Fish Assemblage Structure Comparison between Freshwater and Estuarine Habitats in the Lower Nakdong River, South Korea

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Received: 6 June 2020; Accepted: 3 July 2020; Published: 5 July 2020

Abstract: Variabilities of biological communities in lower reaches of urban river systems are highly influenced by artificial constructions, alterations of flow regimes and episodic weather events. Impacts of estuary weirs on fish assemblages are particularly distinct because the weirs are disturbed in linking between freshwater and estuarine fish communities, and migration successes for regional fish fauna. This study conducted fish sampling at the lower reaches of the Nakdong River to assess spatio-temporal variations in fish assemblages, and effects of estuary weir on structuring fish assemblage between freshwater and estuary habitats. In total, 20,386 specimens comprising 78 species and 41 families were collected. The numerical dominant fish species were Tachysurus nitidus (48.8% in total abundance), Hemibarbus labeo (10.7%) and Chanodichthys erythropterus (3.6%) in the freshwater region, and Engraulis japonicus (10.0%), Nuchequula nuchalis (7.7%) and Clupea pallasii (5.2%) in the estuarine site. The fish sampled were primarily small species or the juveniles of larger species at the estuary region, while all life stages of fishes were observed at the freshwater habitats. The diversity patterns of fish assemblages varied greatly according to study site and season, with higher trends at estuarine sites during the warm-rainy season. No significant difference in diversity between freshwater and estuarine sites during the cold-dry season were found. Multivariate analyses of fish assemblage showed spatial and seasonal differences of assemblage structures. Higher effects of between-site variability but not within seasonal variability at each site were observed. Variations in assemblage structures were due to different contributions of dominant species in each habitat. Common freshwater species characterized the fish assemblage in the freshwater region, while marine juveniles were significantly associated with the estuarine habitat. The results from the ecological guild analyses showed distinct ecological roles for freshwater and marine species, and overlapping roles for fish sampled at the fishways. The lower reaches of the Nakdong River are an important ecosystem for both freshwater and marine juveniles. Nakdong River estuarine residents and migrant fishes, however, have been negatively affected by the construction of the weir (gravity dam), due to the obstruction to migration from and to freshwater habitats. Conservation and management policies aimed at minimizing anthropogenic influences on estuary ecosystems should focus on evaluating ecological functions of estuary weirs.

Keywords: fish assemblage; lower reaches; Nakdong River; estuary weir; marine juveniles
1. Introduction

Fish assemblages in coastal habitats influenced by rivers consist of a variety of species with diverse life-history strategies and broad functional categories of freshwater, diadromous and estuarine-dependent species. Lower reaches of river systems are characterized by high biological productivity and diversity [1]. Biological communities in these regions are generally influenced by tides, rainfalls, and anthropogenic disturbances [2–4]. In particular, episodic weather events and anthropogenic stressors have significant effects on the structure and functioning of biological communities through declines of biomass, species richness and abundance [5].

Diadromous fish species in temperate Korean rivers include eels (Anguillidae), salmons (Salmonidae) and sweetfishes (Plecoglossidae) [6–8]. Some coastal fishes, including Coilia nasus and Mugil cephalus, also exhibit occasional upstream movements from coastal waters to lower river reaches [9,10]. Estuary weirs, however, restrict up or downstream dispersal for migratory fishes due to creation of a sharp salinity gradient, controlling spatial distribution in river catchments [11–13]. Fish assemblages in lower river reaches are greatly affected from anthropogenic structures, such as barriers, dams or weirs at both local and catchment scales [12,14,15], contributing to significant discontinuities especially in diadromous fish assemblages [16].

The Nakdong River estuary is an important spawning and nursery ground for many aquatic animals, supporting a productive fishery [17]. In 1987, an estuary weir was constructed to prevent saltwater intrusion into shallow freshwater habitats. The weir has lowered freshwater flows transporting nutrients and sediments to the estuary, threatening the health of estuarine habitats [13,18], such as shifts in population structure of animal communities. Several studies have reported alteration of animal community structures following construction of dykes, weirs, or any other obstruction in estuary environments [19–21]. Kwak and Huh [20] observed that the dominance of fish assemblages in the coastal Nakdong River estuary shifted from demersal to pelagic species after weir construction. The shifts were mostly due to changes in the sediment depositional dynamics caused by the irregular discharge of freshwater, causing changes in circulation patterns within the estuary. Han et al. [16] also documented the loss of species richness following weir construction. Weirs adversely affected diadromous species by blocking their migration routes, but favored nonnative fishes [16,22].

Although many studies have investigated the community structure of estuarine fishes worldwide, and the impacts of estuary weir on fish assemblage structures [15,23–25], such studies are scarce in areas along the southern coast of Korea. Of the few, Hwang et al. [26] have investigated temporal occurrence patterns of fishes in the western Mangyeong Estuary prior to construction of a seawall in 2010, completely enclosing its lower reaches. Park et al. [27] also reported juvenile fish assemblage in the shallow sandy beach of the lower tip of the Nakdong River estuary. Several previous studies have suggested that seasonal variations in fish abundance are primarily the result of species-specific recruitment [28], with environmental factors as strong determinants, especially water temperature and salinity [29–32]. Because lower river reaches play an important role as the nursery habitats for estuarine residents, juveniles of marine species, and temporary habitats for migratory fishes, research evaluating the impacts of weirs within river reaches needs to be conducted for recommendations on restoring connectivity within estuaries where weirs have been constructed and for determining where weirs should be removed.

Anthropogenic effects on freshwater and estuarine fish assemblages are mostly felt at catchment scales. Research, therefore, needs to focus on the impacts at these large scales [33,34]. Thus, this study aimed to examine variations in species composition and abundance at large spatial scales of fishes inhabiting the lower Nakdong River reaches of Korea by evaluating the ecological function of each habitat and the influence of estuary weir on fish assemblage.
2. Materials and Methods

2.1. Study Area and Sampling

The study area comprised of the lower Nakdong River, located in the southeastern part of the Korean Peninsula (Figure 1). The Nakdong River weir was constructed 6 km north from the mouth of the estuary (Figure 1). Three and two stations were established to investigate the spatio-temporal patterns of fish assemblages at the freshwater and estuary regions (two study sites), respectively. Stations extended from the southern end of the Nakdong River to 30 km north, into the freshwater site. Additional samplings were also conducted at the fishways (two pool fish ladder type and a gate type) within weir; pool ladder type (length = 24 m, width = 1.8 m, slope = 2.9°), gate type (length = 50 m, width = 9 m, slope = n.a.). Sampling depths were approximately 5 m at the freshwater site, and between 10 and 15 m at the estuarine site. The mean tidal range at the study area was 1.2 m for spring tides and 0.4 m for neap tides.

![Figure 1](image_url)

Figure 1. Sampling stations from freshwater (A1, A2 and A3) and estuary (B1 and B2) sites investigating the effects of weir on fish assemblages at the lower Nakdong River, South Korea.

Fish samples were collected monthly from June 2010 to May 2011 at the freshwater and estuarine stations, as well as at fishways within the weir. Samplings were grouped on annual mean temperature for further analysis based on seasonality. Two seasons (i.e., cold and warm seasons) were determined based on temperatures around 17 °C. Temperature data were obtained for Busan province from the Korea Weather Data Open Portal (https://data.kma.go.kr/). Because warm and cold seasons in Korea coincide with rainy and dry seasons, respectively, the seasons were classified as cold-dry (November–March) and warm-rainy (May–October) seasons. Sampling was conducted using a 15 m long, 13 m wide, 3.5 cm mesh bottom trawl with a 1 cm liner covering the codend. Towing speed of ca. 1 knot for 40 min, covering an estimated area of was 16,000 m², was conducted at each sampling event. A single tow at each station was carried out during the day (between 09:00 and 12:00) simultaneously at the freshwater and estuary regions. Fishway samplings were conducted at the gate and ladder during flood tides. Fish were sampled, the species recorded, and released. Fishway samplings were conducted only during warm-rainy seasons (between May and October) in both 2010 and 2011. In the ladder type fishways, fishes were collected using cone-traps with 20 mm mesh. A set-net (length 10 m, height 4 m, mesh body 50 mm, mesh bag 20 mm) was installed within the gate-type fishway and fish samples were collected after 12 h. All fish samples caught from fishways were checked for species
names, tagged adult specimens using various tags, and then released alive for further fish tracking study. Both surface (between 1 m and 2 m) and bottom (between 10 m and 15 m) water temperatures and salinities were monitored monthly at each sampling location using a portable instrument (Thermo Scientific Orion 3-star). Immediately after capture, fish samples from stations were stored in ice and transported to the laboratory for processing. Taxonomic classification and species name were checked by FishBase [8].

2.2. Ecological Guild and Habitat Type of Fishes

Five ecological guilds were identified for this study. Guilds were estuarine residents (ER), freshwater species (FW), marine occasional visitors (MV), marine juvenile (MJ), and diadromous (catadromous, anadromous, or amphidromous) migrants (DM), according to native Korean fishes [7,35]. Fish were further categorized into pelagic and benthic.

2.3. Data Analyses

Full factorial analyses of covariance (ANCOVA) was used to test the effects of site and depth covarying with the seasonal trends of water temperature. A Bonferroni correction for multiple comparison was used to determine post-hoc significance.

The Shannon–Wiener index ($H'$) was used to estimate community-level diversity [36]. A logarithmic transformation ($\log(x + 1)$) of fish abundance (number of specimens) was performed to correct for heteroscedasticity and to reduce the weight of overly abundant species in analyses. Three independent two-way ANOVA with an orthogonal design were used to analyze the spatial (two sites) and seasonal (two seasons) effects (independent variables) on fish species richness, abundance and diversity (dependent variables). Prior to ANOVA analysis, homogeneity of variance was tested using Levene’s test [37]. Further test onto the dependent variables, the ANOVA tests were also conducted using a split file analysis, with the dependent variable of season paired with site and vice versa. The split file analysis on the ANOVA allowed the data output to be separated by factor to allow visualization of case subsets.

Further inferential and descriptive analyses were performed to assess abundance trends with spatial and temporal patterns. Permutation multivariate analyses of variance (PERMANOVA) on $\log(abundance + 1)$ based on Bray–Curtis similarity matrices were conducted [38]. Analysis factors for the PERMANOVA were site (two fixed levels: freshwater and estuary), station (nested within site, two random levels), and season (two fixed levels: cold-dry and warm-rainy seasons). Similarity matrices were used in a PERMANOVA to test for factor effects. In cases in which PERMANOVA detected a significant difference at the 0.05 level, posteriori pairwise PERMANOVA comparisons were used to determine which interaction terms differed significantly among variables within each level of factors. PERMANOVA assigns components of variation (COV) of differing magnitudes to the main factors and interaction between combinations of main factors. The larger COV indicates greater influence of a particular factor or interaction term on the structure of the data [39]. The non-metric multidimensional scaling (nMDS) ordination technique was used to visualize factor effects. To assess statistical significance among factor levels, a canonical analysis of principal coordinates (CAPs) was used [39]. Correlation coefficients between each factor and the canonical axis were used as evidence for species contributions to observed differences. Individual species with both correlations higher than 0.4 and total abundance larger than 1% were plotted on CAP axes 1 and 2 for additional visualization of results.

Statistical software used was Systat (Systat version 18, SPSS Inc., Chicago, IL, USA) and PRIMER v7 with the PERMANOVA+ module [39,40]. A 0.05 level for statistical significance was used in analyses.
3. Results

3.1. Environmental Variables

Water temperature and salinity in the study area varied according to seasonal patterns (Figures 2 and 3). Water temperatures at the freshwater site were the lowest in January (1.5 °C) and the highest in September (25.2 °C). In the estuary, water temperature ranged from 7.3 to 25.7 °C at the surface and from 9.1 to 23.8 °C at the bottom, both depths showing similar trends with season. No significant differences of water temperature between stations within each season were detected (ANCOVA; P > 0.05). Peak water temperatures were observed in August and September, for both freshwater and estuarine habitats, and minima during January and February (Figure 2). Salinity in the estuarine region varied seasonally, ranging from 5.0 to 34.1‰ at the surface and from 25.1 to 34.3‰ at the bottom. Significantly lower salinity at the surface was observed during the rainy season in the estuarine stations (Figure 3; ANCOVA, P < 0.05).

![Figure 2. Seasonal changes in the surface and bottom water temperatures at freshwater (A) and estuary (B) regions at the lower Nakdong River.](image1)

![Figure 3. Seasonal changes in the surface and bottom salinities at estuary site at the lower Nakdong River.](image2)

3.2. Fish Species Composition

In total, 20,386 individuals belonging to 78 species and 41 families were collected during the study period. Cyprinidae (10 species), Callionymidae (five species), Engraulidae (five species), and Clupeidae (four species) were the most widely represented families (Table 1 and Table S1). Numerically, the five dominant species at the freshwater site were Tachysurus nitidus, Hemibarbus labeo, Chanodichthys erythropterus, Pseudogobio esocinus and Squalidus gracilis, accounting for 98.0% of the total catch. Engraulis japonicus, Nuchequula nuchalis, Clupea pallasii, Trachurus japonicus and Favonigobius...
**gymnauchen** were the most numerically abundant estuarine fish species, making up 84.7% of the total abundance. Most of the specimens of the dominant species were juveniles of marine fishes, but only *Fa. gymnauchen* was an estuarine resident (Supplementary Material Table S1). In terms of richness, 68 freshwater and estuary habitats, respectively, being the most common. In addition, 9 and 12 fishway species co-occurred with fish species in *Coilia nasus* freshwater habitats (18 species) or fishways (19 species; Table 1). Only three species co-occurred in abundance. Most of the specimens of the dominant species were juveniles of marine fishes, but only *P. pusilla* were the most numerically abundant estuarine fish species, making up 84.7% of the total abundance.

Table 1. List of fish species, ecological guild (EG), habitat type (HT), and occurrences of fishes in freshwater (Fr), estuarine habitats (Es), and estuary weir fishway (Fw) stations in the lower Nakdong River, South Korea; ER = estuarine residents, FW = freshwater species, MV = marine occasional visitors, MV(j) = MV included juveniles, MJ = marine juvenile, DM = diadromous migrants; B = benthic, P = pelagic.

| Family          | Species          | EG   | HT | Fr | Es | Fw | Family          | Species          | EG   | HT | Fr | Es | Fw |
|-----------------|------------------|------|----|----|----|----|-----------------|------------------|------|----|----|----|----|
| Acropomatidae   | Acropomus japonicus | MJ   | P  | •  |    |    | Acropomus nigripinnus | MJ   | P  |    |    |    |
| Ammodyclidae    | Ammodon peronatus | MV   | P  | •  |    |    | Ammodon peronatus | MV   | P  |    |    |    |
| Apogonidae      | Apogon lineatus  | P    |    |    |    |    | Apogon lineatus | MV   | P  |    |    |    |
| Bagridae        | Takis (s)is tatis | FW   | B  | •  | •  |    | Takis (s)is tatis | MV   | P  |    |    |    |
| Callicoreinae   | Callicoreinae    | MV   | B  | •  |    |    | Callicoreinae | MV   | B  |    |    |    |
| Callionymidae   | Callionymus importatus | MV  | B  | •  |    |    | Callionymus importatus | MV   | B  |    |    |    |
| Carangidae      | Carangidae       | MV   | P  | •  |    |    | Carangidae | MV   | P  |    |    |    |
| Centrolophidae  | Centrolophus sp. | MJ   | P  | •  |    |    | Centrolophus sp. | MV   | P  |    |    |    |
| Clupeidae       | Clupea pilchardus | MJ   | P  | •  |    |    | Clupea pilchardus | MV   | P  |    |    |    |
| Conocorynidae   | Conocorynus punctatus | P  |    |    |    |    | Conocorynus punctatus | MV   | P  |    |    |    |
| Congridae       | Conger niphobles | MV(J) | B  | •  |    |    | Conger niphobles | MV(J) | B  | •  |    |    |
| Cynoglossidae   | Cynoglossus sp.  | MV   | B  | •  |    |    | Cynoglossus sp. | MV   | B  |    |    |    |
| Cyprinidae      | Cyprinus carpio  | FW   | P  | •  |    |    | Cyprinus carpio | MV   | P  |    |    |    |
| Cynoglossidae   | Cynoglossus jenkinsi | MW  | B  | •  |    |    | Cynoglossus jenkinsi | MW  | B  |    |    |    |
| Cyprinidae      | Cyprinus carpio  | FW   | P  | •  |    |    | Cyprinus carpio | MV   | P  |    |    |    |
| Dermogenidae    | Dermogenesis sp. | FW   | P  | •  |    |    | Dermogenesis sp. | MV   | P  |    |    |    |
| Engraulidae     | Engraulis japonicus | DM   | P  | •  | •  |    | Engraulis japonicus | MV   | P  |    |    |    |
| Engraulidae     | Engraulis japonicus | DM   | P  | •  | •  |    | Engraulis japonicus | MV   | P  |    |    |    |
| Engraulidae     | Engraulis japonicus | DM   | P  | •  | •  |    | Engraulis japonicus | MV   | P  |    |    |    |
| Engraulidae     | Engraulis japonicus | DM   | P  | •  | •  |    | Engraulis japonicus | MV   | P  |    |    |    |
| Engraulidae     | Engraulis japonicus | DM   | P  | •  | •  |    | Engraulis japonicus | MV   | P  |    |    |    |
| Engraulidae     | Engraulis japonicus | DM   | P  | •  | •  |    | Engraulis japonicus | MV   | P  |    |    |    |
| Engraulidae     | Engraulis japonicus | DM   | P  | •  | •  |    | Engraulis japonicus | MV   | P  |    |    |    |
| Engraulidae     | Engraulis japonicus | DM   | P  | •  | •  |    | Engraulis japonicus | MV   | P  |    |    |    |
| Engraulidae     | Engraulis japonicus | DM   | P  | •  | •  |    | Engraulis japonicus | MV   | P  |    |    |    |
| Engraulidae     | Engraulis japonicus | DM   | P  | •  | •  |    | Engraulis japonicus | MV   | P  |    |    |    |
3.3. Spatial and Seasonal Variation in Species Richness, Abundance and Diversity

Mean species richness, abundance, and diversity varied by study site and season (Figure 4). Mean species richness at the estuary was higher during the warm-rainy than the cold-dry season, whereas no differences were found between the two seasons at the freshwater site \((F = 3.724, P < 0.05)\). The mean abundances of fishes were higher during the warm-rainy season at both the freshwater and estuary, with the lowest value during the cold-dry season at the estuary \((F = 2.182, P < 0.05)\). Diversities also varied between study sites. A higher diversity was found at the estuary than at the freshwater site during the warm-rainy season only \((F = 0.054, P < 0.05)\).

![Figure 4. Variations in mean species richness, abundance, and diversity of fish assemblages with study site and season in the lower Nakdong River, South Korea.](image)

The two-way ANOVA confirmed diversity patterns, in that there were significant effects of the site, but not season (Table 2). The two-way interactions were also significant for species richness and diversity, with the exception of abundance (Table 2). Split file ANOVAs showed significant trends of species richness and diversity with site for the warm-rainy season \((P < 0.05)\). No significance for any community variable was observed between sites during the cold-dry season \((P > 0.05)\). Abundance differences were significant between the freshwater and estuarine site during the cold-dry season only. Within-site seasonal comparisons showed a significant difference for abundance at the estuary habitat and diversity at the freshwater site \((P < 0.05)\).

| Source          | df | Species Richness | Abundance | Diversity |
|-----------------|----|------------------|-----------|-----------|
|                 |    | \(F\) | \(P\)     | \(F\) | \(P\) | \(F\) | \(P\) |
| Site            | 1  | 9.056 | \textbf{0.004} | 7.775 | \(0.007\) | 7.840 | \textbf{0.007} |
| Season          | 1  | 1.815 | 0.184     | 4.000 | 0.051 | 0.348 | 0.558 |
| Site \(\times\) Season | 1  | 8.262 | \textbf{0.006} | 0.823 | 0.369 | 6.093 | \textbf{0.017} |
| Residual        | 53 |       |           |         |        |       |       |

Mean abundances of the eight dominant species varied seasonally within each habitat (Figure 5). In the freshwater habitat, the mean abundances of \(\text{He. labeo}\) and \(\text{Ps. escocinus}\) were higher in the warm-rainy season, while \(\text{Ch. erythropterus}\) was abundant during cold-dry season (ANOVA, \(P < 0.05\)). The estuarine fishes showed tendencies of higher abundance during the warm-rainy season only \((P < 0.05)\). No seasonal differences of mean abundances were observed for \(\text{Ta. nitidus}\) in freshwater habitats, and for \(\text{Nu. nuchalis}\) in the estuary region (ANOVA, \(P > 0.05\)).
3.4. Fish Assemblage Structure

PERMANOVA tests revealed fish assemblages were significantly associated with study site and season, but not station (nested within study site), with the COV of site being the highest, indicating the strongest factor determining variation within samples (Table 3). A statistically significant two-way interaction between site and season was also observed (Table 3). Pairwise comparisons of site and season showed evidence of significant differences in fish assemblage structure between freshwater and estuarine site within each season, and also between cold-dry and warm-rainy season with each of study site (PERMANOVA pairwise tests, all $P < 0.05$).

Table 3. Mean squares (MS), pseudo-F ratios, significance levels ($P$), and components of variation (COV) for permutation multivariate analyses of variance (PERMANOVA) tests using Bray–Curtis similarity matrices from abundance of fish assemblages showing differences in site (Si), station (St, nested within Si), season (Se), and interactions terms in the lower Nakdong River, South Korea; bold letters indicate significance at $P < 0.05$.

| Source       | df | MS       | Pseudo-F | $P$    | COV  |
|--------------|----|----------|----------|--------|------|
| Si           | 1  | 70860.0  | 30.243   | 0.007  | 50.884|
| Se           | 1  | 7596.3   | 6.333    | 0.025  | 15.548|
| St (Si)      | 3  | 2353.8   | 1.227    | 0.131  | 6.207 |
| Si $\times$ Se | 1  | 7611.4   | 6.346    | 0.023  | 22.014|
| St (Si) $\times$ Se | 3  | 1181.2   | 0.616    | 0.988  | $-11.419$|
| Residuals    | 47 | 1918.3   |          |        | 43.798|

The non-metric MDS ordination of similarity of mean fish assemblages depicted a clear visual difference between freshwater and estuarine site along with the nMDS ordination horizontally, with the former and the latter site lying right and left side of the plot, respectively (Figure 6). Conversely, the points during both cold-dry and warm-rainy seasons at the estuarine site were interspersed throughout the nMDS plot. At the freshwater site, the points for the cold-dry season lie toward the bottom of the plot, while those for the warm-rainy season were at the upper plot area.
Canonical analyses on principal coordinates were performed on significant interactions as a further test on PERMANOVA analyses. The CAP plot for the site–season interaction showed strong evidence for the factor-indicating group separation between sites, and between seasons within each site (Figure 7). Seven fish species were key in separating the estuarine site from the freshwater site, and four species characterized the fish assemblages in freshwater habitats. *Cyprinus nasus* had an intermediate contribution on both sites during the warm-rainy season (Figure 7). Clear seasonal differences in fish assemblages were found at the estuarine site, showing a strong contribution for six species on the warm-rainy season and only a contribution from *Notemigonus nuchalis* to trends in the cold-dry season. Weak seasonal classifications in fish assemblages were evident at the freshwater site, with weak trends of species contributions on each season (Figure 7).
3.5. Ecological Guild and Habitat Type of Fish Assemblages

The analysis of ecological guilds by the number of species within each site across each season showed a high influence of 12 and 13 freshwater species (FW) during the cold-dry and the warm-rainy season, respectively. Collectively, two diadromous migrants (DM) and one estuarine resident (ER) were recorded at the freshwater site during both seasons (Figure 8). In the estuarine site, 13 and 20 marine occasional residents (MV) occurred during the cold-dry and warm-rainy seasons, respectively. No freshwater species were found at this region. All ecological guilds occurred in fishway samples, with dominant freshwater and marine occasional residents (Table 1), indicating that fishways play a role in connecting freshwater and estuary habitats. Marine juveniles (MJ) were only recorded at fishways and the estuary site, with the greatest number recorded in the latter. Freshwater habitats comprised mostly of pelagic species, with the benthic-species number higher at the estuary and fishway regions.

![Figure 8](image-url)

**Figure 8.** The number of species by ecological guild and habitat type in freshwater (Fr), fishway (Fw) and estuary (Es) sites during cold-dry (CD) and warm-rainy (WR) seasons; ecological guilds were estuarine residents (ER), freshwater species (FW), marine occasional visitors (MV), marine juveniles (MJ), and diadromous migrants (DM).

4. Discussion

A total of 18 and 63 species were collected from freshwater and estuary habitats, respectively, whereas 19 fish species were recorded from fishways. The number of species and diversity was considerably higher at estuary stations. Higher species richness in estuarine regions, compared with freshwater or blackish habitats, has been reported worldwide [41,42]. De Moura et al. [42] indicated that species richness was significantly higher in channels linking estuaries to freshwater ecosystems, due to the regular inflow of saltwater, allowing access for several marine species. Additionally, higher species richness, especially toward estuary mouths, is strongly influenced by marine processes, supporting a greater number of species [43]. Processes such as salinity gradients within the estuary have been shown to strongly influence fish species richness [44]. Such influences, however, may not be general in fish assemblages for all estuaries. Species richness has also been shown to be influenced by regional and local processes affecting colonization, such as processes affecting connectivity between estuaries and the adjacent marine habitats [45].

Of the 63 fish species recorded in the estuarine stations, five were numerically dominant (*En. japonicus, Nu. nuchalis, Cl. pallasii, Tr. japonicus* and *F. Gymnauchen*). Estuarine fishes were predominantly juveniles of marine fishes, indicating the importance of the estuary as a nursery [27,46]. The dominance of juvenile fishes in our observations is in general agreement with other studies worldwide (e.g., [47–50]), as well as in Korea (e.g., [26,27,51]). The greater abundance of juveniles
observed in this study indicated the strong dependence of species on the estuary for shelter, survival, and refuge from predators during early stages of their life cycle [48]. As an additional importance of estuaries, most of the marine species that use the estuary as a nursery ground have commercial and recreational value. Among the dominant marine juveniles, *Cl. pallasii*, *Pa. olivaceus*, *Tr. japonicus* and *Tr. lepturus* are the most important fishery resources in Korea [52].

Eighteen fish species were collected in the upper part of estuary weir, of which 14 species were freshwater residents and two species diadromous migrants (*Co. nasus* and *Mu. cephalus*). Among the dominant freshwater species, *Ch. erythropterus* and *He. labeo* are endemic to the Nakdong River [53,54], and *Ta. nitidus* comprises a minor group of freshwater fishes in the Nakdong River [55]. It is worth noting that *Opsariichthys uncirostris*, the common species in freshwater and estuary habitats of the lower Nakdong River [10], was not a major species observed in this study. The low occurrence of *Op. uncirostris* is likely due to extensive dredging between 2009 and 2011 in the lower Nakdong River. The river dredging caused deteriorated water quality and compromised critical habitats, causing the observed low numbers of aquatic organisms [56]. Highly tolerant species to such disturbances, including *Ta. Nitidus*, were abundant in the current study, unlike more sensitive species, such as *Op. uncirostris* [57].

The estuarine weir of the Nakdong River was constructed in 1987, despite many arguments against it, due to the many potential negative impacts on the ecosystem [58,59]. One such impact may be on the changes of fish assemblage structures. The major change in fish assemblage is a decrease of total species number, especially freshwater fishes after the construction of estuary weir [60]. Changes in fish functional categories were also observed from demersal to pelagic in estuary fish assemblages [20]. In addition, migratory fishes also have shown dramatical reduction of their upstream migration route and relative abundance due to blockage of their passage by the estuary weir [60]. Thus, the role of fishways in determining linkages between freshwater and estuarine habitats may be particularly significant for shaping fish communities, especially communities of diadromous migrants.

The results of this study show similar proportions of fish species within freshwater, marine, and stenohaline (estuarine residents and diadromous migrants) guilds in the fishway samples. Fishways were constructed for the provision of passages for animals migrating from estuary to freshwater habitats. Relatively few diadromous species, however, were found in this study, despite the fishways, even with many diadromous species present in the lower reaches of the Nakdong River [10,61]. Because of the obstruction of the estuary weir in fishes’ migration into the upper river, several studies have reported reduced migratory fishes in the Nakdong River estuary [10]. Yang et al. [61] reported fishways in the weir of Nakdong River estuary to have limited use, based on the relatively low species richness of anadromous fishes upstream from the structure. In addition, reduced freshwater flow caused by low precipitation can also exacerbate negative impacts on migratory fishes, due to fishways from weir construction becoming of even less efficiency in the provision of adequate passage [62,63]. Effective alternatives for providing fish passage, such as new fish passage designs, implementing recovery of affected habitats, and implementing adaptive management practices, are urgent and necessary for areas in Korea where fishways exist or are planned.

Overall diversity patterns of fish assemblages did not show significant seasonal patterns. A higher fish abundance, however, in the estuarine site was evident during the warm-rainy season. Seasonal variations in fish abundance are mainly due to the presence of species utilizing the Nakdong River estuary during the warm-rainy season for reproduction. For example, the increase in the abundance of *Cl. pallasii*, *En. Japonicus*, and *Tr. japonicus* occurred mainly during the warm-rainy season for *Cl. pallasii* following their spawning periods [64], and during the spring-early summer for *En. japonicus* and *Tr. japonicus* [65,66]. Those same species are also abundant at adjacent near-coastal waters of southeastern Korea during the spring and summer [56,67]. One may thus conclude that the abundances of those species during the warm-rainy season are likely due to the nursery grounds provided by the estuary, whereas the consistent occurrence of *Nu. nucalis* during all seasons suggests that estuaries are the main habitat for their entire life cycle [20].
5. Conclusions

In conclusion, the lower reaches of the Nakdong River are an important ecosystem for a diverse array of fish species. Of the 78 species sampled in this study, 57 and 14 originated from marine and freshwater areas, respectively, even with limited access to their habitats by the estuary weir. Most of the species sampled in estuaries were exclusively represented by juveniles, highlighting the importance of this ecosystem as a nursery ground. As in many estuaries across the world, many of the species observed in this study were occasional residents. The effect of obstructions, such as the estuary weir, on their success was reflected by the reduction of species richness in areas upriver of the weir than in the previous observation [60]. Studies such as this, investigating the dynamics of species assemblage in lowland river systems impacted by physical obstructions, are critical for the conservation efforts of habitats supporting ecologically and economically important species.

Supplementary Materials: The following are available online at http://www.mdpi.com/2077-1312/8/7/496/s1, Table S1: List of species including Families, Scientific names, Common names and their abundances (N) in freshwater and estuary sites, and total abundance as well as percentages (%N).

Author Contributions: All authors have read and agree to the published version of the manuscript. J.M.P.; methodology, validation, formal analysis and writing—original draft preparation, R.R.; writing—review & editing; H.H.J.; conceptualization, H.C.C.; investigation and data curation.

Funding: This research was funded by the Korea Institute of Ocean Science & Technology [grant numbers PE99813].

Acknowledgments: We are grateful to Ki Mun Nam and Dong Jin Lee for assistance with samplings and data analyses. Field surveys were conducted in accordance with the approval of “Research & Training Fishery” in the Ministry of Ocean and Fisheries, Korea.

Conflicts of Interest: The authors declare no conflict of interest.

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