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Numerical Modeling of Instream Flow for Corbicula Habitat Preservation in Aquatic Ecosystem of Seomjin River Estuary, South Korea

Chunggil Jung [1], Gayeong Lee [2] and Jongyoon Park [3,*]

[1] Forecast and Control Division, Han River Flood Control Office, 328 Dongjakdaero Seocho-gu, Seoul 06501, Republic of Korea; wjd823@korea.kr
[2] Research Center for Water, ECOLABS, Daehak-ro, Yeosu-si 59626, Republic of Korea; gyeongwork@naver.com
[3] Environmental Assessment Group, Korea Environment Institute, Sejong 30147, Republic of Korea
* Correspondence: jongyoonpark@kei.re.kr; Tel.: +82-44-415-7311

Abstract: South Korea's River Act mandates the maintenance of instream flow to support river ecosystems. This regulation has evolved from early river management practices to more advanced, systematic approaches, including the Instream Flow Incremental Methodology (IFIM). Despite these advancements, river management in South Korea, particularly in the Seomjin River Basin, continues to face numerous challenges. In this study, a three-dimensional numerical model was developed to simulate the hydrodynamic and salinity conditions of the Seomjin River Estuary. This study proposes optimal instream flows to support critical habitats for the Corbicula bivalve, which has seen a significant decline due to salinity intrusion by environmental changes. Using the Environmental Fluid Dynamics Code (EFDC), the model simulates salinity and river discharge with calibration and validation by incorporating historical data. Subsequently, this study evaluates how river discharge affects salinity in four major Corbicula habitats (Dugok, Shinbi, Mokdo, and Hwamok). Finally, we determine the minimum flow (instream flow) needed to sustain Corbicula habitats. In short, this study found that the minimum flow rates (instream flow) required to meet target salinities varied significantly across these sites and under different tidal conditions. These findings highlight the necessity of adapting river flow management practices to preserve the ecological health for Corbicula in the Seomjin River Estuary. Furthermore, this study suggests integrating an additional water supply to be used with local water management plans by suggesting short-term and long-term alternatives in order to sustain adapting river minimum flow (instream flow).

Keywords: instream flow; salinity; Seomjin river; EFDC; Corbicula; water supply alternatives

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1. Introduction

In South Korea, the maintenance of instream flows in rivers is legally grounded in the River Act. The calculation of instream flow was integrated into the formulation of basic river plans, with national announcements on instream flow made only twice, in 2006 and 2015, with the exception of occasional updates during the announcement of river plans. Historically, the concept of instream flow emerged naturally as people settled near rivers and engaged in activities such as transporting goods by boat or collecting food, including fish and shellfish. However, systematic research on this concept began in the 1940s in the western United States, where reduced river flows led to a decline in fish species, such as salmon [1]. In the 1970s, methodologies and conceptual frameworks for determining ecological flows were developed. Prior to the introduction of the Instream Flow Incremental Methodology (IFIM) [2], the predominant method for setting ecological flow in rivers in the United States (US) and United Kingdom (UK) involved defining the minimum flow as a percentage of the daily average flow to protect fish [3]. The IFIM assesses ecological flow by analyzing both macro- and micro-habitat requirements for fish using modeling techniques such as Physical Habitat Simulation (PHABSIM), which remain prevalent today. Currently, various terms, such as environmental flow, ecological flow, and minimum flow, are used to refer to the necessary flow for river conservation. Brown et al. [4] noted that instream flow encompasses non-environmental purposes, such as water quality improvement and hydroelectricity, and differs from environmental flow by not accounting for natural flow variability. Tharme [5] reported that approximately 207 methods for calculating environmental flows were employed across 44 countries. In South Korea, Kang et al. [6] highlighted the need for hydrological methods that consider flow variability and adjustments to required flow categories. Kang et al. [7] examined monthly variations in instream flow considering flow fluctuations and climate change scenarios in the Geum River Basin.

Additionally, the construction of major facilities, such as the Seomjin Dam (1965) and Juam Dam (1992) in the upper reaches of the Seomjin River, has led to fluctuations in downstream water levels and reduced discharge as part of economic development plans [5]. Environmental impacts including sedimentation and landfilling in estuaries have contributed to seawater intrusion into freshwater areas, thereby expanding the estuarine environment. Various measures have been proposed, including increasing the discharge volumes from the Seomjin and Juam Dams, reallocating water stored for hydropower to maintenance purposes, improving management systems, and developing water distribution plans. However, these measures have not been implemented based on a rigorous scientific evaluation of their pre-project impacts [8].

In the management of river water in South Korea, maintaining instream flow involves ensuring water quality and sustaining aquatic ecosystems, with human water use being a lower priority. Therefore, instream flow represents a fundamental and minimal prerequisite for integrated water management, with the Seomjin River Estuary posing a particularly challenging environment. The Seomjin River, the fourth largest river in South Korea, remains largely undeveloped and lacks embankments, dams, and significant riverside development. However, the habitat of Corbiculidae, particularly Corbicula, has drastically diminished in the Seomjin River estuary, leading to a significant decline in Corbicula resources. However, comprehensive scientific analyses of the causes of and potential solutions to these issues are lacking [9]. Corbiculae, small filter-feeding bivalves found in freshwater and brackish environments, are of both commercial and ecological importance for water purification. On the Seomjin River, Japanese Corbiculae account for approximately 30% of South Korea's Corbicula production. Nonetheless, high-salinity intrusion from seawater encroachment in the estuary is expected to affect Corbicula habitat, size, and growth [10]. Fishermen in the Sumjin River estuary area claim that the relationship between salinity concentration and river flow rate affects the productivity of the Corbicula (freshwater clam) ecosystem. In this context, studies by Miguel Cañedo-Argüelles et al. (2012) [11] and Metogbe Belfrid Djihouessi (2024) [12] involve simulating various flow scenarios to analyze how fluctuations in water levels and salinity impact biodiversity. They assess the seasonal and annual flow patterns necessary to maintain the ecological integrity of the delta, which is under threat from climate change and human activities. Therefore, this study accepted the relationship between flow rate and salinity concentration through validated findings, theoretical hypotheses from prior studies, and field experiments.

Local residents in the Seomjin River Estuary are primarily concerned with securing instream flow, decreasing Corbicula production, and identifying the causes of these issues. The reduction in Corbicula resources is attributed to factors such as decreased freshwater inflow, which has led to increased salinity and deteriorated water quality in the Seomjin River. To address these challenges, this study's aims are the following: (1) develop a three-dimensional numerical model using the Environmental Fluid Dynamics Code (EFDC) to simulate current conditions in the Seomjin River estuary, and (2) use this model to propose optimal maintenance flows for key Corbicula habitat areas using previous studies [13,14].

This study has clear differences with previous works [13,14]. The final result of this study was a simulation and analysis of salinity intrusion distance using a validated model, aiming to suggest suitable habitat zones to mitigate salinity impacts [13]. Similarly, study [14] focused on building scenarios to reduce high salinity levels in affected areas using a validated model, ultimately aiming to develop strategies for salinity reduction. In contrast, while this study also uses a validated model for analysis, it specifically focuses on estimating the required flow in key areas to maintain the optimal salinity level for Corbicula (freshwater clam) habitats. This study is more fundamental than those studies, introducing a new application method for river instream flow currently conducted at the national level. As a result, our findings are the closest to practical water management and are being directly applied in national policy, with ongoing evaluation. Therefore, while the methodology of using the same model aligns with existing studies, the final outcome (required flow) and the methodology to derive it show clear distinctions. Moreover, this study stands out due to its direct reflection in national policy, underscoring its practical relevance.

2. Materials and Methods

2.1. Focus Area in Seomjin River Basina

The Seomjin River Basin, located in the central–western region of South Korea's southern coast, is one of the country's five major river basins from South Korea. Jung et al. and Lee et al. [13,14] explained the environmental characteristics of the basin.

This study focused on an open estuary approximately 10–15 km from the river mouth, where Corbiculae are harvested by local fishermen, as this area serves as their primary habitat. Since the early 2000s, fishermen have reported damage to Corbicula habitats due to the increasing intrusion of high-salinity seawater. The study aimed to quantify the extent and range of salinity intrusion affecting the habitat, using optimal salinity levels for Corbiculae (between 15 and 20 psu) as identified in previous research [15].

As illustrated in Figure 1, the Seomjin River estuary in South Korea provides critical breeding grounds for Corbiculae, located 10–15 km downstream near the Seomjin Bridge and Seomjin River Bridge. Although fishermen have suggested that Corbiculae may also inhabit the Hwamok area, located 5–10 km downstream, this has not been confirmed. The Hwamok area has also undergone significant marine changes, reducing the likelihood of it serving as a viable habitat for Corbiculae. Therefore, in this study's EFDC model analysis, we focused on the primary breeding areas near the Seomjin and Seomjin River Bridges (specifically in the Dugok, Sinbi, and Mokdo regions) while also including the Hwamok area for further analysis.

2.2. Estimation Methods for Instream Flow

Scientific inquiry into estimating instream flow for river maintenance emerged in the 1970s. Before the introduction of the IFIM [2], the concept of minimum flow, which defines the flow rate as a certain percentage of the average daily flow to protect fish, was the main method used to set environmental flows in the US and UK [3]. The core of the IFIM is Physical Habitat Simulation, which determines flow by linking the habitat conditions of the target species with the hydrological conditions of the river. Petts [16] categorized the main methods for evaluating environmental flows into three approaches: the hydrological approach represented by the Range of Variability Approach (RVA) developed by Richter et al. [17], the habitat approach represented by PHABSIM and its derived methods, and decision-making methods involving expert groups. Petts emphasized that future environmental flow settings should consider climate change and patterns, geomorphological changes and cycles, biological diversity, and the harmony of traditions and customs. However, recent developments have indicated that integrated water resource management and the relationship between environmental flows are included in eco-hydrology [18]. These approaches primarily target ecosystems, and have evolved from protecting key species to considering ecosystem diversity and the overall river environment, including the evaluation of flow rates.

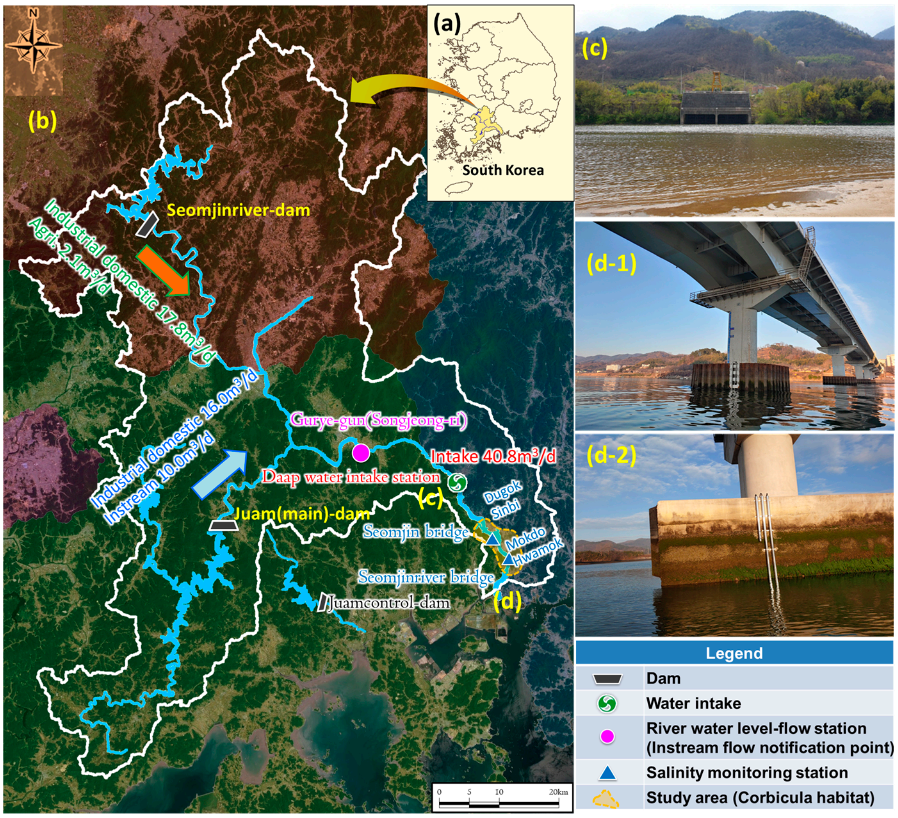

Figure 1. Monitoring sites in focus area. Multi-purpose water supply at Seomjin river and Juam dams, instream flow notification station, and river water intake at Daap. (**a**) From map of South Korea, the study area has been zoomed out including Seomjin Rive Basin, (**b**) map of the whole Seomjin River Basin, (**c**) Daap water intake facility, (**d-1**) salinity monitoring site at Seomjin bridge, (**d-2**) salinity monitoring site at Seomjin River bridge.

In South Korea, the concept of environmental flow first appeared in the River Act Enforcement Decree (Presidential Decree No. 5783 1971). Currently, the definitions and elements necessary for calculating the environmental flow are specified by the River Act and its Enforcement Decree. Traditionally, the environmental flow has been defined as the minimum flow required to maintain the main functions of a river [7]. Research on methods for calculating environmental flows began with the development and application of these methods in 1995 [19]. In South Korea, most studies have defined instream flow and management flow, suggesting the consideration of factors such as flow rates, water quality, ecosystems, water use, and landscape for determining environmental flow. According to domestic guidelines [20], the required environmental flow must be determined by considering factors such as water quality conservation, ecosystem protection, and other necessary elements (e.g., landscape preservation, prevention of seawater intrusion, estuary blockage prevention, protection of river facilities and water intake sources, and maintenance of groundwater levels). Some of these additional factors, such as seawater intrusion prevention, estuary blockage prevention, the protection of river facilities and water intake sources, and the maintenance of groundwater levels, involve subjective and non-quantifiable methods. Previous research [8] reevaluated the environmental flow of the Seomjin River Basin by focusing on water quality, ecosystems, and the average low-flow rate, which is currently a standard item for the main river section.

2.3. Salinity for Sustainable Corbicula Habitation

To determine the habitat standards for Corbicula, we reviewed the experimental literature to estimate the appropriate environmental conditions. Previous studies related to Corbiculae in the Seomjin River system have investigated various factors, including the growth and survival of Japanese Corbicula larvae under different breeding conditions [21], the effects of seawater salinity from the West Sea on the infiltration and mortality of *Corbicula japonica* [22], salt tolerance of the Yamato shijimi [23], and guidelines for enhancing fishing grounds in lakes and ponds [24]. Although these studies focused on the same species found in the Seomjin River, differences in habitat locations limited the direct application of their findings to Corbiculae in the Seomjin River.

Research in South Korea has also examined the distribution and growth characteristics of Japanese Corbicula in the Seomjin Estuary under varying salinity gradients [25]. Monitoring salinity changes (spring and neap tides) and Corbicula habitat density revealed that the highest habitat density occurred in areas with salinity ranging from 10 to 15 psu [25]. However, the intermittent nature of salinity measurements posed limitations in accurately assessing the habitat conditions. Additionally, Jung et al. and Japan's Fisheries Agency [13,24] conducted feeding and filtration experiments to directly evaluate the impact of salinity on Corbiculae in the Seomjin River.

In this study, habitat criteria for Corbiculae were proposed based on findings from Seo et al., the Korea Institute of Ocean Science and Technology, and Lee et al. [25–27]. The majority of Corbiculae in the Seomjin River are freshwater species that thrive in low-salinity environments, with an optimal salinity range identified between 15 and 20 psu.

2.4. EFDC Model Description

This study used the Environmental Fluid Dynamics Code (EFDC) model as numerical modeling. It is used to simulate salinity dynamics and transportation in the linkage between a marine and river. For more detailed information, one can refer to the following previous studies [13]. There are many studies explaining the structure of the model and the components of the equation regarding groundwater and salinity [28–30]. Also, Kim [29] showed globally hydraulic and water-quality dynamics through a thorough understanding of the model's hydraulic and water quality analyses [30]. The EFDC model has been used to study flow dynamics and manage saltwater intrusions. Son [31] used the EFDC model to assess salinity movement into river and mitigate salinity-induced damage. Additionally, ref. [30] developed the Hydrological Simulation Program—Fortran (HSPF) and modified the EFDC model to better simulate the conditions and flow through multifunctional weirs in the main river channels. Further details on the model can be found in the literature [32,33]. There are many numerical models to simulate estuarine conditions. Nevertheless, the EFDC model is highly effective for simulating estuarine conditions due to several key strengths. The strengths of this model are that it has comprehensive hydrodynamic capabilities, can perform multi-dimensional simulation, is a flexible grid system, has sediment and water quality modules, and is an open-source and customizable model. These strengths make the EFDC a versatile and reliable tool for simulating estuarine systems, allowing detailed assessments of flow, salinity, sediment, and pollutant transport under natural and anthropogenic influences. The primary objective of this study was to select a model that would be most suitable for practical hydrological applications, particularly one that offers ease of use and yields clear, intuitive results. Consequently, the EFDC model was applied in this research.

2.5. Model Application for Estimation of Instream Flow Using EFDC Modeling

This study concentrated on modeling and simulating the focus area, encompassing both the downstream river section and the surrounding estuarine region. To accurately represent the downstream flow dynamics, we used streamflow data from observation stations at Gurye-gun (Songjeong-ri) as the upstream boundary conditions. Tidal-level data were used at three stations (Gwanyang Bay, Yeosu, and Samchenopo) for the downstream boundary conditions. The model also incorporated facilities that influence river flow, with a constant daily extraction of water from the river. Real-time water temperature and other data (precipitation, temperature, solar radiation, humidity, and wind speed) were obtained from observation stations in Hadong-gun. Further details on the process are available in

Jung et al. and Lee et al. [13,14]. The EFDC model used in this study was based on the one previously established by Jung et al. and Lee et al. [13,14], ensuring continuity.

Our goal was to derive the optimal salinity concentration for Corbicula habitats based on historical ecological experiments and to adjust the streamflow boundary conditions at Gurye-gun (Songjeong-ri) using a pre-existing model to estimate the minimum flow required to maintain the appropriate salinity for Corbiculae. To achieve this, we first conducted salinity modeling at four key Corbicula habitat sites (Dugok, Shinbi, Mokdo, and Hwamok). Next, we developed a flow–salinity regression model by analyzing the salinity modeling results from the EFDC model and the streamflow data from Gurye-gun (Songjeong-ri). Finally, using the regression model, we estimated the minimum flow (maintenance flow) required in Gurye-gun (Songjeong-ri) to achieve the target salinity concentrations at the four key Corbicula habitat sites (Figure 2). The four key Corbicula habitat sites were Dugok (18–20 km from the estuary), Shinbi (13–15 km), Mokdo (9–13 km), and Hwamok (7–9 km). Among these, Hwamok and Mokdo were found to have the most active seawater salinity intrusion.

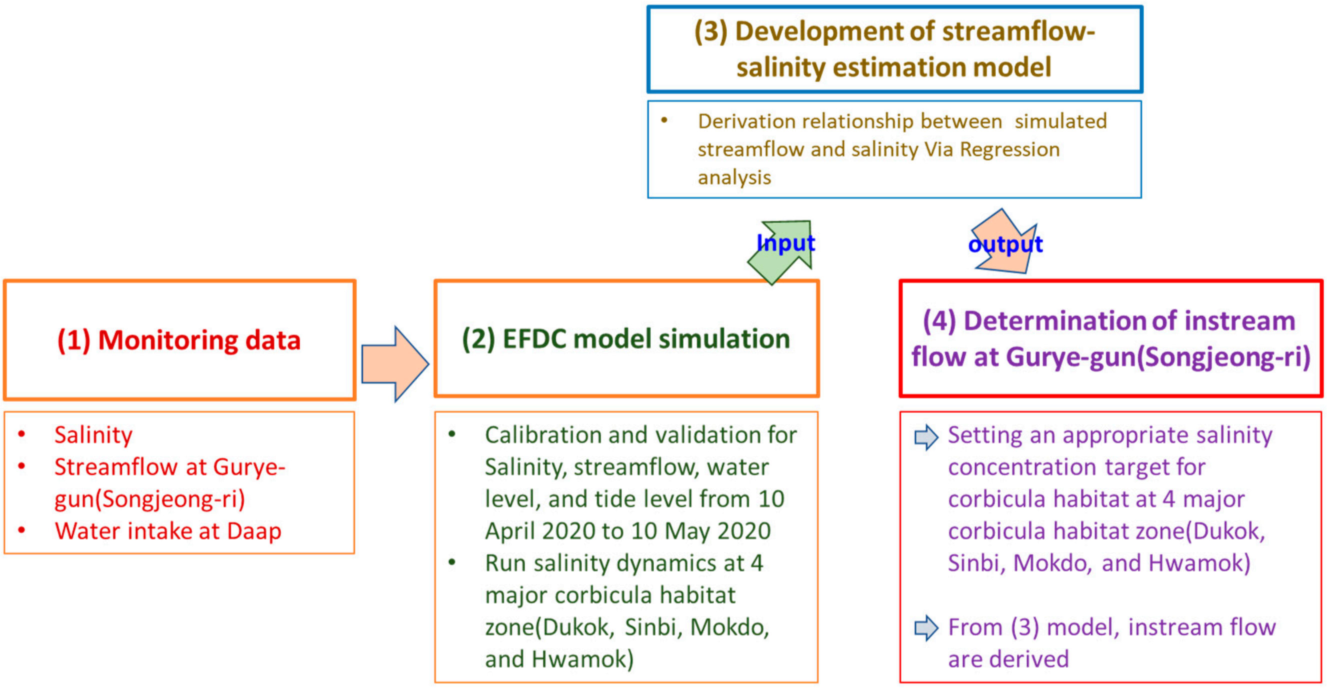

Figure 2. Process of model application for estimating instream flow.

3. Results

3.1. Application of Input Data for Simulation of Current River Environment

3.1.1. Daap Water Intake and Riverbed Cross Section by Sand Mining Works

The Daap Water Intake Facility is located about 26 km upstream from the Seomjin River's mouth. It supplies up to 400,000 tons of water per day, sourced from the Seomjin Dam (178,000 tons), Juam Dam (160,000 tons), and the Seomjin River itself (62,000 tons). This water serves both residential and industrial needs in the Jeonnam Eastern Region, including the Yeosu National Industrial Complex. Since its establishment in 1978, the facility has encountered challenges, particularly after sand mining activities in 1994 caused the riverbed to drop by approximately 2 m at the intake point. This raised concerns about seawater intrusion and difficulties in water withdrawal. In response, the intake location was relocated 4.2 km upstream in 2005, and the facility's capacity was expanded (Table 1) [13,14].

Table 1. Status of official river maintenance flow (instream flow) at Gurye-gun (Songjeong-ri) site.

Daap Facility	Juam Dam	Seomjin River Dam	River
Water withdrawal volume (10^4 m^3/d)	16.0	17.8	6.2
Water intake condition	≥7.94 m^3/s (7.94 = 5.50 (instream flow, 1979 yr) + 2.06 (water secured from Seomjin Dam) + 0.38 (existing water rights))		

In other words, the Daap Water Intake Facility primarily draws water from dams, but also extracts up to 62,000 tons per day from the river. Consequently, it operates under constraints to mitigate the impacts on the Seomjin River Estuary during low-flow conditions and prevent excessive river water extraction. Since 2018, the facility has been authorized to withdraw water only when the river flow in Gurye-gun (Songjeong-ri) exceeds 7.94 m^3/s (Table 1).

Sand mining in this area occurred for 27 years (1972 to 1998) and the government banned new sand mining permits to protect the river in 1999. Between 1981 and 1994, sand mining exceeded one million cubic meter annually, peaking at 2.7 million cubic meter in 1994 (2.5 times the amount in 1978). The most intense sand mining activity took place between 1978 and 1989 within the primary Corbicula habitat, located between Corbicula activity zones. This resulted in a significant drop in riverbed elevation, with reductions reaching up to 12.58 m and an average decrease of 4.94 m throughout the habitat zone. The lowering of the riverbed has directly contributed to increased salinity intrusion. More detailed accounts of sand mining can be found in the literature [13,14]. Figure 3b illustrates the riverbed elevation changes caused by sand mining over the last 40 years in Songjeong-ri, Gurye-gun. The figure shows a maximum riverbed lowering of 1.28 m in Gurye-gun (Songjeong-ri), and compared to 1978, there was a significant increase in salinity intrusion distance by 2017, likely affecting the estuarine Corbicula habitat.

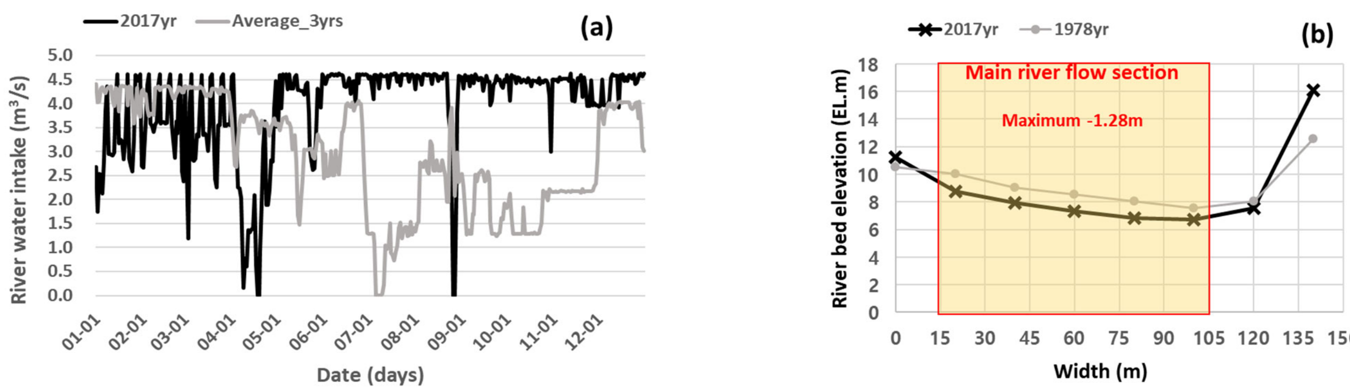

Figure 3. Hydrological data measured using current instream flow criterion: (**a**) daily Daap water intake, and (**b**) changes of riverbed cross-section at Gurye-gun (Songjeong-ri) station.

3.1.2. Measured Hydrological Data: Streamflow, Salinity, and Tide

This section focuses on the establishment of the observed data necessary to calibrate the EFDC model, as shown in previous papers [13,14]. Our objective was to assess the salinity levels in the Seomjin River estuary and examine their relationship with factors such as river discharge, riverbed changes, and tidal levels. To achieve this, we installed fixed salinity gauges at two locations (Seomjin Bridge and Seomjin River Bridge) to create a time-series dataset of salinity concentrations (Figure 1). Since 15 February 2020, these gauges have been installed at three different depths (upper, middle, and bottom) from riverbed location to provide continuous monitoring.

Salinity at Seomjin Bridge fluctuated between 0.0 and 23.8 psu, with an average value of 3.3 psu. Meanwhile, at Seomjin River Bridge, salinity levels varied from 0.0 to 29.7 psu, with an average of 14.3 psu. Since seawater salinity is generally considered to be above 30 psu [34], the river water near Seomjin River Bridge became noticeably more saline during neap tides, driven by tidal changes ranging from EL.m −2.36 to EL.m 2.0 at the Gwangyang station.

The river flow in Gurye-gun (Songjeong-ri) varied and increased with precipitation. Without rainfall data, the flow remained steady between 17 and 20 m/s, supplemented by releases from the dam. Since 2006, the fixed river maintenance flow at Gurye-gun (Songjeong-ri) has been 4.62 m^3/s. During the EFDC simulation period from 15 February to 9 May 2020, there were no days when the flow was below the maintenance flow. However, during the drought year of 2017 in the Seomjin River Basin, the flow at Gurye-gun (Songjeong-ri) dropped below the intake condition of 7.94 m^3/s for four days, reaching a minimum of 6.45 m^3/s. This shortage led to the implementation of intake restrictions at the Daap Water Intake Facility. Although these restrictions are aimed at ensuring minimal flow for the normal functioning of the Seomjin River Estuary during droughts, this level of flow does not fully meet the growth conditions required for key estuarine species such as Corbicula.

3.2. Applicability of Model Using Verification Analysis

Calibrating and validating the models are essential to assess their accuracy and performance. This study utilized a model developed in previous research, with detailed information available in [13]. The Nash–Sutcliffe Efficiency (NSE) is a common metric used to evaluate hydrological model performance. It measures the accuracy of model simulations by comparing them to observed data, with values ranging from $-\infty$ to 1. An NSE value closer to one indicates a closer match between model predictions and actual observations [35]. The accuracy of modeling is assessed by making a comparison between simulated and observed results, with NSE values ranging from $-\infty$ to 1. A value near 1 signifies a strong agreement between the model's predictions and the actual measurements [35]. All modeling results (downstream flow, salinity, tidal levels) indicated satisfactory indices during calibration and validation periods from 10 March 2020 to 10 May 2020 (each month for two months). So, all information and results related to simulation for verification can be referenced from Jung et al. [13].

3.3. Simulation Results of Flow Rate and Salinity Concentration in Corbicula Habitat

To simulate the salinity in the Seomjin River estuary based on streamflow at the Gurye-gun (Songjeong-ri) site, we categorized the observed daily average flows from the past 10 years during the non-flood season (November to March) into eight ranges, with maximum (40 m^3/s) and minimum (5 m^3/s) values. Additionally, to account for the impact of the Daap Water Intake Facility on estuarine flow, we used four flow ranges based on the actual intake quantities (2.523, 3.125, 3.192, and 4.630 m^3/s). The Seomjin River estuary is influenced more by tides than by river flow; therefore, we analyzed salinity trends for both spring and neap tides.

Table 2 shows that the salinity concentrations in the bottom layer were generally higher than those at the surface based on simulated results. As Corbicula, a key species, lives on the riverbed, bottom salinity is crucial to their habitat. The bottom salinity at Dugok, Shinbi, Mokdo, and Hwamok ranged from 0.4 to 14.2 psu (average 4.3 psu), 5.4 to 20.5 psu (average 11.4 psu), 10.3 to 23.2 psu (average 15.7 psu), and 26.4 to 29.5 psu (average 27.8 psu), respectively, showing an increase of 0.2 to 2.8 psu compared to average salinity. The salinity difference between upstream (Dugok) and downstream (Hwamok) was 15.3 psu at 5 m^3/s and 26.0 psu at 40 m^3/s. As the Songjeong flow increased, the salinity changes at the upstream and downstream sites became more pronounced than those at the surface. During neap tides, salinity concentrations at Mokdo and Hwamok were similar, whereas at Shinbi and Mokdo, salinity increased, indicating salinity stratification during the neap tide. The vertical salinity distribution during neap tide showed that reduced seawater inflow and strong salinity stratification led to a greater influence of streamflow with increasing downstream effects. The differences increased downstream, and the impact of streamflow was less than that of the average salinity.

Table 2. The simulated salinity concentrations at the bottom layer using EFDC modeling of the major sites.

Discharge at Gurye-gun (Songjeong-ri) (m^3/s)	Daap Intake (m^3/s)	Model Simulated Result (psu)							
		Dugok		Sinbi		Mokdo		Hwamok	
		Spring Tide	Neap Tide	Spring Tide	Neap Tide	Spring Tide	Neap Tide	Spring Tide	Neap Tide
5	2.523	12.2	11.7	19.3	23.3	22.4	25.0	29.3	29.6
	3.125	13.2	12.1	19.9	23.4	22.8	25.1	29.4	29.6
	3.912	14.8	12.7	20.8	23.5	23.5	25.2	29.5	29.7
	4.630	16.5	13.4	21.7	23.6	24.1	25.3	29.7	29.8
10	2.523	5.8	8.5	14.4	22.7	18.5	24.3	28.5	29.3
	3.125	6.1	8.8	14.7	22.8	18.8	24.4	28.6	29.3
	3.912	6.6	9.1	15.2	22.9	19.2	24.4	28.6	29.4
	4.630	7.2	9.5	15.7	23.0	19.6	24.5	28.7	29.4
15	2.523	3.4	6.2	11.7	22.1	16.3	23.6	28.0	29.1
	3.125	3.5	6.4	11.9	22.2	16.4	23.6	28.0	29.2
	3.912	3.7	6.6	12.2	22.3	16.7	23.7	28.1	29.2
	4.630	4.0	6.9	12.5	22.3	16.9	23.8	28.1	29.2
20	2.523	2.2	4.4	9.8	21.5	14.6	23.0	27.6	29.0
	3.125	2.2	4.5	10.0	21.5	14.7	23.0	27.6	29.0
	3.912	2.4	4.7	10.2	21.6	14.9	23.1	27.7	29.0
	4.630	2.5	4.9	10.4	21.7	15.1	23.2	27.7	29.0
25	2.523	1.4	3.0	8.4	20.9	13.2	22.4	27.3	28.8
	3.125	1.5	3.1	8.6	20.9	13.4	22.4	27.3	28.8
	3.912	1.6	3.3	8.8	21.0	13.5	22.5	27.4	28.8
	4.630	1.6	3.4	8.9	21.1	13.7	22.5	27.4	28.9
30	2.523	0.9	2.0	7.2	20.2	12.1	21.7	27.0	28.6
	3.125	1.0	2.1	7.3	20.3	12.2	21.7	27.0	28.6
	3.912	1.0	2.2	7.5	20.4	12.3	21.9	27.0	28.7
	4.630	1.1	18.54	7.6	20.5	12.5	21.9	27.1	28.7
40	2.523	0.4	17.36	5.3	18.7	10.2	20.3	26.3	28.2
	3.125	0.4	16.03	5.4	18.8	10.2	20.4	26.3	28.2
	3.912	0.4	14.82	5.5	18.9	10.4	20.5	26.4	28.3
	4.630	0.4	13.72	5.6	19.0	10.4	20.6	26.4	28.3

Based on the simulation results, maintaining a salinity range of 15–20 psu at the Dugok site supported the highest distribution of Corbiculae during both spring and neap tides under minimum river flow and maximum intake conditions. In the Shinbi and Mokdo areas, this salinity range was maintained during spring tide but exceeded 20 psu during neap tide due to salinity stratification. Finally, the Hwamok area had high salinity levels of approximately 30 psu [34], making it unsuitable for Corbicula habitats.

3.4. Estimating Relationship Between River Flow Rate and Salinity Model and Derivation of River Maintenance Flow (Instream Flow)

In estuarine environments, salinity generally follows a power law relationship with river discharge, where the exponent (power-dependence coefficient b) indicates the degree to which freshwater affects salinity [36]. To anticipate future changes in optimal salinity conditions for Corbiculae, we simplified the salinity data derived from the EFDC model to an exponential function based on river discharge (Figure 4).

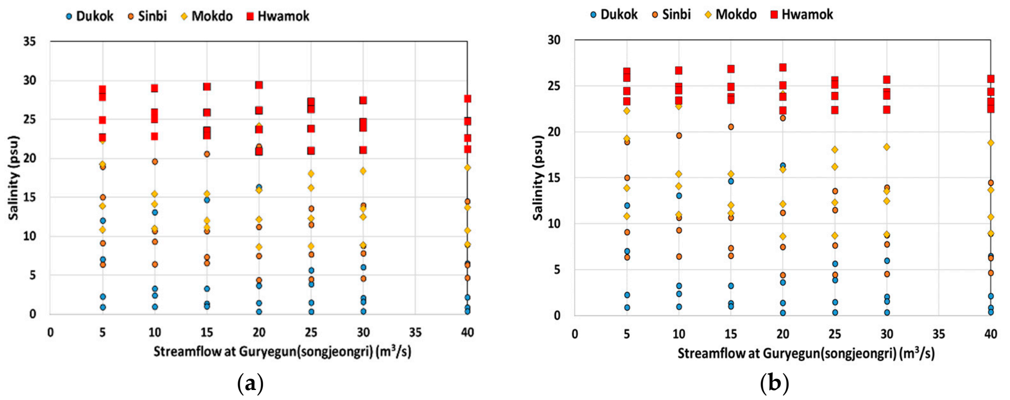

Figure 4. Estimation of relationship between streamflow and salinity using Daap water intake and with streamflow at Gurye-gun (Songjeong-ri) station during (**a**) spring tide and (**b**) neap tides.

In this study, we developed a quantitative predictive model for salinity based on Gurye-gun (Songjeong-ri) discharge and average salinity over the entire period, as well as during spring and neap tides, at the Dugok, Shinbi, Mokdo, and Hwamok sites. The model is expressed as S(salinity, psu) = aQ(Songjeong discharge, $m^3/s)^b$. This equation defines the relationship between the flow rate at Gurye-gun(Songjeong-ri) and the salinity concentration at major sites in the Seomjin River estuary as a regression formula. Here, a and b are dimensionless regression units that serve as coefficients to adjust for the gradient of salinity increase or decrease relative to flow rate and to correct for quantitative unit differences. The results, shown in Table 3, indicate that all correlation coefficients are above 0.9, suggesting that the model is applicable. Additionally, the exponent values for the entire period decrease from –1.114 at the upstream Dugok site to –0.123 at the downstream Hwamok site, indicating a reduction in the effect of Gurye-gun (Songjeong-ri) discharge on salinity downstream. This suggests that, similar to the EFDC simulation results, the influence of tidal effects or salinity stratification becomes more significant downstream. For spring tide, the exponent decreases from –1.318 at Dugok to –0.148 at Hwamok, and for neap tide, it decreases from –0.941 to –0.081. This shows that Gurye-gun (Songjeong-ri) discharge has a greater impact during spring tide compared to neap tide.

Table 3. Regression exponential function and predicted instream flow for target salinity at major sites during spring and neap tides.

Coefficients	**Dugok**		**Sinbi**		**Mokdo**		**Hwamok**	
	Spring	**Neap**	**Spring**	**Neap**	**Spring**	**Neap**	**Spring**	**Neap**
A	118.267	52.678	56.592	30.173	46.589	32.246	37.846	30.859
B	–1.318	–0.941	–0.625	–0.220	–0.418	–0.231	–0.148	–0.081
Salinity	$118.267Q^{-1.318}$	$52.678Q^{-1.941}$	$56.592Q^{-0.625}$	$30.173Q^{-0.22}$	$46.589Q^{-0.418}$	$32.246Q^{-0.231}$	$37.846Q^{-0.148}$	$30.589Q^{-0.081}$
Target salinity (psu)	10	10	15	15	15	15	20	20
Predicted instream flow (m^3/s) by regression function	7	7	9	25	16	28	76	>100

Using a simplified salinity–discharge regression model, we estimated the minimum river flow required to achieve the target salinity at each key site based on the Songjeong discharge. We set the target salinities to 10 psu for Dugok, 15 psu for Shinbi and Mokdo, and 20 psu for Hwamok, considering the salinity range of 15–20 psu derived from the existing literature and the practical feasibility of achieving these levels while minimizing ecological impacts. To achieve these target salinities, the estimated minimum river flow rates over the entire study period were 7 m^3/s for Dugok, 12 m^3/s for Shinbi, 21 m^3/s

for Mokdo, and 92 m^3/s for Dugok, Shinbi, Mokdo, and Hwamok, respectively. During spring tide, the required flow rates ranged from 7 to 76 m^3/s, with the flow rate at Dugok remaining the same as the overall period but decreasing for Shinbi, Mokdo, and Hwamok. During the neap tide, the required flow rates were estimated to range from 7 to over 100 m^3/s, showing a significant increase for Shinbi, Mokdo, and Hwamok. To achieve 20 psu at Hwamok, a discharge of more than 100 m^3/s is necessary (Table 3).

4. Discussion

According to the results, as shown in Table 4, achieving the target salinity during spring tide required flows of 7 and 16 m^3/s at the respective sites. For three sites, excluding Hwamok, these flow rates were sufficient to meet the target salinity during spring tide. At the Songjeong-ri site, the 10-year average (2011–2020) for the minimum (Q275) and low flow (Q355) rates are 21.0 and 14.0 m^3/s, respectively. These values suggest that, under average conditions, river flow is adequate to maintain the target salinity throughout the year. However, during neap tide, the required flow rates significantly increased at all sites except Dugok. This is because of seawater intrusion and retention in the estuary, which leads to higher salinity and notable salinity stratification in the lower river layers. While the flow rates at Shinbi and Mokdo during neap tide require maintenance levels similar to those of Q275, an additional water supply might be needed, whereas Hwamok is already fully saline and does not require additional river flow. Thus, the regions requiring management are Dugok, Shinbi, and Mokdo, with an additional water supply needed for Shinbi and Mokdo during neap tide.

Table 4. Final instream flow (m^3/s) considering Daap intake and number (days/yr) of days when maintenance flow is insufficient at Gurye-gun (Songjeong-ri) site.

Category		Dugok		Sinbi		Mokdo		Hwamok	
		Spring	**Neap**	**Spring**	**Neap**	**Spring**	**Neap**	**Spring**	**Neap**
Target salinity (psu)		10	10	15	15	15	15	20	20
Instream flow (m^3/s)		7	7	9	25	16	28	76	>100
Instream flow (m^3/s) with Daap intake(3.1 m^3/s)		10.1 (+3.1)	10.1 (+3.1)	12.1 (+3.1)	28.1 (+3.1)	19.1 (+3.1)	31.1 (+3.1)	79.1 (+3.1)	>100
Number of days when instream flow was insufficient (days/yr) in drought year	2009	118 days	118 days	148 days	291 days	280 days	300 days	327 days	329 days
	2015	3 days	3 days	9 days	200 days	85 days	233 days	352 days	356 days
	2017	9 days	9 days	52 days	270 days	166 days	287 days	344 days	348 days

To determine the number of additional water supply days, we added the average intake rate from the Daap Water Intake Facility (3.1 m^3/s) to the actual river flow at Gurye-gun (Songjeong-ri) to meet the required flow for the estuary. The number of days with insufficient flow during drought years, as shown in Table 4, indicates that even during the extreme drought of 2009, Dugok could maintain natural flow (including dam water supply) for 247 days, and Shinbi could sustain flow for 217 days during spring tide. Therefore, to reassess the instream flow required for Corbiculae, the following factors should be considered. Finally, for normal years, excluding drought periods, the currently suggested river flow is generally sufficient. Therefore, the criteria should be based on the average conditions for maintaining adequate flow.

Ultimately, this study emphasizes the importance of quantifying the shortfall and planning for future supply needs to ensure the consistent availability of instream flow under current water supply conditions. To achieve this, a water supply reliability analysis was conducted based on observed dam data and river water levels from the 29-year period of 1991–2019. According to the results in Table 4, it was deemed infeasible to supply the instream flow needed to meet target salinity during neap tide. Instead, the required instream flow was analyzed to meet salinity standards during spring tide. As shown in Table 5, in the Dugok area, all required instream flows were met over 26 years under current water supply conditions. However, in downstream areas such as Mokdo and Hwamok, the instream flow could not be secured every 5 and 3 years, respectively. Additional supplies of 24.2, 119.6, and 257.1 million m^3/year would be needed to meet these requirements. However, the effective storage of Sumjin River Dam, the primary water source for this study area, is 429 million m^3. In Hwamok, securing an additional supply equivalent to 28% of the dam's effective storage would be necessary. This volume, roughly equivalent to a 400 million-ton multi-purpose dam, is realistically unattainable, indicating the need for measures extending to the Mokdo district. Under current water supply conditions, it is necessary to prioritize operational strategies over structural solutions, such as the integrated operation of existing dams, reduction in non-essential hydropower water, and optimal estimation of water supply volumes. In this context, by implementing short-term reductions in non-essential hydropower and recalculating supply volumes to align with actual usage, it would be possible to secure an additional 48.7 and 70.9 million m^3, respectively. This approach would enable a stable supply of river maintenance flow to support Corbicula (freshwater clam) habitats throughout the year, including during drought periods. In conclusion of this discussion, long-term basin management plans should incorporate the water needs for estuarine ecosystems alongside the demands of existing users. By focusing on non-structural measures, a balanced, long-term water supply plan can be developed to support both aquatic ecosystem health (e.g., Corbicula) and help address the local water conflicts that have persisted over the past 40 years.

Table 5. Instream flow shortfalls and water resource securing measures.

Category			Dugok, Sinbi	Mokdo	Hwamok
Taget salinity (PSU)			10	15	20
Target instream flow (m^3/s)			10.40	17.00	23.00
Supply reliability (%)			96.2	80.8	63.4
Instream flow shortfall risk frequency			Once every 26 years	Once every 5 years	Once every 3 years
Total shortfall volume (million m^3/year)			24.2	119.6	257.1
Water resource securing measures (million m^3/year)	Mid-term	Optimal dam management	48.7 (Seomjinriver dam 38.3, Juam (main) dam 3.8, Boseongriver dam 2.8, Dongbok dam 2.8)		
	Long-term	Demand management for industrial and residential water (5~13% reduction)	26.9~53.8 (Redistribution of dam water supply) 5%: Dam agricultural water (18.1) + Dam domestic and industrial water (8.8) ⇒ 26.9 10%: Dam agricultural water (36.3) + Dam domestic and industrial water (17.5) ⇒ 53.8 13%: Dam agricultural water (47.8) + Dam domestic and industrial water (23.1) ⇒ 70.9		
	Total		75.6~119.6		

5. Conclusions

In conclusion, the Seomjin River Estuary has faced issues due to stakeholder complaints (from Gwangyang and Hadong residents), such as reduced flow due to dam construction and increased water intake at multi-pressure intake facilities. These changes have been attributed to decreased Corbicula production owing to salinity damage. To address these regional and integrated water management issues, this study focused on estimating the necessary flow for the Corbicula habitat at the Gurye-gun (Songjeong-ri) site, using ecological protection criteria as a basis for the proposed river maintenance flow (instream flow). In order for the results of this study to be applied in watershed management, it is essential to secure the required flow during times of shortage and drought, develop operational strategies for additional water supply, and manage upstream dams appropriately. This requires the establishment of both short- and long-term basin management plans and verification studies before these measures are institutionalized. Subsequent consultation with basin management authorities is also necessary. Ultimately, if these results are used as a foundation for verification research, and if integrated water management systems involving stakeholders are implemented, this study could help to lay the groundwork for resolving acute regional water conflicts that have persisted for the past 40 years. Also, as an open estuary, the Seomjin River estuary requires a foundational policy framework that addresses future water management strategies and mitigation measures in response to rising sea levels and other climate change impacts, as highlighted by Mohd et al. [37]. To improve water management practices over the next 40 years, it is essential to prioritize the development of policies that account for climate-related uncertainties. Such plans should be integrated into the state and regional water management master plans. Finally, future studies should conduct practical research to evaluate the feasibility of the proposed non-structural short- and long-term methods for securing additional water resources, as well as to develop structural techniques for an integrated water management strategy.

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