivers are among the world's most endangered and threatened ecosystems. Thus, water quality assessment is a significant aspect of river management worldwide. The acts and techniques for enhancing surface water quality in North America began in the early 1970s, followed by Europe and China in the 2000s and 2009s (Hawkins, 2015; Hering et al., 2010; Liu et al., 2016). In 1989, the Republic of Korea enacted the "Comprehensive Measures for Supplying Clean Water" act, with the prime objective of reducing major pollutants (TP, TN, BOD) from surface waters (MOE, 2015). Considering the multifaceted discrepancy in water quality over time and space, it is essential to have two types of information in order to manage river water quality effectively: (a) spatial and temporal characterization of the pollutants and (b) information about the driving factors regulating water quality (Liu et al., 2016; Varol et al., 2012).

Previous research has revealed that rainfall and LULC are dominant factors determining the dynamics of river water quality (Jin et al., 2020; Mamun et al., 2021). Heavy rainfall caused by Asian monsoons alters the flux of pollution inputs from the adjacent catchment to the river ecosystems (Jin et al., 2020). Earlier studies

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have also indicated that rivers with significant agricultural and urban land cover have higher nutrient and organic loads than rivers with natural forest and wetland cover (Kim et al., 2007; Mamun et al., 2021). However, South Korea's topographical circumstances are fragile due to its hilly terrain, which accounts for 65 percent of its land area and complicates water management (Jin et al., 2020). Additionally, the simultaneous consequences of excessive human usage of rivers and monsoon climate intensified river pollution. Therefore, the "Four Major Rivers Restoration Project (FMRRP)" was launched to control flooding, protect water resources, and manage water quality by constructing 16 weirs in the Han, the Nakdong, the Geum, and the Yeongsan Rivers (Lah et al., 2015). These weirs have altered the river ecosystem's functioning, extended the water residence time, and significantly impacted river water quality (Lah et al., 2015; Shim et al., 2018).

The Geum River is one of Korea's four major rivers and serves as a source of drinking, irrigation, and industrial water, tourist attractions, and habitats for aquatic organisms (Shim et al., 2018). It has suffered from intensive land usage, fast population growth, and continual development (Lah et al., 2015). It passes through Daejeon Metropolitan City and Sejong, Gongju, Buyeo, Nonsan, and Iksan City. Previous studies on the Geum River reported severe environmental issues like increased algal bloom, sediment deposition, and fish kills (Atique et al., 2020; Shim et al., 2018). In order to solve these problems, it is essential to understand the effects of monsoon, weirs, and land use on nutrients, organic matters, suspended solids, and algal chlorophyll. Moreover, understanding the relationship between nutrient content and algal biomass is critical for managing river eutrophication and defining the river's trophic condition (Dodds et al., 2002). Eutrophication in freshwater reservoirs and lakes has been successfully addressed using empirical analyses that relate algal biomass to the water column nutrients (Maberly et al., 2002; Mamun et al., 2020; Smith and Smith, 1985). The development of similar empirical models for rivers is a pressing need for providing an objective framework for river water quality management, as these models can predict key ecosystem features that are vital for the structure and function of lotic food webs (Dodds et al., 2002).

That is why the present study intended to clarify links between nutrient concentrations and algal biomass and identify the influence of LULC and summer monsoon on nutrients, organic matters, suspended solids, algal chlorophyll, and ionic concentration. This study also characterizes the spatio-temporal variations of river water quality.

2. Materials and methods

2.1. Study area

The Geum River is Korea's third-largest river system, flowing into the Yellow Sea. The river has a total length of 401 km and a catchment area of 9,866 km^2 (Shim et al., 2018). In the upper part of the watershed, the rivers flow through cities and are the primary source of nutrients and organic pollutants. Later, it flows through Nonsan and Iksan city, the most significant sources of nutrients and organic matters, from paddy fields and livestock farming (Fig. 1). Therefore, urbanization and intensive farming could affect the Geum River water quality. The Sejong, Gongju, and Baekje weirs were built in the Geum River to manage flooding and refurbish ecologically degraded areas as part of the FMRRP (2009–2012) (Lah et al., 2015). However, shortly after the construction of the weirs, the river faced severe algal bloom, and many experts and environmentalists in Korea feel that the weirs are to blame for stagnant water and over algal growth (Park, 2012). The climate of the studied area is temperate, with four distinct seasons (Spring, Summer, Fall, and Winter). The average rainfall was 1194 mm in the Geum River basin area during the study period, and approximately 60 % of the rainfall occurred during the summer monsoon (Fig. S1; supplementary file).

2.2. Analysis of water quality parameters and LULC

The Korean Ministry of Environment (MOE) collects monthly surface water quality data as part of a nationwide ecological health

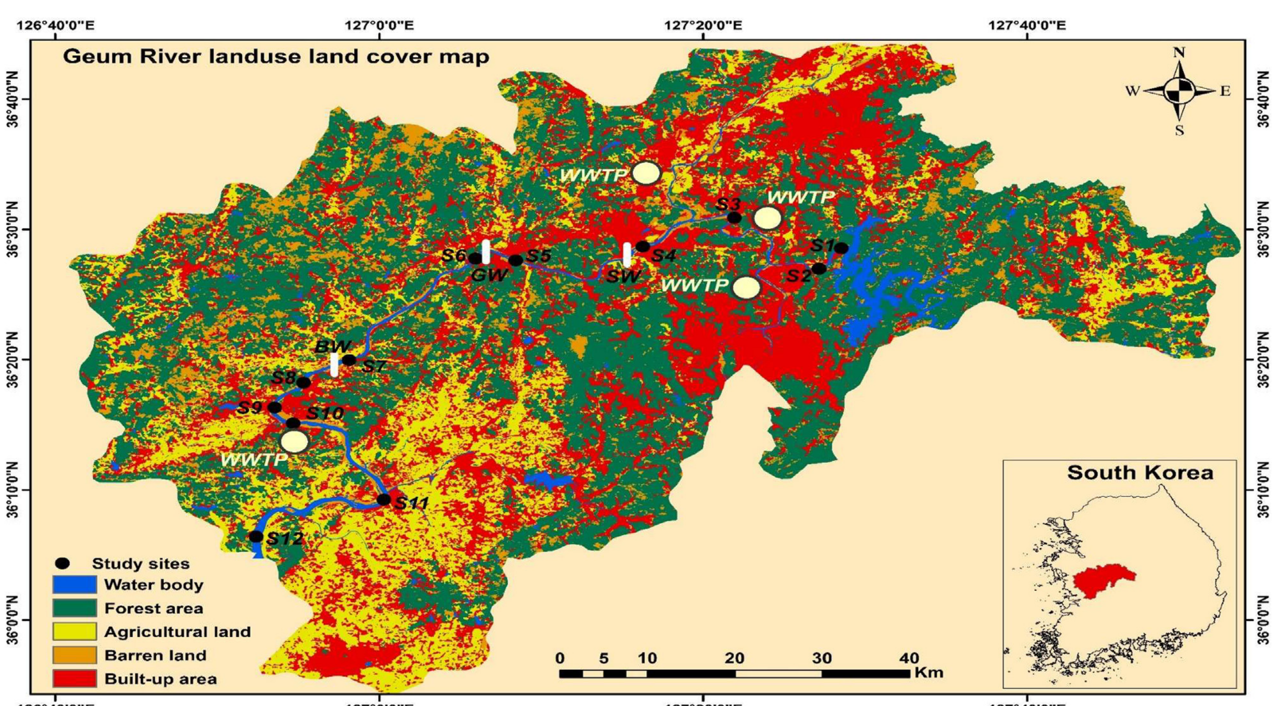

Fig. 1. Map showing the sampling sites in the main stream of Geum River. SW: Sejong Weir, GW: Gongju Weir, BW: Baekje Weir and WWTP: waste water treatment plant.

study. We compiled water quality data from MOE Water Information Network (available online: https://water.nier.go.kr (accessed on 05 January 2022). We investigated nine water quality parameters at 12 selected sites in the mainstream of Geum River during 2013–2020. A portable YSI Sonde Model 6600 multiparameter analyzer was used onsite to measure WT, EC, and DO directly. The sampling, preservation, and analytical procedures for TSS, COD, BOD, TP, TN, and CHL-a, were conducted following MOE-approved techniques (MOE, 2000). LULC data were obtained from ESRI 2020 global land cover data (Karra et al., 2021).

2.3. Biodegradability index and trophic state classification

The biodegradability index was determined by dividing BOD by COD. It was categorized as having a BOD/COD ratio of 0.4, indicating a high degree of degradability; 0.2–0.4, indicating a moderate degree of degradability; and 0.2, indicating a low degree of degradability (Lai et al., 2011). The TP, TN, and CHL-a concentrations were used to classify the Geum River's trophic status (Dodds et al., 1998).

2.4. Calculation of WQI in Geum River

The WQI was calculated using all water quality variables (excluding WT) by the weighted arithmetic index approach (Brown et al., 1972).

Step 1: Calculate the unit weight factors for each water quality variable by the following formula:

$Wg = K/Sg$; where, $K = 1/\sum 1/Sg$ and Sg = Standard desirable value of the gth parameters. On Summation of all selected parameters unit weight factors, Wg = 1 (Unity).

Step 2: Calculate the sub-index (Qg) value using the following formula:

$Qg = (Vg-Vo)/(Sg-Vo)*100$. Where, Vg = Mean concentration of the gth parameters; Sg = Standard desirable value of the gth parameters; Vo = actual values of the parameters in pure water (generally Vo = 0, for most parameters except for DO = 14.6).

Step 3: Combining Step 1 and 2, WQI is calculated as follows: overall $WQI = \sum WgQg/\sum Wg$.

The water quality status and possible water usage of Geum River on the basis of WQI value are shown in the Supplementary File (Table S1) (Brown et al., 1972).

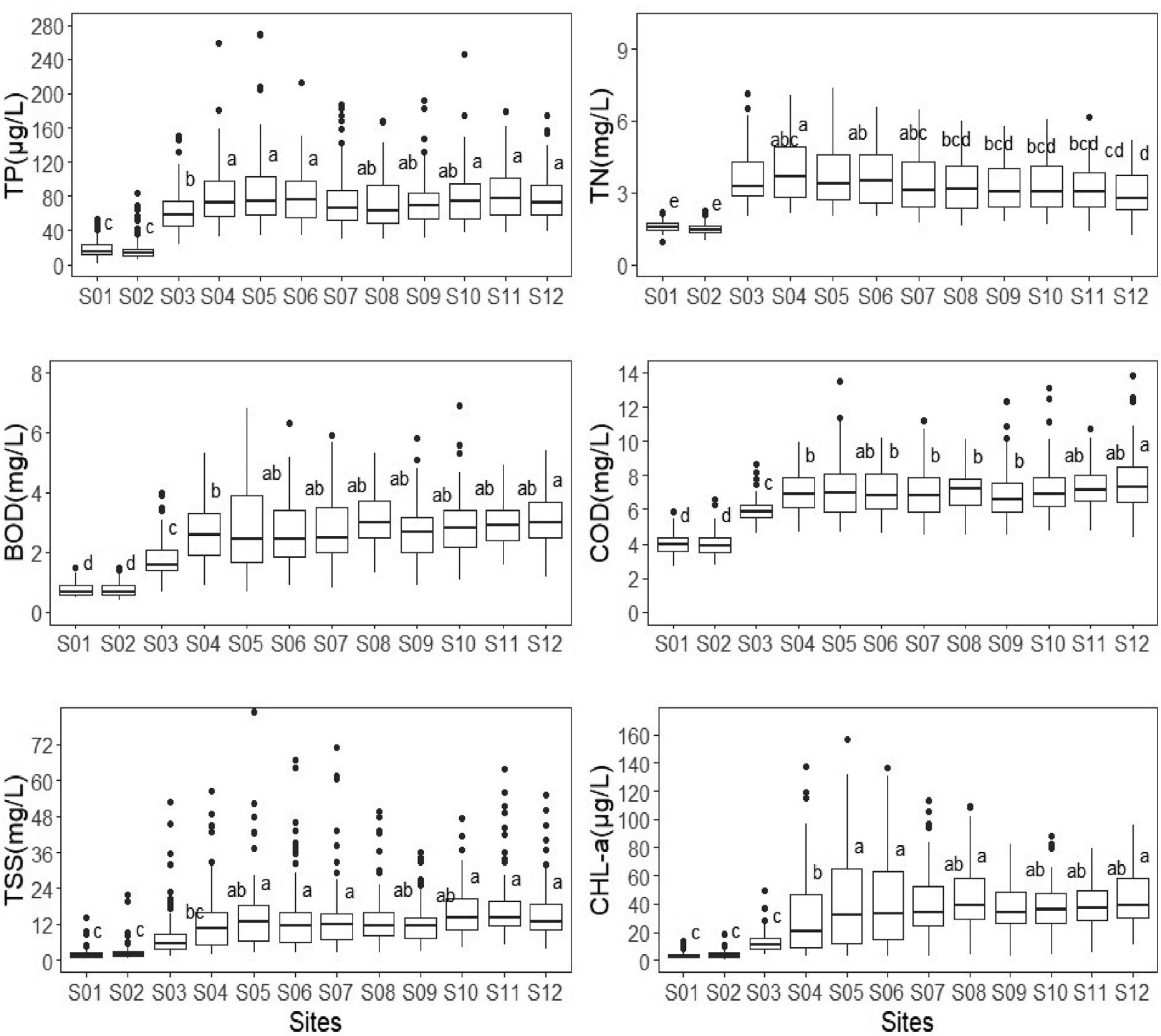

Fig. 2. Variation in nutrients (TP: total phosphorus, TN: total nitrogen), organic matters (BOD: biological oxygen demand, COD: chemical oxygen demand), suspended solids (TSS: total suspended solids), and algal chlorophyll (CHL-a: chlorophyll-a) based on sites in the Geum River.

2.5. Statistical analysis

Water quality parameters were $\log_{10}$ converted to escalate the data normality prior to conducting empirical analysis. SigmaPlot software was used to analyze regression and create empirical models to study the causal links between water quality factors and LULC data. Box plots with ANOVA and Tukey's test were used to visualize the spatial and seasonal variations of water quality variables in the Geum River using R version 4.1.1. The letters "a," "b," "c," and "d" in the box plot are derived from the *p*-value and are assigned according to two simple rules: the highest mean receives the letter "a," and means with no significant difference receive the same letter.

3. Results

3.1. Spatial variation of water quality parameters

Nutrients (TP, TN), organic matters (BOD, COD), suspended solids (TSS), and algal chlorophyll varied significantly from S01-S12 (Fig. 2). The mean TP varied from 18.4 to 85.5 μg/L among sites S01-S12 in the Geum River. Sites S05 showed the highest TP concentration (85.5 μg/L) while the lowest TP level was in S01 and S02 (18.42 μg/L, 18.47 μg/L). It was noticeable that TN, BOD, COD, TSS, and CHL-a were consistently lower in S01 and S02 than other sites. Dodds et al. (1998) proposed that TP levels greater than 75 μg/L indicate eutrophic rivers. Average TP concentrations above 75 μg/L were found in sites S05, S11, S06, S10, S04, S12, S07. Mean TN values ranged from 1.48 to 3.87 mg/L among sites. The highest value of TN was observed in site S04 (3.87 mg/L). Dodds et al. (1998) suggested that mean TN concentration greater than 1.5 mg/L indicate eutrophic rivers. The average TN level was above 1.5 in all sites except S02. High BOD and COD levels point out organic matter pollution in the rivers. The average BOD level ranged from 0.76 to 3.13 mg/L in the Geum River, and the highest was observed in S12. The COD level above 7 mg/L in water can only be used for industrial purposes (MOE, 2015). The mean COD level above 7 mg/L was found in sites S12, S10, S11, S05, S08, S06. The TSS concentration in the river is a result of natural erosion and sediment transport processes (Shim et al., 2018). The river found the highest mean TSS level in S11 (18.7 mg/L). CHL-a is the primary parameter utilized in eutrophication management in aquatic environments (Dodds et al., 1998). Mean CHL-a varied from 3.75 to 46 μg/L in the river. The highest CHL-a was found at site S12

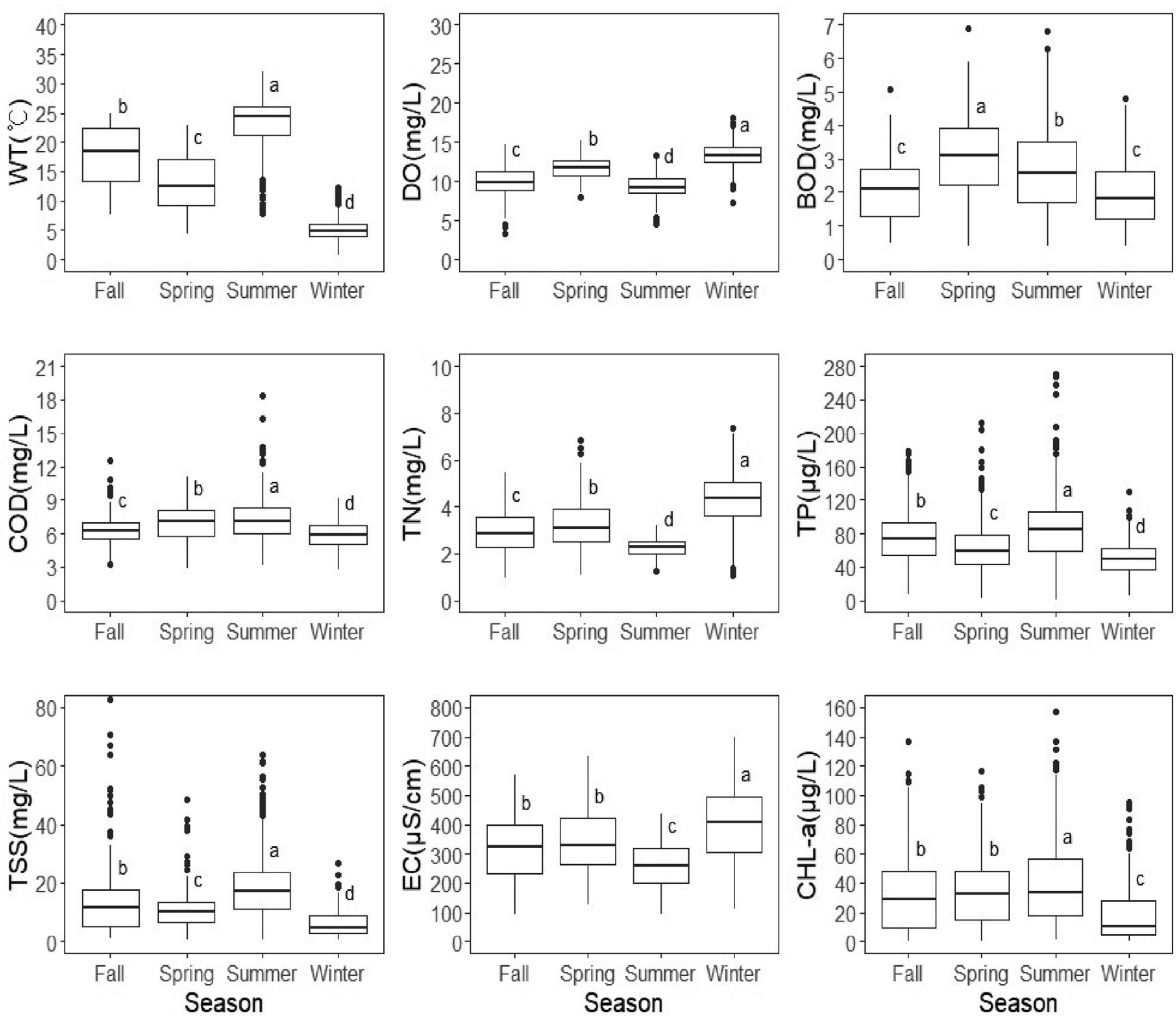

Fig. 3. Variation in water temperature (WT), dissolved oxygen (DO), nutrients (TP: total phosphorus, TN: total nitrogen), organic matters (BOD: biological oxygen demand, COD: chemical oxygen demand), suspended solids (TSS: total suspended solids), electrical conductivity (EC) and algal chlorophyll (CHL-a: chlorophyll-a) based on the season (Spring: Mar-May, Summer: Jun-Aug, Fall: Sep-Nov, Winter: Dec-Feb) in the Geum River.

(46 μg/L). CHL-a concentrations above 30 μg/L are considered eutrophic by Dodds et al. (1998). The average CHL-a level was higher than 30 μg/L in all sites except S01, S02, and S03.

3.2. Temporal variations of water quality variables

The concentrations of WT, DO, BOD, COD, TN, TP, TSS, EC, and CHL-a were significantly varied in the river based on the season (Fig. 3). The highest average WT was observed during summer (23.3℃). DO levels in the river were relatively low in summer (9.31 mg/L) and high in winter (13.3 mg/L) due to seasonality effects. Concentrations of TN (2.24 mg/L) and EC (258μS/cm) were in lower concentrations during summer than any other season due to the dilution effect. The average BOD level was higher during spring due to the low river flow. The mean COD, TSS, and TP levels were higher during summer than in other seasons due to the high flow of water in the river. The CHL-a level is also higher during the summer season.

3.3. Biodegradability index and trophic state classification

The highest BOD and COD ratios were found during the spring season, indicating more degradable matter in the river (Fig. S2; supplementary file). The lowest BOD:COD level was observed during all the seasons in the S01 and S02. The trophic state condition in the river was assessed based on TN, TP, and CHL-a levels (Fig. 4). The river was in a eutrophic state from S03 to S12 during all the seasons based on TN concentration, indicating nitrogen-rich systems. Throughout the study period, the river showed a eutrophic state during summer and fall from S04 to S12, while it was a mesotrophic state during winter based on TP level. The CHL-a level indicated that the river was in eutrophic conditions from S04 to S12 during spring, summer, and fall. On the other hand, it showed olig-

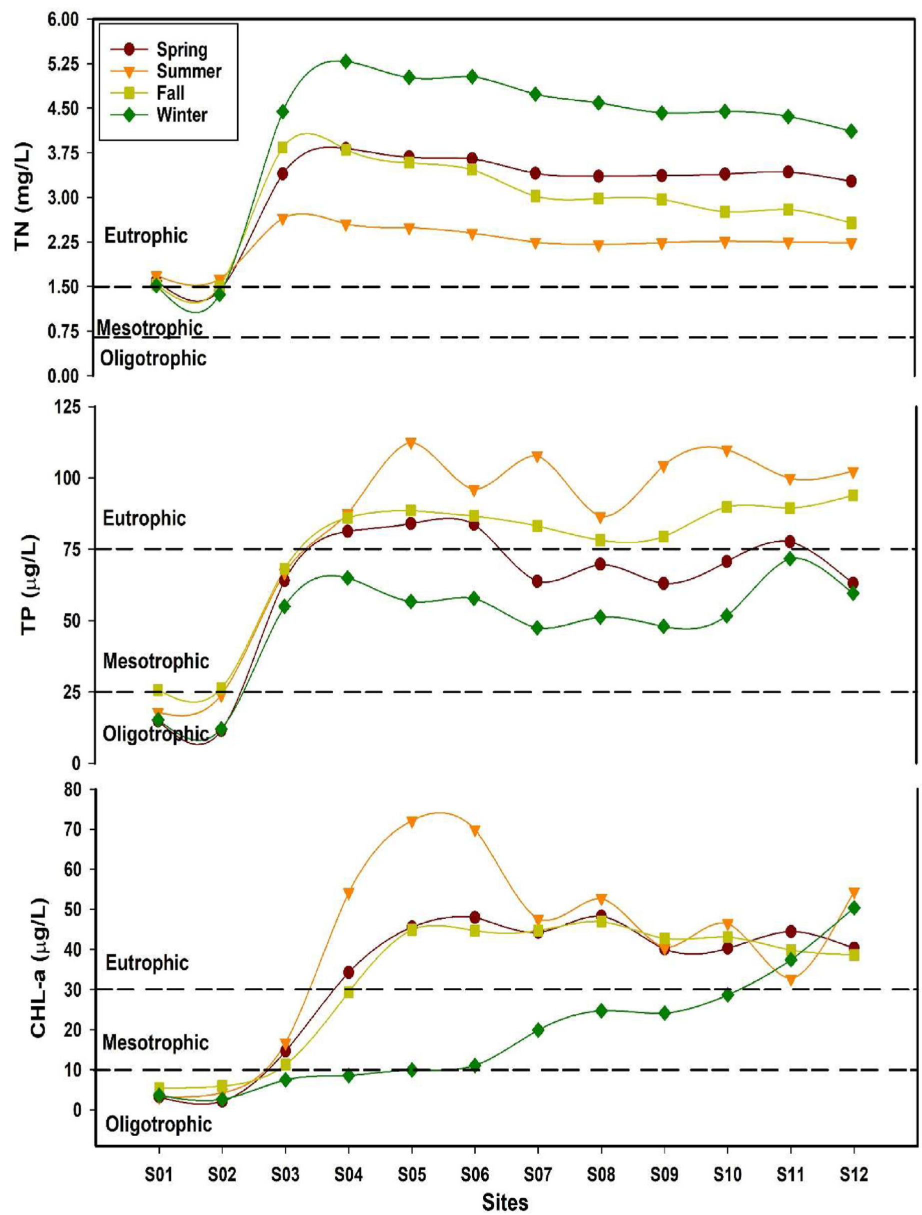

Fig. 4. Trophic state classification of Geum River based on nutrients (TP: total phosphorus, TN: total nitrogen) and algal chlorophyll (CHL-a (Spring: Mar-May, Summer: Jun-Aug, Fall: Sep-Nov, Winter: Dec-Feb).

otrophic to mesotrophic states from S04 to S10 and then displayed eutrophic states in S11 and S12 during winter.

3.4. Relations among LULC with nutrients and organic matters

Regression analysis evaluating the relations among LULC with nutrients and organic matters indicated a distinct impact of land-use land-cover on TP, TN, BOD, and COD in the Geum River basin (Fig. 5). Agricultural and built-up area coverage positively affected TP, TN, BOD, and COD, but forest coverage had a negative effect. Agricultural coverage was significantly correlated with BOD but not with TP, TN, and COD. The built-up area significantly affected the TP and TN levels but not BOD and COD. The TP, TN, BOD, and COD concentrations decreased dramatically as forest cover increased.

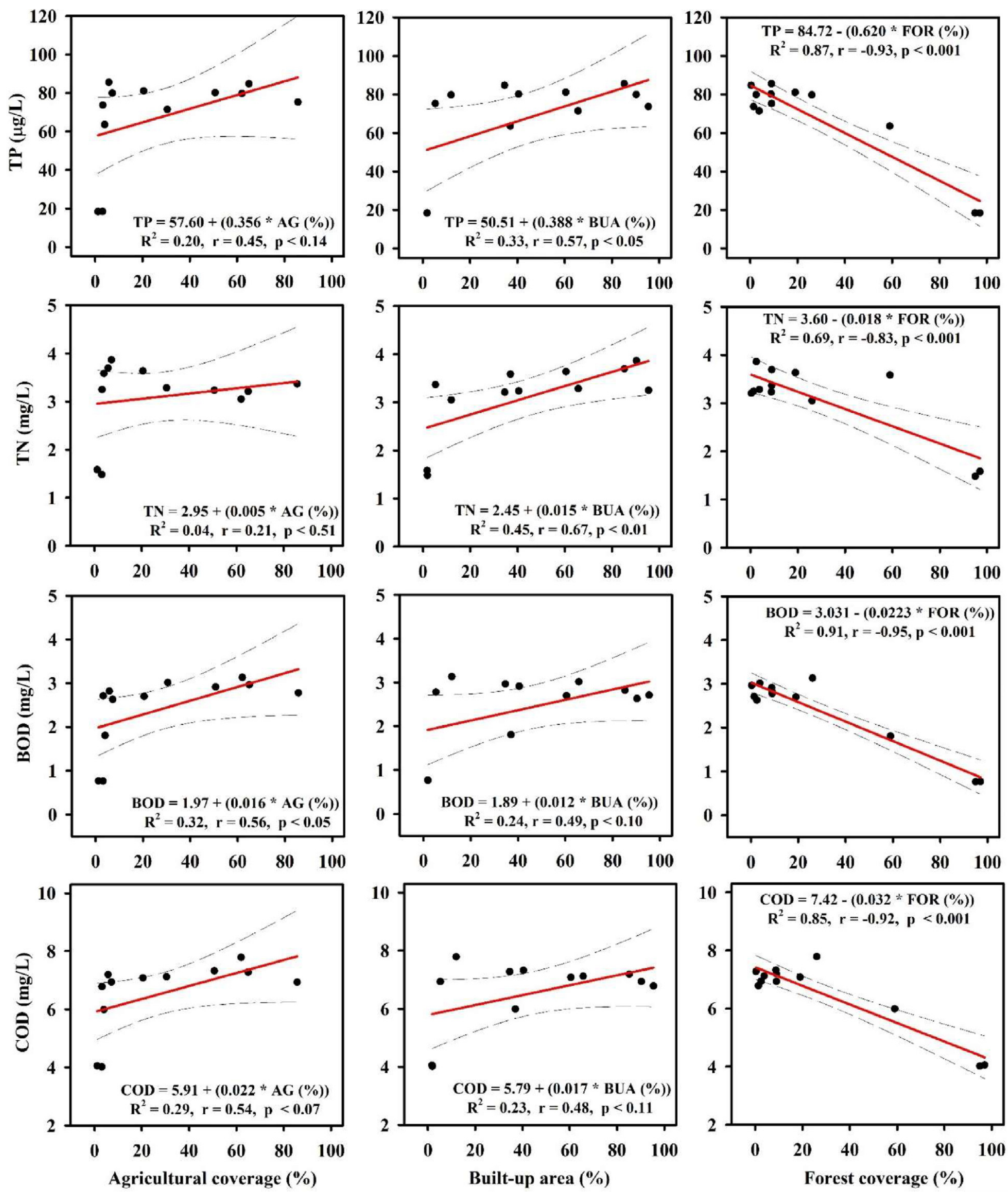

Fig. 5. Relationship among land cover with nutrients (TP: total phosphorus, TN: total nitrogen), and organic matters (BOD: biological oxygen demand, COD: chemical oxygen demand).

3.5. Suspended solids, nutrients, and algal chlorophyll dynamics

Regression analysis was used to elucidate the interaction effects between TSS, TP, and TN (Fig. S3; supplementary file). The present study suggests that TSS is a better predictor for TP than TN in the Geum River. The algal chlorophyll-a level is highly regulated by TP and TN and depends on the Geum River seasonality (Fig. 6). TP highly regulates the CHL-a level than TN during winter, spring,

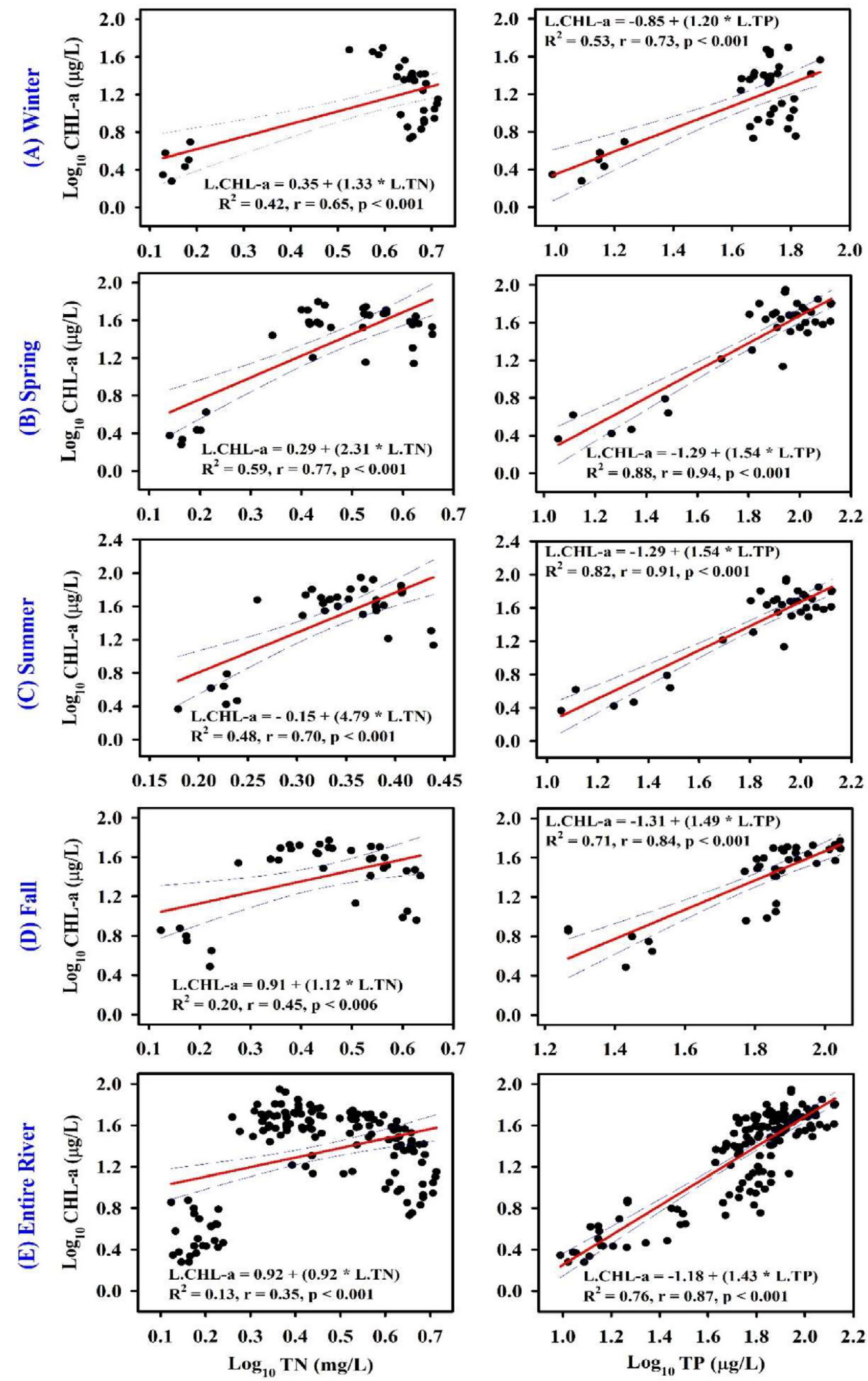

Fig. 6. Empirical relationship of algal chlorophyll (CHL-a) with total nitrogen (TN) and total phosphorus (TP) (Spring: Mar-May, Summer: Jun-Aug, Fall: Sep-Nov, Winter: Dec-Feb).

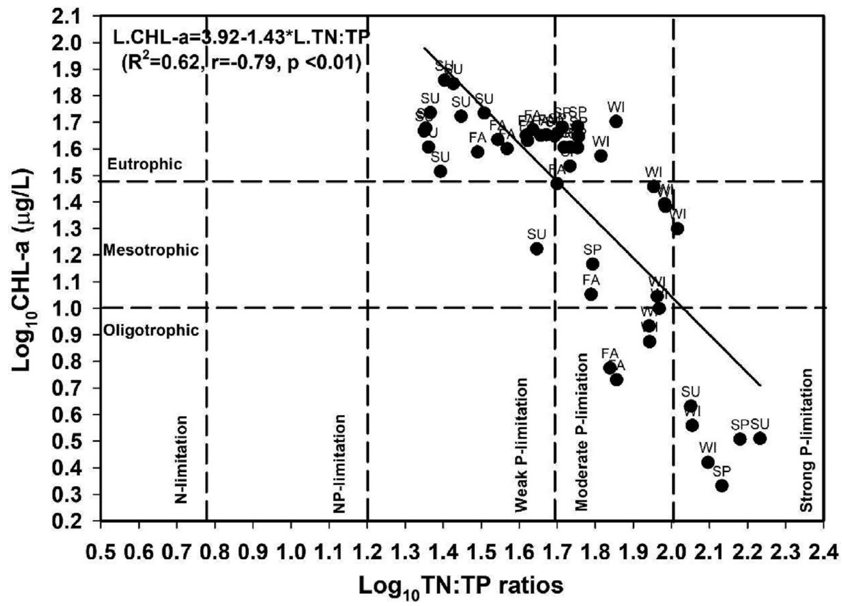

Fig. 7. Nutrient limitation status determination based on empirical relationship of algal chlorophyll (CHL-a) with TN:TP ratios.

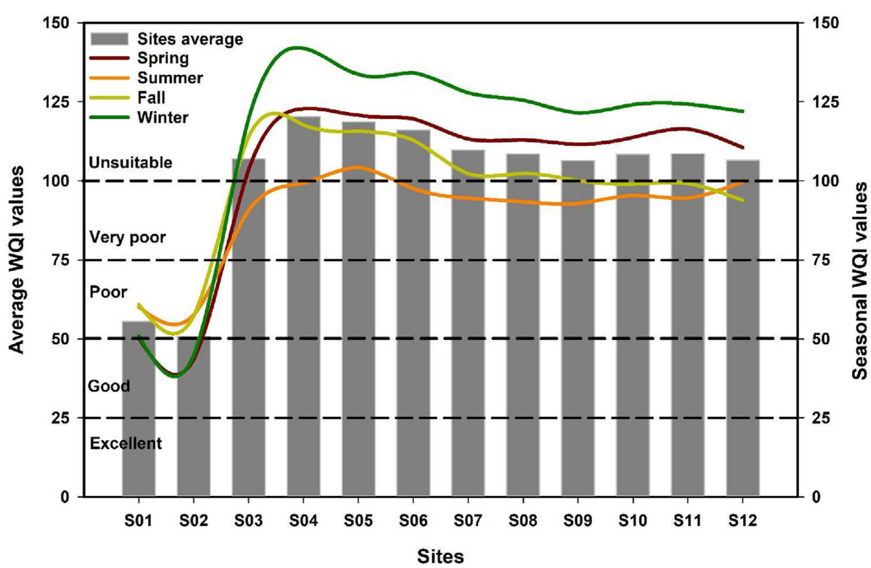

Fig. 8. Spatial (S01-S12) and temporal (Spring: Mar-May, Summer: Jun-Aug, Fall: Sep-Nov, Winter: Dec-Feb) variation of water quality index (WQI) in the Geum River.

summer, and fall. The entire river empirical model also suggests that TP (R^2 = 0.76, $p < 0.001$) is the better predictor for CHL-a compared to TN (R^2 = 0.13, $p < 0.001$). To determine the nutrient limitation status of algal chlorophyll, TN:TP ratios are commonly accepted as an indicator variable. Empirical analysis revealed that a higher TN:TP ratio indicates a greater chance of P-limitation (Fig. 7). The current study showed a substantial decrease in CHL-a concentrations when TN:TP ratios increased, indicating a P-limitation scenario.

3.6. Water quality index

The WQI allows for determining the overall waterbody's quality and identifies possible threats associated with water consumption (Fig. 8). The results showed that all sites except for S01 and S02 were unsuitable (WQI > 100), indicating that adequate treatment is necessary prior to any type of usage. Geum River WQI scores ranged from 50.83 to 120.40. The river's water quality was unsuitable from S03 to S12 during winter and spring and poor to very poor during summer (except S05).

4. Discussions

4.1. Sites and seasonal variation and monsoon effects on water quality

Water quality variables from S01 to S12 varied heterogeneously in the Geum River. The findings reported here indicate that domestic and industrial wastewater treatment plants (WWTPs) can considerably influence the river water quality. Such findings have been reported from prior Korean river studies, likes as the Han River (Jang et al., 2009; Lee and Byun, 2001), Geum River (Jang et al., 2009, Bae and An, 2006), Nakdong River (Jang et al., 2009; Lee et al., 2008), and Yongsan River (Choe and Lee, 2005; Sin and Lee, 2020) watersheds. In these rivers, organic matters (BOD and

COD) and nutrients (TP and TN) inflowing into the lotic environments from the WWTPs caused nutrient enrichments, low dissolved oxygen, high ionic concentrations, and hazardous chemicals (Bae and An, 2006; Jang et al., 2009; Mamun and An, 2021). These conditions led to frequent algal blooms, decreases in species diversity, and habitat degradation (Bae and An, 2006; Jang et al., 2009; Mamun and An, 2021). Additionally, Hamdhani et al. (2020) reported from 147 published publications that WWTPs severely impacted aquatic ecosystems worldwide. A recent global study documented that globally produced domestic and municipal wastewater amounts to 360 km^3/year and significantly impacts rivers and streams (Macedo et al., 2021). The extensive agricultural land cover across the watershed also has a detrimental effect on the river's water quality. S01 and S02 had better water quality than other sites, indicating headwater zone had better water quality. Weir construction can regulate the riverine transport of suspended solids, nutrients, and organic matters (Lah et al., 2015). Eutrophication is facilitated from S03 to S12 by inflowing water with higher TP and TN contents. A rise in BOD and COD levels leads to poor water quality. A water body with higher TSS levels is more likely to have been polluted by either natural or human activities. There has been a rise in CHL-a concentration in river water following the installation of a weir. The present findings are in line with some previous studies that weir construction can stimulate the algal growth in the river (Johnson and Penaluna, 2018; Mamun and An, 2021; Sin and Lee, 2020). CHL-a-based eutrophic river conditions can reduce DO and negatively impact ecosystem processes. On the basis of our findings, immediate action is needed to reduce pollution in the Geum River from S03 to S12.

Summer monsoons upsurge the inflow and outflow of Korean rivers. As a result, it shortens water residence time, regulating TP, TN, BOD, COD, EC, and TSS loading and algal growth in the watershed. This study shows that the TP, TSS, COD, and CHL-a levels were higher during summer than in other seasons. Furthermore, the higher level of TSS during summer was endorsed to a surge in TP in the river. TP, TSS, and COD inputs are inextricably linked to the Geum River basin's flow regime. Therefore, increased TP inputs during the monsoon season may affect algal development in the river. The summer season had the highest average WT. Due to the impact of seasonality, a strong inverse association was identified between WT and DO. Due to the diluting effect, the summer monsoon season lowered the river's average EC and TN content. Some previous studies corroborate the present results in Korean ecosystems (Atique et al., 2020; Sin and Lee, 2020).

Moreover, BOD: COD ratios are helpful indicators to determine the organic matter biodegradability in the aquatic ecosystem. The results indicate an increase in degradable organic matter load during spring from WWTPs and agricultural and livestock farms. TN level exhibited a eutrophic state from S03 to S12 during all the seasons, indicating nitrogen-rich systems. The results are consistent with some earlier studies on Korean streams and rivers (Lah et al., 2015; Mamun et al., 2021). During summer, the river showed a eutrophic state from S04 to S12, while it was a mesotrophic state during winter based on TP level, indicating summer monsoon effects. The CHL-a level suggested a eutrophic river during all the seasons except winter.

4.2. Influence of LULC on nutrients and organic matters

Anthropogenic activities can increase rivers' TP, TN, BOD, and COD levels, resulting in eutrophication. An earlier study indicated that a built-up area and intensive farming had amplified nutrients and organic matter in surface waters (Alford et al., 2016). Agricultural farming is a critical source of sediment, nutrients, and organic matters to river systems. Agricultural land leakage and seepage are also accountable for contamination in downslope waters. This study reveals that nutrient and organic matter pollution are positively connected with intensive agricultural systems and built-up areas. Consistent with the current outcomes, nutrients and organic matter were found to have positive correlations with watershed inhabitants and the proportion of developed land, as reported by Alford et al. (2016), Lah et al. (2015), and Shim et al. (2018). Forest coverage negatively correlated with nutrients and organic matter.

4.3. Solids, nutrients, and chlorophyll-a dynamics

TP and TN can enter the river systems from point (WWTPs) and nonpoint sources (urban and agricultural runoff). Most TP and TN are bound to sediments during surface runoff (Mallin and Cahoon, 2020). Sharpley et al. (1993) stated that 75–90 % of P might be linked to SS. The strong TP, TN, and TSS relationship adversely affects water quality (Mallin and Cahoon, 2020). The present outcomes suggested that TSS could act as a TP carrier in the river.

The greatest prominent limnologist in modern eras, Hutchinson (1957), reported that "Phosphorus is in many ways the most critical element for the ecologist, because it is more likely to be deficient, and thus to limit the biological productivity of any region of the earth's surface than the other major biological elements are." This statement led to the development of the empirical models between algal chlorophyll and water column TP for eutrophication management (Dillon, 1974; Dodds and Smith, 2016). Earlier research in lentic systems showed that TP was the better predictor for algal growth (Dillon, 1974). These insights were applied to stream and river systems. However, it was quickly found that TP was an inadequate indication of algal growth in lotic systems due to the intricate interaction of TP, TN, WT, pH, SD, flow, habitat conditions, and invertebrate and fish feeding (Corkum, 1996; Munn et al., 2010; Pringle, 1987). As a result, the correlations between TP and algal biomass display high variability in lotic systems, making them unsuitable for eutrophication control. However, the current findings corroborate Hutchinson's (1957) and Dillion's (1974) assertions since the river has been transformed from lotic to lentic systems due to the construction of three weirs. Weir structure in the river enhanced water residence time and decreased water column washing, demonstrating that TP is the most crucial factor regulating algal development. In addition, the present findings support certain prior findings in river systems confined by weirs (Kwak et al., 2016; Li et al., 2013). Moreover, it is common practice to utilize TN:TP ratios as an indication of algae's nutrient limitation status. P-limitation is thought to be more likely in systems with larger TN:TP ratios (Dodds, 2006). The current investigation demonstrated a tendency toward declining CHL-a concentrations as TN:TP ratios inclined, specifying strong P-limitation.

4.4. Water quality index

Geum River's average WQI value (>100) indicates it is polluted to a higher extent, making it unsuitable for drinking, irrigation, and industrial use. The river's high WQI scores are primarily due to wastewater influx from industrial and household WWTPs, agricultural runoff, and persistent trash dumping by populations living alongside the river (Bora and Goswami, 2017). Such high WQI values were also found in the Yeongsan River, Korea, and reported that high WQI scores are caused mainly by various anthropogenic activities, including direct wastewater inflow from industrial and residential areas and agricultural runoff (Mamun and An, 2021). Similar results were found in the Cauvery River (Kalavathy et al., 2011) and Himalayan rivers and streams (Dudgeon, 1991) due to the release of domestic sewage. The WQI values increased during the winter due to concentrated wastewater discharged without dilution. Similar seasonal variations of WQI were reported by Hemamalini et al. (2017) in India and Ahmed et al. (2015) in Iraq. Overall, WQI scores were high, representing a concern about water consumption.

5. Conclusions

The present study suggested that WWTPs and LULC are significant nutrients and organic pollutants sources. Furthermore, seasonal water quality variations in the river are remarkably influenced by the summer monsoon. High WQI values of the river indicate higher pollution levels, specifying its unsuitability for drinking, irrigation, and industrial usage. Regression analysis revealed that TSS is a good predictor for TP and TP was the most critical factor for algal growth. These findings suggest that reducing TSS loading in river water would have several positive consequences, including better water clarity and reduced nutrient and algal development. Additionally, several measures should take to protect the river's water quality, including reducing the amount of industrial and domestic waste that is discharged into the river from Daejeon Metropolitan City and Sejong, Gongju, Buyeo, Nonsan, and Iksan City, implementing cutting-edge wastewater treatment technologies, restricting fertilizer use and developing new management strategies.

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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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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jksus.2022.102270.

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