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## Article

# Cause Analysis of Salinity Intrusion by Environmental Changes Considering Water Intake and Sand Mining on Seomjin River Estuary Using EFDC Model for Maintaining Corbicula Habitats

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**Abstract:** Anthropogenic development can strongly influence natural river processes, leading to environmental changes that negatively affect important habitats and biodiversity, and consequently reduce economically important natural resources. This study investigated the effects of salinity intrusion on the habitat of the clam *Corbicula japonica* in the Seomjin River estuarine zone. We employed the Environmental Fluid Dynamics Code (EFDC) model, which incorporates topographic data and hydrological changes, to simulate salinity concentrations. Two salinity measurement facilities were installed in Seomjin River estuarine and operated to optimize the EFDC model. The results show that reduced flow rates due to intake have a negligible impact on the increased salinity. Maintaining optimal salinity (15–20 psu) during neap tides at the Seomjin River Bridge requires constant high flow rates, which poses significant challenges. Saltwater stratification is identified as the primary cause of pronounced salinity stratification, particularly during neap tides. Addressing this issue through river discharge and intake facility operation is challenging. Structural measures, including riverbed restoration and underwater barriers, are recommended to improve resistance to seawater intrusion. Future research should aim to develop scenarios to reduce salinity concentrations, quantify the reduction efficiency, and propose region-specific measures.

**Keywords:** Seomjin River; salinity intrusion; EFDC; saltwater stratification; estuarine environmental challenges; corbicula

## 1. Introduction

The Seomjin River, ranking fourth among South Korea's five major rivers, remained largely unaffected by man-made interventions such as estuary embankments or riverside development. However, since 1980, the construction and operation of key structures, such as the Seomjin River Dam, Juam Dam, Suo Dam, and Daap Water Intake in the upper reaches of the Seomjin River, coupled with landfill of Gwangyang Bay, have led to a reduction in freshwater inflow owing to the rise in sea level and the counterflow of seawater. This has caused a substantial influx of seawater into inland areas, resulting in estuarine marine-isation and posing a significant environmental challenge in the region [1]. Major facilities such as the Seomjin River Dam and Juam Dam on the Boseong River are situated in the upper reaches of the Seomjin River mainstream. The downstream flow was altered and discharge decreased owing to the construction of the expanded Seomjin River Dam in 1965 and the completion of the Juam Dam in 1992, in line with the government's economic development plan [2]. Additionally, various impacts, such as estuarine dredging and landfiling, have resulted in saline water inflow into the upper reaches of the estuary, causing gradual expansion [3]. Consequently, marine-isation of the Seomjin River has occurred, and the habitat and resource quantity and quality

of clams (genus *Corbicula*) inhabiting the Seomjin River estuary have significantly diminished. This emerging trend poses serious local issues such as aquaculture industry and agricultural damages, ; however, there is a lack of information on the causes of these problems.

Aside from being a commercially valuable and essential aquatic resource for human consumption, corbicula species play a crucial role in the purification of aquatic ecosystems as filter-feeding bivalves. In particular, the Seomjin River constitutes approximately 30% of South Korea's clam production. However, marine-isation in the Seomjin River has led to an increase in salinity, resulting in the intrusion of saline water into upstream areas of the estuary, including the upper reaches of the Ha River. This intrusion is anticipated to have adverse effects on clams, such as a reduction in suitable habitat and a decline in average clam size, growth rate, and flesh quality [4].

The decrease in corbicula resources can be attributed to the aforementioned factors, such as reduced freshwater inflow, which led to increased salinity and deteriorated water quality in the Seomjin River. However, research providing a simulation of flow patterns and salinity changes in the estuarine system, along with identification of the causes of these changes and optimal salinity levels for corbicula habitats, remains insufficient. The Environmental Fluid Dynamics Code (EFDC) is a representative model capable of simulating river flows and substance dynamics. The EFDC model has been applied globally in various studies, focusing primarily on tidal and water quality analyses of estuarine coastal areas [5,6]. In South Korea several studies have been completed on the use of models to understand flow dynamics and improve the management of saltwater intrusion. For example; Son [7] reevaluated saltwater intrusion and the prevention of salinity-induced damage in the Nakdong River Estuary using the EFDC model, Han [8] conducted numerical model experiments using finite-difference grid systems to investigate the characteristics of average tides in Gwangyang and Jinju Bays, Kwak [9] utilized the EFDC model to study the spatiotemporal mixing characteristics of Seomjin River discharge water, and Kang et al. employed the EFDC model to reproduce three-dimensional circulation patterns considering tides, water temperature, and salinity in the Gwangyang and Jinju Bays [10]. Kang et al. also investigated changes in the density-driven layer due to discharge from the Seomjin and Nam River dams. Although studies have been conducted on the formation and destruction processes of stratification due to freshwater inflow[11] and the behavioral characteristics and residence time of discharge water from the Nam River dam [12], there has been a lack of modeling for analyzing the causes and impacts of salinity intrusion in the Seomjin River estuary.

Therefore, this study aimed to elucidate the causes of salinity intrusion and increased high-salinity penetration distance in the Seomjin River estuarine zone, inhabited by *Corbicula japonica*, by simulating changes in salinity concentration based on past river environmental variations. To achieve this aim, a three-dimensional numerical model, specifically the EFDC, was developed for the mainstream and estuarine areas of the Seomjin River. In addition, actual tidal and water level measurements were recorded and salinity sensors were strategically placed within the target areas to establish a salinity dataset. This dataset was used as the basis for the model calibration and validation.

The results of the study will be used to ultimately establish management measures that can sustain the corbicula fishery by identify and present the causes of clam damage for national and local governments.

## 2. Materials and Methods

### 2.1. Study Area

The Seomjin River Basin, located in the central-western region of the southern coast of South Korea, is one of the five major river basins in South Korea. Geographically, it is situated between approximately 126° 51'50" and 127° 53'05" E and 34° 40'26" and 35° 50'0" N. The Seomjin River Basin covers an area of 4,913.22 km<sup>2</sup> with a river length of 222.14 km[13] (Figure 1). The mean elevation level (EL) was recorded as 301.58 m (Figure 2) [13]. The land use distribution comprises 876.29 km<sup>2</sup> of arable land, 3,400.61 km<sup>2</sup> of forested area, 67.12 km<sup>2</sup> of developed land. Approximately 69.2% of

the total watershed area consists of forested land [13]. Upstream of the Seomjin River main stream, key facilities such as the Seomjin and Juam dams on the Boseong River are strategically located. Owing to the expansion of the Seomjin Dam in 1965 and the completion of the Juam Dam in 1992, downstream sulfur fluctuations and reduced discharge water occurred, primarily to supply a substantial amount of water outside the watershed, in line with the government's economic development plan. Concurrently, various impacts such as sand mining and landfilling in the estuary have led to an influx of saline water into the upstream estuary, causing long-term ecological changes in the watershed [13].

The study area represents tidal river zone located approximately 10–15 km away from the open estuary. Corbicula mainly inhabit this region and are predominantly harvested by local fishermen. However, since the early 2000s, there have been persistent complaints from fishermen owing to the intrusion of high-salinity seawater into corbicula habitats, resulting in reduced abundance, size, and quality of the resource. In this study, we aimed to quantify the penetration amount and intrusion distance of high-salinity seawater that affects corbicula. To achieve this, we selected the optimal salinity concentration for corbicula habitat based on the available literature, specifically choosing 15 to 20 psu as the suitable salinity concentration range [14].



**Figure 1.** Study area and monitoring sites; map of the Seomjin River Basin, Dam, Water intake, water level station, salinity monitoring stations.

## 2.2. Description of the EFDC Model

The Environmental Fluid Dynamics Code (EFDC) is a three-dimensional numerical model developed by the Virginia Institute of Marine Science in the United States. It was designed to simulate the fluid dynamics and material transport in coastal, estuarine, reservoir, wetland, and lake environments. The model facilitates the reproduction of seawater flow and material movement, offering ease of two-dimensional and three-dimensional vertical and horizontal modeling. The EFDC is a comprehensive model applicable to marine and freshwater environments for predicting water flow and water quality changes. It comprises four main components: hydrodynamics, water quality, sediment transport, and toxicological analysis. The hydrodynamic component employs a three-dimensional groundwater equation that considers temperature and salinity. It models 22 state variables including temperature, salinity, dissolved oxygen, three groups of phytoplankton, and carbon, nitrogen, phosphorus, and silica cycles [15]. Because the EFDC model is widely used worldwide, it is recommended that users of the model refer to published literature, for example Kim

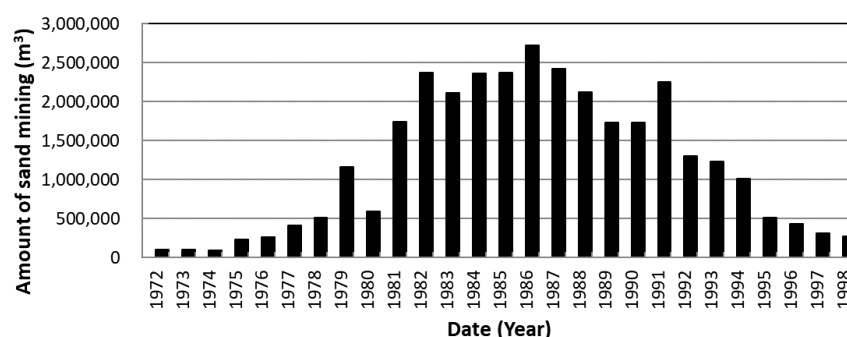
et al., for a comprehensive understanding of the model's hydraulic and water quality analysis structure [16].

### 2.3. Data Setup for Simulation Model

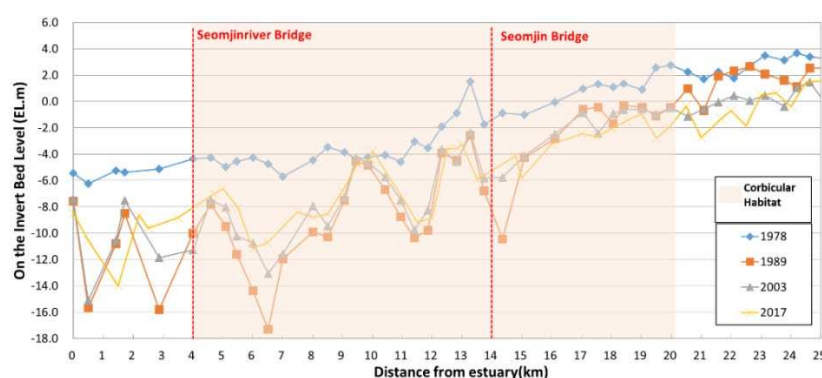
#### 2.3.1. Environmental Changes Data at Daap Water Intake and Sand Mining Works

The Daap Water Intake Facility is located in Gosari, Gwangyang City, Jeollanam-do, approximately 26 km upstream from the mouth of the Seomjin River (Figure 1a). It supplies up to 400,000 tons of water daily (including 178,000 tons from the Seomjin Dam, 160,000 tons from the Juam Dam, and 62,000 tons from the Seomjin River) to support residential and industrial water requirements in the Jeonnam Eastern Region, including the Yeosu National Industrial Complex. Since water extraction commenced in 1978, challenges have arisen owing to the lowering of riverbed levels at the intake location by approximately 2.0 m in 1994 owing to sand mining activities in rivers, raising concerns about seawater intrusion and complications in water extraction. To overcome these issues, the intake location was relocated 4.2 km upstream in 2005, and the facility's capacity increased to its current state.

Sand mining in Seomjin River persisted between 1972 and 1998. In 1999, to protect the Seomjin River, the government imposed a ban on sand mining permits [17]. Figure 2 shows the annual quantity of sand mined from the Seomjin River Basin. From 1981 to 1994, sand mining exceeded one million m<sup>3</sup> annually, reaching a maximum of 2.7 million m<sup>3</sup> in 1994 (2.5 times that of 1978) [18]. Figure 3 illustrates the changes in riverbed elevation due to sand mining over a 40-year period (1978–2017). As shown in Figure 3, significant sand mining occurred from 1978 to 1989 in the primary corbicula habitat zone extending from the Seomjin River Bridge to Seomjin Bridge. During this period, the maximum decrease in riverbed elevation was 12.58 m, with an average reduction of 4.94 m throughout the habitat zone, directly contributing to an increase in salinity intrusion.



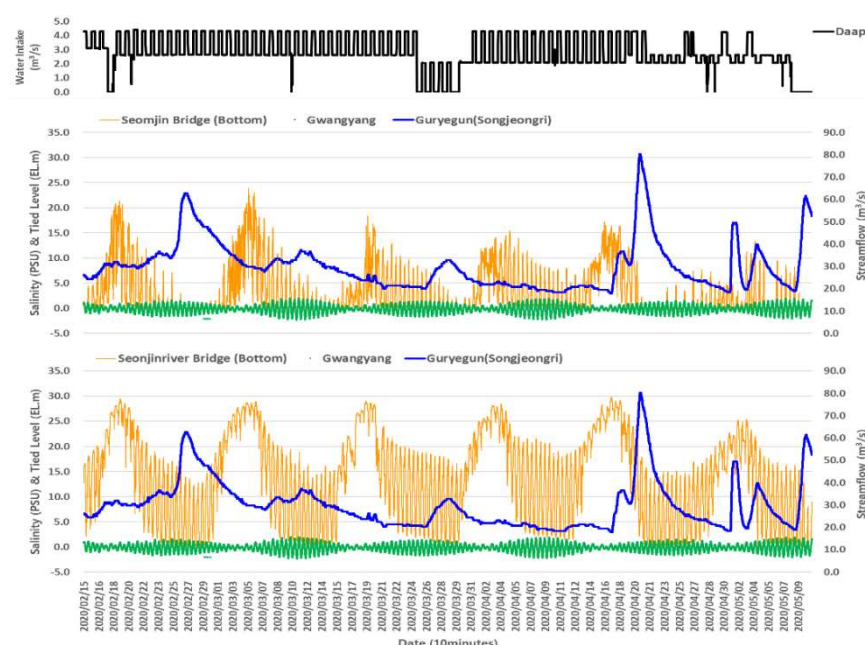
**Figure 2.** Annual quantity of sand mined (m<sup>3</sup>) from the Seomjin River between 1972 and 1998.



**Figure 3.** Riverbed elevation level (EL, m) changes in corbicula habitat in the Seomjin River over a 40-year period (1978–2017).

#### 2.3.2 Measured Hydrological Data for Simulation of EFDC Model.

This section focuses on the measured data required for calibrating the EFDC model, as shown in Figure 4. The goal of this study was to measure the salinity in the Seomjin River estuary and explore its correlation with factors such as river discharge, riverbed change, and tidal level. Fixed salinity gauges were installed at two locations (Seomjin Bridge and Seomjin River Bridge) to construct a time-series dataset of salinity concentrations (Figure 1). Fixed salinity gauges, operational since February 15, 2020, were installed at three intervals (upper, middle, and bottom) at each location on the riverbed to continuously monitor salinity. The salinity data utilized the lower-layer (bottom) data from the Seomjin River Bridge and Seomjin River Bridge, considering the density current measurements. The salinity range at Seomjin Bridge was 0.0–23.8 psu, with an average of 3.3 psu. Closer to the estuary, the Seomjin River Bridge exhibited a salinity range of 0.0–29.7 psu, averaging 14.3 psu. Typically, the average salinity of seawater is defined as more than 30 psu [19]. Thus, during neap tides, the Seomjin River Bridge experiences river water transforming into seawater, maintaining a high salinity concentration, influenced by tidal variations from EL.m -2.36 to EL.m 2.0 at the Gwangyang station. The stream flow in Guryegun (Songjeong-ri) varies and increases with precipitation. In the absence of rainfall, the flow rate was maintained between 17 and 20 m<sup>3</sup>/s, including an artificial dam supply (Figure 4).



**Figure 4.** Graphs representing the measured hydrological data; (Top) Observed salinity graph at Seomjin Bridge and (Bottom) Seomjin River Bridge.

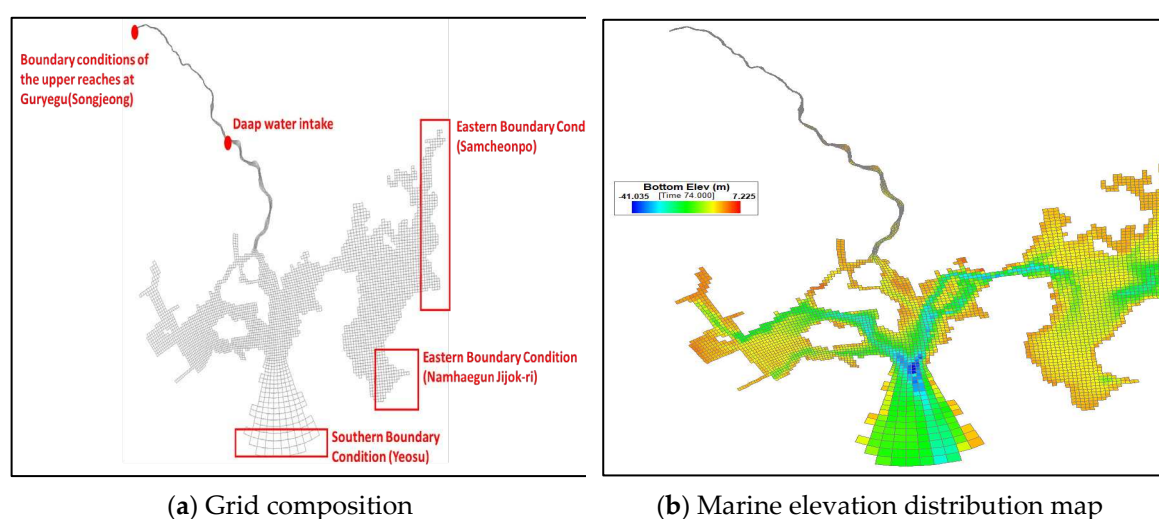
## 2.4 Model Application for Salinity Simulation

This study focused on the modeling and simulation of the Seomjin River estuary, incorporating downstream rivers and adjacent estuarine regions. To accurately represent the downstream flow dynamics of the Seomjin River, the Guryegun (Songjeong-ri) and Hadonggun (Eupnaeri) streamflow observation stations were designated as upstream boundary conditions. Downstream boundary conditions were established by including tide level observation stations located south and east of Gwangyang Bay, extending from Yeosu to Samcheonpo (Figure 5a). The modeling domain included facilities related to river flow, with an intake facility extracting a constant daily flow from the river. The water temperature of the river and meteorological data were recorded in real-time at the Hadonggun observation stations (Figure 1).

Topographic and bathymetric data for the Seomjin River were obtained from the Seomjin River Basic Plan, 2021 [13], and included approximately 41 km of river from the Seomjin River Estuary to Guryegun (Songjeong-ri). Marine data were extracted from the numerical bathymetric data of the National Maritime Institute (<http://www.kmi.re.kr>) and adjusted based on mean sea level (MSL) standards (Figure 5a). Also, this study used input data for the model utilized optical satellite

images and Synthetic Aperture Radar (SAR) satellite data, obtained through marine research, to create a digital elevation model (DEM) and bathymetric model from the Korea Institute of Ocean Science and Technology (KIOST). A curvilinear grid was implemented to construct the grid, allowing for appropriate reflection of the river and sea flows. The grid consisted of 8,088 cells with 20 vertical layers. River grids were set with a width of seven cells and variable lengths between 50–100 m, whereas marine grids were approximately 200 m (Figure 5a). River and marine elevations were interpolated using the Seomjin River Basic Plan, 2021 and numerical bathymetric data (Figure 5b). The marine elevation was converted from digital low (DL) to elevation low (EL). The bottom elevation ranged from -41.035 to 7.225 m, showing an increasing trend upstream. River and marine depths ranged from 0.05 to 41.908 m (Figure 5b).

To set the initial hydrological input conditions, water level and discharge information from the Water Resources Management Integrated Information System in Guryegun (Songjeong-ri) and Gwangyangsi (Namdo Bridge) were analyzed and used as input data. Additionally, hourly abstraction quantity data from the Daap Water Intake Facility were incorporated. Water temperature data were obtained from real-time water temperature measurements in Guryegun and the water temperature observed at the Gwangyang monitoring station (Figure 1).



**Figure 5.** Environmental fluid dynamics code (EFDC) model setup for this study; a) the grids used to determine marine and river flows, b) the bottom elevation range of the study area.

## 2.4 Salinity Stratification Phenomenon

Estuaries form unique environments and maintain equilibrium states based on the long-term and periodic mixing of two water bodies with distinct physical and chemical properties. Therefore, in estuarine research, the behavior of saltwater intrusion varies according to changes in the influences of river discharge, tidal movements, and their dynamic equilibrium. Tides driven by celestial forces occur approximately every 12.3 h (semidiurnal) or 24 h (diurnal). Tides are a major source of saltwater intrusion and a mixed energy supply for estuaries, influencing salinity stratification. Neap and spring tides have different effects on salinity, causing variations in stratification characteristics. Stratification is prominent when there is minimal turbulence within the estuary and mixing by tidal advection is weak. In such cases, a distinct two-layer flow forms between freshwater and seawater, creating a salt wedge where denser seawater intrudes into the estuary in a wedge shape. When turbulence causes mixing between freshwater and seawater, the density lines tilt, resulting in partially mixed conditions. In cases of strong turbulence and significant mixing, intense vertical mixing occurs, creating a well-mixed estuary with almost no difference in depth density [20].

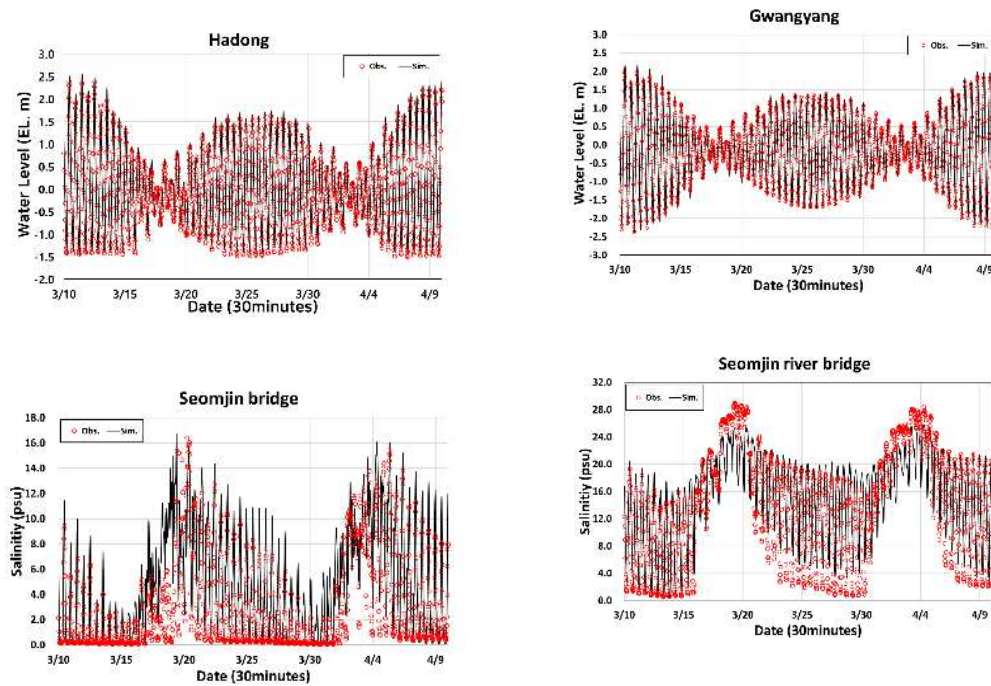
### 3. Results

#### 3.1. Model Calibration and Validation

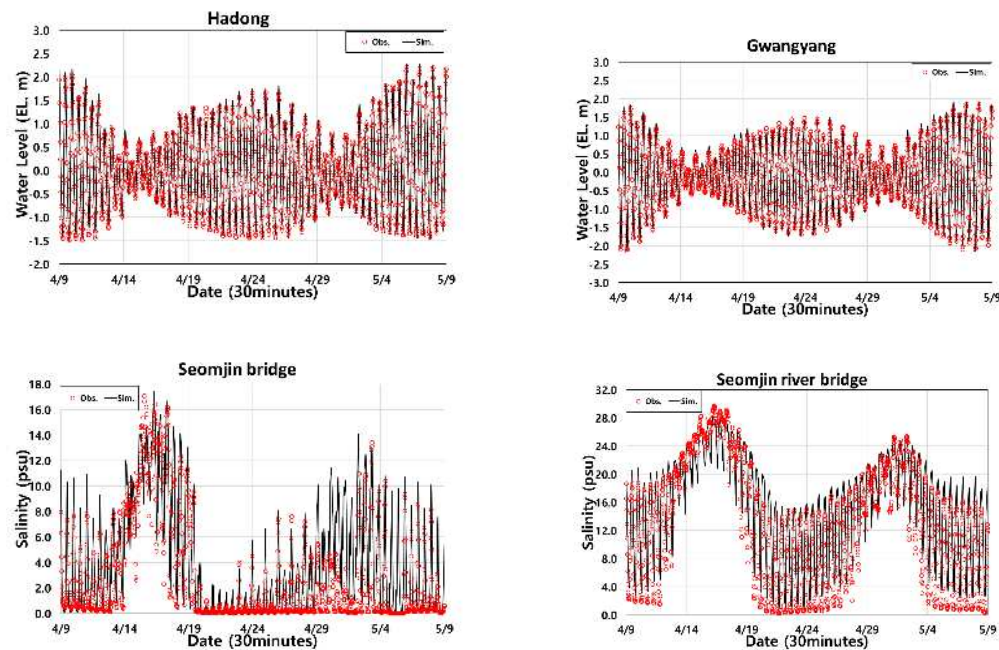
Model calibration and validation processes are essential for assessing the suitability of numerical models. In this study, for model calibration and validation, river water levels observed at the Hadong water observation station and the Gwangyang tidal observation station, and salinity measurement data obtained through salinity sensors at locations relevant to corbicula habitat, specifically, the Seomjin Bridge and Seomjin River Bridge, were utilized.

In hydrology, the Nash-Sutcliffe Efficiency (NSE) is a widely used metric for assessing the performance of hydrological models. It quantifies the accuracy of a model by comparing its simulated values to the observed values, with a range of  $-\infty$  to 1. A value closer to 1 indicates a better match between model predictions and actual observations [21]. The model calibration utilized time-series data from March 10, 2020, to April 10, 2020 (one month). Model performance, evaluated using various indices, was deemed acceptable. Notably, the Nash-Sutcliffe efficiency (NSE) for tidal levels and water levels showed values of 0.98 and 0.95, respectively. Salinity was corrected using observed data from the Seomjin River Bridge and Seomjin Bridge for the same period and the NSE values were 0.75 and 0.46, respectively, in the model results, indicating a satisfactory level of model calibration (Figure 6). Model validation utilized time-series data from April 10, 2020, to May 10, 2020 (one month), with tidal levels verified using data from the Gwangyang tidal station and water levels verified using data from the Guryegun (Songjeong-ri) water level observation station. The validation results for the tidal and water levels are shown in Figure 6. The NSE values of 0.98 and 0.95 for the tidal and water level data, respectively, indicating that the model was successfully validated.

The salinity concentration measurements had NSE values of 0.46 (Seomjin Bridge) and 0.75 (Seomjin River Bridge), indicating good and satisfactory performance, respectively. The observed errors in the salinity concentration data were mitigated by initially calibrating the sensors during installation using standard reagents of 5, 10, 15, 20, 25, 30, and 40 psu for sensor settings. Ensuring reliability in salinity observations below 5 psu was challenging, particularly from Seomjin Bridge, where a significant number of days exhibited salinity levels below 5 psu, resulting in increased errors. Therefore, for observations with salinity levels above 10 psu, the NSE value of 0.85 was high, indicating that the errors were mitigated, especially considering that this study used salinity values of 10 psu or higher in the model results.



(a) Calibration



(b) Validation

**Figure 6** Comparison graphs of results between a) observed (calibration) and b) simulated (validation) results : Hadong river water level , Gwangyang River water level, Seomjin Bridge salinity, and Seomjin River Bridge salinity.

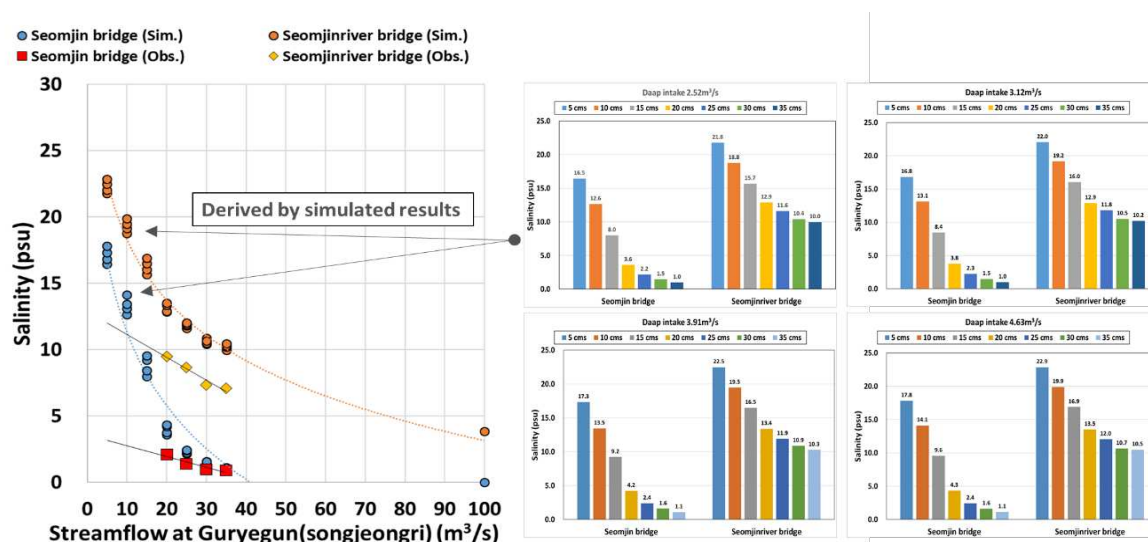
### 3.2. Impact Analysis by Daap Water Intake with River Flow

To simulate the salinity dynamics and intrusion distance due to the Daap Water Intake facility, the cross-sectional data measured in 2017, as part of the basic river plan, were fixed in the model. The flow input conditions were set at the Guryegun (Songjeong-ri) location, applying the range of maximum and minimum flows (5–35 m<sup>3</sup>/s) from March to May averaged over the past 10 years. The actual withdrawal rates measured from past to present for each flow range (2.523, 3.125, 3.912, and

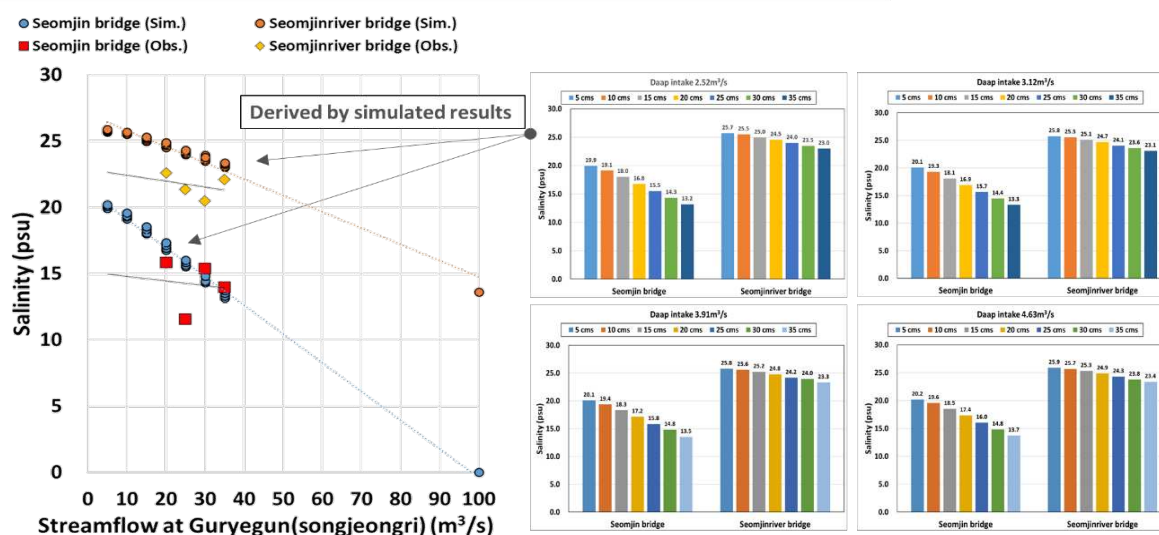
4.630 m<sup>3</sup>/s) were simulated separately using the EFDC model. In particular, the salinity dynamics based on tidal levels during spring and neap tides were distinctly different. Therefore, the simulation results were analyzed separately for spring and neap tides.

For the Guryegun (Songjeong-ri) flow rates of 5–35 cm/s during the spring tide, the salinity differences at the Seomjin Bridge, Seomjin River Bridge, and Hwamok points were 15.5, 11.8, and 8.4 psu, respectively, at a water intake of 2.523 cm/s. For the Daap water intake of 3.125 cm/s, these values (the salinity differences) were 15.8, 11.8, and 8.4 psu, and for the Daap water intake of 3.912 cm/s, they were 16.3, 12.2, and 8.6 psu. Finally, at the Daap water intake of 4.630 cm/s, the values were 16.7, 12.4, and 8.7 psu. As the Daap water intake rates increased, the salinity concentrations at each location increased, and higher river flow rates during spring tides resulted in decreased salinity differences. During neap tides, at Guryegun (Songjeong-ri) flow rates of 5 and 35 cm/s, the salinity differences at the Seomjin Bridge, Seomjin River Bridge, and Hwamok points were 6.8, 2.7, and 2.2 psu, respectively, at the Daap water intake of 2.523 cm/s. For the Daap water intake of 3.125 cm/s, these values were 6.8, 2.7, and 2.1 psu, and for the Daap water intake of 3.912 cm/s, they were 6.6, 2.5, and 2.1 psu. Finally, at the Daap water intake of 4.630 cm/s, the values were 6.5, 2.5, and 2.1 psu. Similar to the spring tide conditions, increasing Daap water intake rates led to higher salinity concentrations at each location (Figure 7).

However, during the low-flow season, despite an increase in river discharge up to 35 m<sup>3</sup>/s, the salinity concentration did not significantly decrease due to the phenomenon of saltwater retention even during neap tides. In contrast, during the high-flow season, the substantial tidal range caused pronounced inflow and outflow of seawater, resulting in a lack of salinity stratification. This allowed the river discharge to significantly reduce salinity.



(a) The spring tide

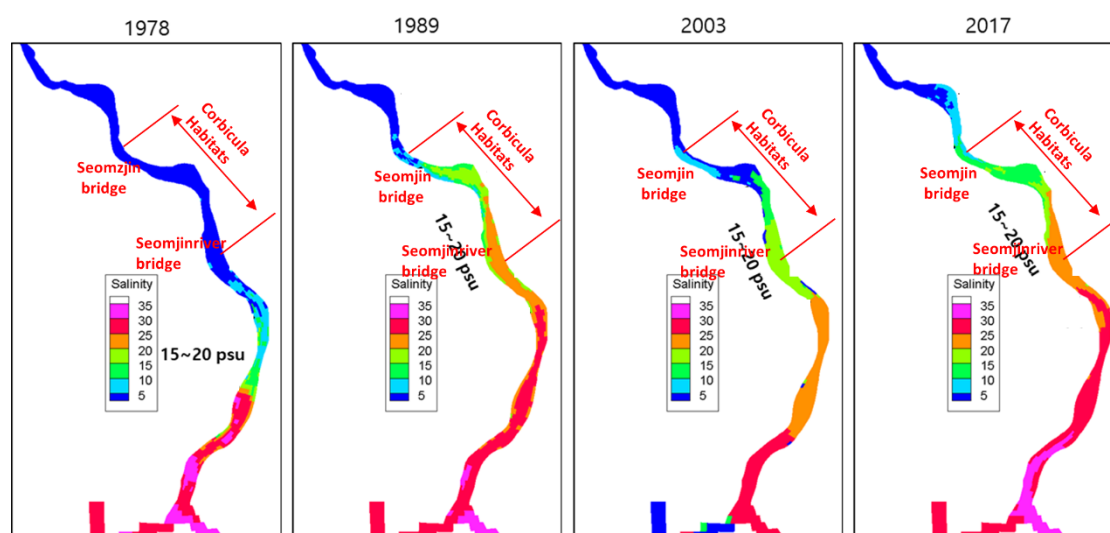


(b) The neap tide

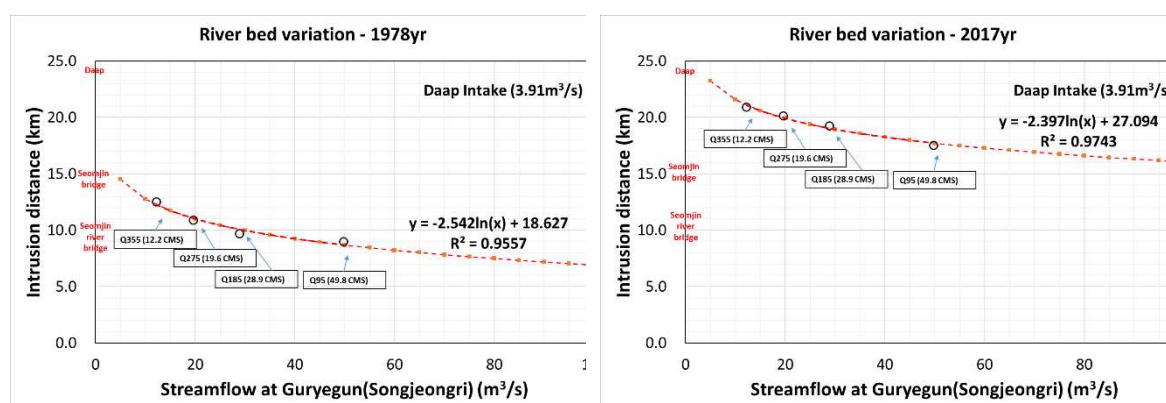
**Figure 7.** Estimation of relationship between reduction of salinity by Daap Water Intake and with streamflow at Guryegun (Songjeong-ri) station during (a) spring and (b) neap tides.3.3. *Impact Analysis by Daap Water Intake with River Flow or Estimation of Salinity Intrusion Distance by Downstream and River Bed Variation*

Riverbed changes were applied to river sections in 1978, 1989, 2003, and 2017. Analysis of the intrusion distances was conducted by applying river flows to Q95 ( 95th high flow), Q185 ( 185th high flow), Q275 ( 275th high flow), and Q355 ( 355th high flow) by analyzing the flow duration. For the analysis of salinity concentration and penetration distance variations in the lower reaches according to flow changes, cross-sectional profiles of the EFDC model were applied based on measurements taken in 1978, 1989, 2003, and 2017. The river discharge was fixed at the 1978 flow rate (Q355) of 12.2 m<sup>3</sup>/s to conduct a one-month simulation incorporating both spring and neap tides twice each. The results indicate that the penetration distance of the optimal salinity concentration for clam habitat, ranging from 15 to 20 psu, increased from 12.5 km in 1978 to 20.9 km in 2017 (Figure 8(a)). This suggests that the suitable salinity concentration range for clam habitats, primarily in the estuarine segment 10–15 km downstream of the Seomjin River estuary, has shifted upstream, causing potential harm owing to the intrusion of high-salinity water into the existing corbicula habitat and the displacement of corbicula populations.

Finally, by applying cross-sectional profiles from 1978 and 2017, along with an average intake rate of 3.91 m<sup>3</sup>/s from the Daap Water Intake facility, this study estimated the correlation between Guryegun (Songjeong-ri) river discharge and salinity intrusion distance (Figure 8(b)). As depicted in Figure 8(b), the salinity intrusion distance in 2017 is deemed impractical to maintain the optimal salinity concentration range (15–20 psu) during both spring and neap tides, even with a river discharge of 100 m<sup>3</sup>/s in Gurye County (Songjeong-ri). Therefore, it is anticipated that structural management measures, rather than solely securing river flow, are necessary for the rehabilitation and preservation of suitable clam habitats.



(a)



(a) River bed variation - 1978

(b) River bed variation - 2017

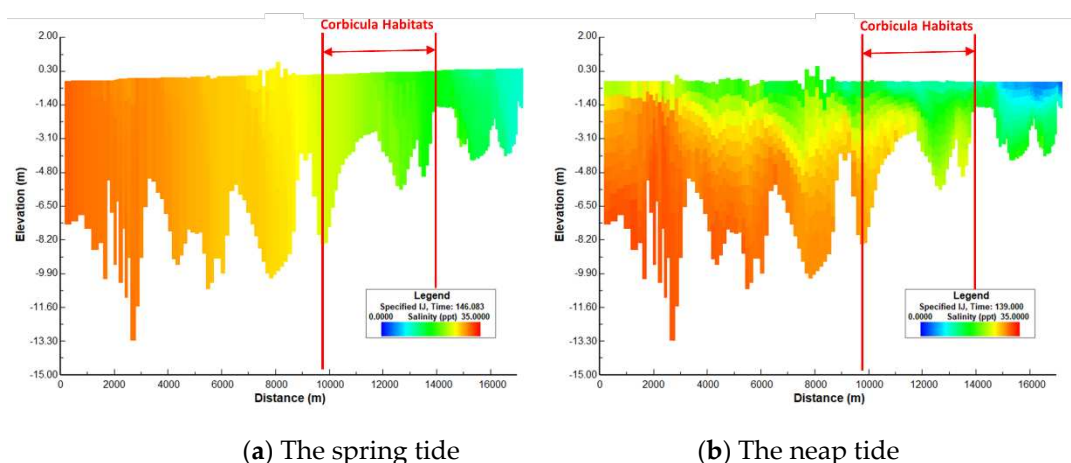
**Figure 8.** Final EFDC results of intrusion distance by river bed variation with streamflow and water intake; a) Spatial distribution of salinity, b) Modelled relationship between Intrusion distance and streamflow

#### 4. Discussion

In this study, the effects of salinity intrusion on the habitat of corbicula were investigated by employing EFDC modeling with topographic data (river cross-sections) and hydrological changes (flow rates and intake rates). Additionally, to observe the salinity concentrations in the clam habitat, two salinity measurement facilities were installed and operated, and the collected data were utilized to optimize the EFDC salinity movement analysis model and ensure its reliability. The results indicated that the increase in salinity owing to a decrease in flow rates corresponding to the intake quantity was negligible. However, the salinity concentrations varied based on the flow rate in Guryegun (Songjeong-ri). In particular, to maintain an optimal salinity concentration range of 15–20 psu for corbicula at the Seomjin River Bridge during neap tides, a constant flow rate ranging from 20 to 40 cm/s was required. This was deemed an extremely challenging requirement even with the inclusion of artificial dam supply quantities. Furthermore, it was found that, during neap tides, maintaining the optimal salinity concentration would be impractical, even with a high flow rate.

The analysis attributed this difficulty to the occurrence of saltwater stratification due to salinity stagnation, which is considered the primary cause. This salinity stagnation phenomenon can adversely affect clam habitats. In the Seomjin River estuary, the salinity concentration in the lower layer was notably higher owing to saltwater stratification, with a significant difference between the

upper and lower layer salinity concentrations, particularly downstream. Additionally, during neap tides, a substantial difference in salinity concentration between the upper and lower layers was observed, indicating a pronounced salinity stratification phenomenon during neap tides compared with spring tides (Figure 9).



**Figure 9.** Vertical spatial distribution of salinity in the study area for describing the salinity stratification phenomenon.

The lack of long-term observed salinity data in this study posed limitations in modeling the intricate salinity dynamics in the actual tidal creek. Therefore, for future research, securing long-term salinity data is essential to enhance the applicability of the model and further investigate the direct relationship between salinity and oyster growth in the observed tidal creek.

## 5. Conclusions

In conclusion, based on the analysis of the characteristics of salinity intrusion in the Seomjin River, we determined that salinity concentrations are predominantly influenced by neap tides. Attempts to push seawater back into the sea by ensuring river discharge and the proper operation of water intake facilities to restore the previously elevated salinity intrusion distance are considered extremely challenging. Structural measures such as riverbed restoration, underwater barrier installation, artificial structures, and flushing effects, which enhance resistance to seawater intrusion, are deemed necessary. Future research should develop scenarios for reducing salinity using artificial structures, quantitatively present reduction efficiency, and provide realistic measures tailored to the specific needs of the region.

**Author Contributions:** Funding acquisition, supervision, P.J.Y.; methodology, data curation, original draft, L.G.Y.; conceptualization, methodology, data curation, original draft, writing, revising—review and editing, supervision, J.C.G.; methodology, data curation. All authors have read and agreed to the published version of the manuscript.

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**Data Availability Statement:** The data presented in this study are available on request from the corresponding author. The data are not publicly available due to our laboratory’s policy and confidentiality agreements.

**Conflicts of Interest:** The authors declare no conflicts of interest.

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