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Development of a Marine Environmental Information System (MEIS) using data on Land–Sea Interactions in the Nakdong River Estuary, South Korea

Jun-Ho Lee[†], Jae Ung Choi[†], Hoi-Soo Jung[†], Jae-Il Kwon[§], and Han Jun Woo[†*]

[†]Korean Seas Geosystem Research Unit
Korea Institute of Ocean Science and Technology
Busan, Republic of Korea

[§]Marine Disaster Research Center
Korea Institute of Ocean Science and Technology
Busan, Republic of Korea

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ABSTRACT

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The Nakdong River in South Korea is about 510 km long and is subject to natural erosion and sedimentation and various potential sources of human pollution, such as urban dumping and input from industrial complexes and many cities. This study developed a marine environmental information system (MEIS) to understand the land–sea interactions and provide data on the characteristics of the brackish water zone around the barrier islands. The MEIS was run in real time (1-s intervals) and made periodic marine observations (one to four times a year). The real-time data were largely obtained from a closed-circuit television and automatic weather stations using long-term evolution communication at two stations in March 2016. Since May 2015, the data have included periodic observations of surface sediment distributions (n = 90), the characteristics of suspended sediments in inlets and channel (n = 4), the brackish water zone environment during spring tide ebb and flood (n = 14, three lines), the seasonal variation in sedimentation along tidal flats (n = 29, three lines), and landscape classifications of the sub-environment (n = 30) in the barrier islands. The collected information includes real-time and a huge heterogeneous dataset characterized by multi-dimensional, multivariate, and spatiotemporal distribution variability. The system enables data management, and open access is necessary. The MEIS will enable effective estuary management and contribute to reducing the damage caused by natural disasters. Real-time prediction information has been integrated with environmental sensitivity index maps, which are provided using a geographic information system to enable a response strategy.

ADDITIONAL INDEX WORDS: *Busan, coastal wetland, dam discharge, sedimentary impacts, tidal currents.*

INTRODUCTION

Most of the major Korean estuaries, including the Gem, Yeongsan, and Nakdong River estuaries, have dams that have caused environmental problems, including restricted water circulation, low water quality, decreased biodiversity, and wetland destruction. The Nakdong River Estuary (NRE) in the Republic of Korea is a typical example of an estuary in which throughput is manipulated artificially. The Noksan Dam, built in 1934, blocks the flow of the West Nakdong River, and the NRE Dam (*i.e.* bank, dike, embankment, *etc.*) was completed between 1983 and 1987 to regulate the flow of the East Nakdong River. With the construction of several large industrial complexes on reclaimed land near the NRE Dam in the last 50 years, the hydraulic circulation in the NRE has undergone dramatic changes in river discharge and geomorphic configuration, such as the formation of a series of barrier islands. The two large dams control the natural river flow and prevent the upstream intrusion of saltwater (Williams *et al*., 2014). The mixing and circulation of water in the estuary has been controlled by the freshwater discharge since the dam's construction (Chang and Kim, 2006). Consequently, the saltwater wedge that once reached approximately 40 km upstream is now blocked at the dams, considerably reducing the tidal prism. The tides in the estuary are semidiurnal and micro-tidal, with a mean tidal range of 1.07~1.50 m (Yoon and Lee, 2008; http://www.khoa.go.kr/sw tc/main.do; http://opendata.kwater.or.kr/main.do). There are various sub-environments in the lagoon, including tidal flats, salt marshes, tidal channels, sand bars, and sand spits (Woo *et al*., 2018). The schematic diagram in Figure 1 shows the regional distribution of the sediments investigated in and around the barrier island system in the NRE. In particular, a sample collected from zone (b) in the protected delta fringe marsh contained the halophytic vegetation *Phragmites communis* Trin. (Gramineae, common reed) or *Scirpus planiculmis* Fr. Schmidt (Cyperaceae). The purpose of this study was to demonstrate the marine environmental information system (MEIS) as a tool for understanding land–sea interactions and providing data on the characteristics of the brackish water zone surrounding the barrier islands in the NRE in southeastern Korea.

METHODS

Beginning in May 2015, the MEIS has been run in real time (1-s intervals) and has made periodic marine observations (one to

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*Corresponding author: hjwoo@kiost.ac.kr

four times a year). The real-time data consist of two items and the periodic marine observation data consist of five items.

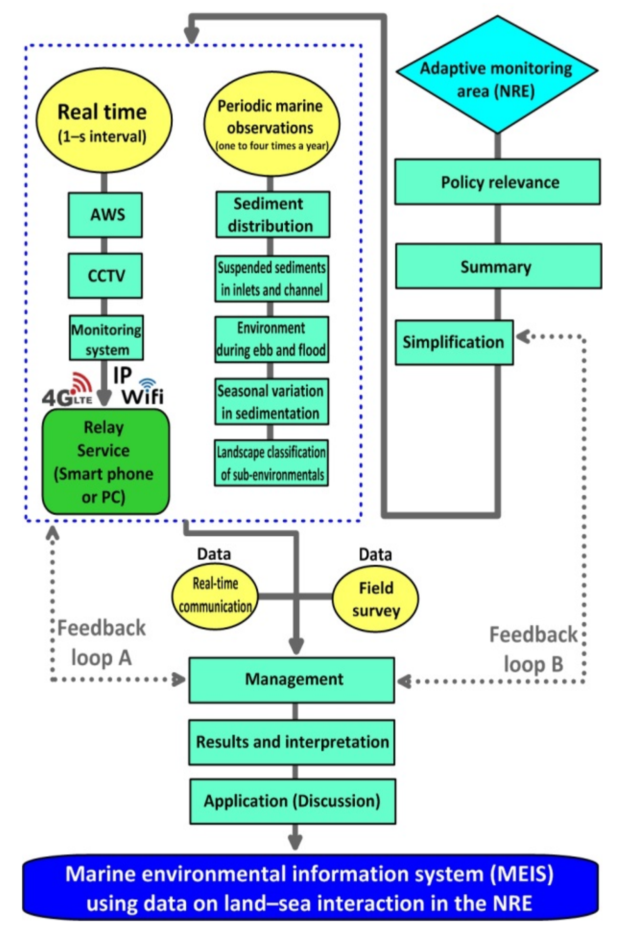

Figure 1. Flow chart of the development, interpretation, and application of the marine environmental information system in the Nakdong River Estuary (NRE), southeastern Korea. The blue dashed rectangle encloses the two steps in the index development of the real-time (1-s interval) and periodic (one to four times per year) marine observations. The dashed arrows indicate the two adaptive feedback loops driving decision changes.

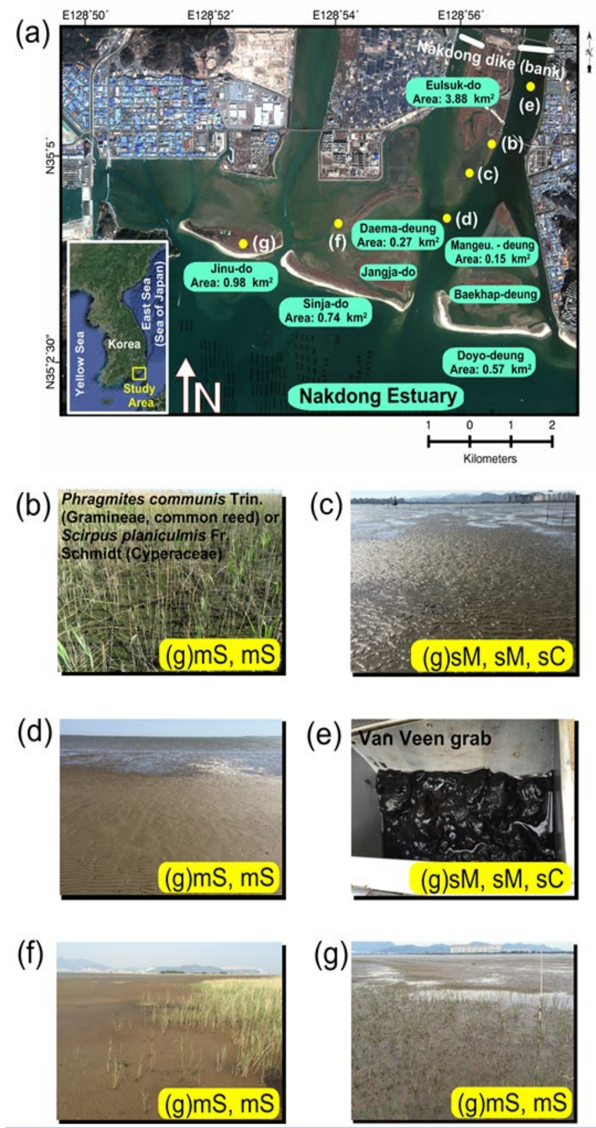

Figure 2. Landsat Enhanced Thematic Mapper Plus (Landsat ETM+) image of the barrier–lagoon system in the Nakdong River Estuary (NRE), southeastern Korea. The Landsat ETM+ image was obtained from KOMPSAT-2, South Korea (a); The sediments were investigated in and around the barrier island system in the NRE (mS, muddy Sand; sC, sandy Clay; sM, sandy Mud; mS, muddy Sand; (g)-, slightly gravelly- (b~g)).

Real-Time Observations

The real-time data have been largely obtained from closed-circuit television (CCTV; operating rate: 100%; 35°03′06″N, 128°55′45″E WGS-84) since June 26, 2017, and an automatic weather station (AWS; operating rate: 81%; 35°03′16″N, 128°55′45″E WGS-84) using 4 generation (4G) long-term evolution (LTE) communication at two stations since March 25, 2016. Both the AWS and CCTV are installed on the east side of the Doyodeung barrier islands in the NRE, approximately 309 m apart (Figure 3a). A monitoring system for the brackish water zone (*i.g.* salinity, temperature, chlorophyll-*a*, *etc.*) is planned for installation near the Eulsukdo Bridge in the first half of the year 2020 (Figure 3a, d).

The AWS equipment consists of a weather observation sensor (WXT536; Vaisala Co., Ltd., Finland), 100 W solar panel (Poly; Ningbo Osda Solar Co., Ltd., China), 100 Ah battery (BX60R; AtlasBX, Korea), 12 V solar controller (SS-6L; Morningstar Co., Ltd., USA), 4G LTE modem for bidirectional communication (LS-LTER; NexG Co., Ltd., Korea), 3 m triangular frame, and software (BS2; Bgain Co., Ltd., Korea) to acquire real-time weather information. The weather observation sensor measures six items in the following measurement ranges in real time: wind direction (0~360 ± 3°), wind speed (0~60 ± 0.3~0.5 m/s), temperature (−52~60 ± 0.3°C), relative humidity (0~100 ± 3.0~5.0%), atmospheric pressure (600~1,100 ± 0.5~1.0 hPa), and rainfall (0~200 ± 5 mm/h). The observed information is transmitted to the laboratory computer server via 4G LTE communication (Figure 3b, e).

The CCTV research equipment consists of a camera (UI-T4210X; Huisun, Co., Ltd., China), a digital video recorder (DS-7204HQHI-SH; Hikvision Co., Ltd., China), two 120 W solar panels (SPM; Spdolar Co., Ltd., China), three 100 Ah batteries, a 12 V solar controller, a 4G LTE modem for bidirectional communication, a 3-m triangular frame, and software (iVMS-4500; Hikvision Co., Ltd., China) to acquire real-time weather information. The camera is a 1/2.9" Sony complementary metal-oxide semiconductor standard and has a 1,080 p (1,920 × 1,080) effective decimal number with H.264 video codec. It is possible to record real-time images at night by installing an infrared sensor. The information is transmitted to the laboratory computer and smartphone application server via 4G LTE communication (Figure 3c, f).

Periodic Marine Observations

The data include periodic observations of surface sediment distributions (n = 90), the characteristics of suspended sediments in inlets and channel (n = 4), data on the brackish water zone environment during spring tide ebb and flood (along three lines), seasonal variations in sedimentation along tidal flats (n = 29, three lines), and landscape classifications of the sub-environment (n = 30, 14 *a priori* groups) in the barrier islands using the method described in the United States Environmental Protection Agency manual from May 2015 (U.S. EPA, 1998).

Sediment (n = 90) was sampled for a sedimentary analysis in August 2015 and August 2016. The grain-size distribution was analyzed using standard sieving for the sand fraction (<4 Φ) and a particle size analyzer (Sedigraph 5100; Micromeritics) for the mud fraction (>4 Φ) at half-Φ intervals. An inclusive graphic method was used to determine sediment type, mean, sorting, skewness, and kurtosis (Folk and Ward, 1957).

The characteristics of suspended sediments in the inlets and channel (n = 4) at four stations over 12.5 hour were determined based on measurements of hydrodynamic parameters and suspended sediment concentrations during the summers of 2015, 2016, and 2017.

In the study of the brackish water zone environment (n = 14, three lines), the temperature, flow direction, flow rate, salinity, pH, and dissolved oxygen concentration of the upper and bottom layers were measured using a multi-parameter display system (YSI 650 MDS; YSI Environmental Co., Ltd., USA) and Seaguard® recording current meter (Aanderaa Co., Ltd., Norway) to assess the ebb and flood of the spring tide during April and July 2018.

The seasonal variations in sedimentation along the tidal flats (n = 29, three lines) were measured using a differential global positioning system. Geomorphic changes by sediment deposition/erosion were measured for 1 year (May 2015~2016) along two transects (Jinu-do (JW) and Sinja-do (SJ) lines) on the tidal flats and for 2 years (May 2015~2017) along one transect (Eulsuk-do (ES) line).

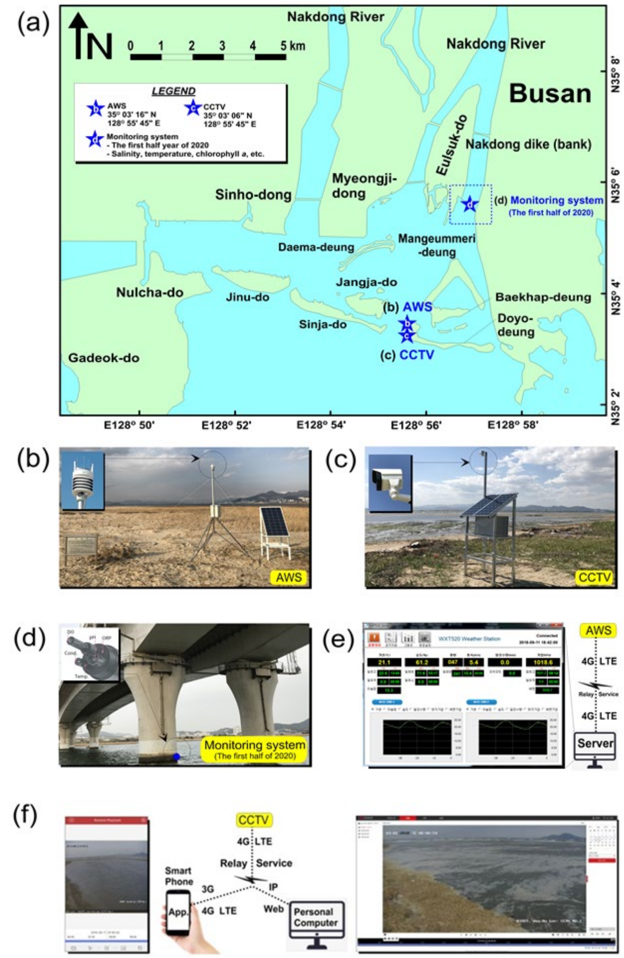

Figure 3. Pilot implementation of the marine environmental information system using real-time (1-s interval) data collection in the Nakdong River Estuary, South Korea (a); The real-time data are largely obtained from an automatic weather system (AWS) and closed-circuit television (CCTV) using 4G LTE communication at two stations on the east side of the Doyodeung barrier islands (b, c); An additional monitoring system (salinity, temperature, chlorophyll-*a*, *etc.*) is planned for installation near the Eulsuk-do bridge by the first half of 2020 (d); Screen capture image showing six parameters measured in real time from the AWS browser using 4G LTE (e); 4G LTE enables real-time acquisition of CCTV information using a smartphone application or personal computer browser with a web connection (f).

The development of landscape-based environmental classifications (n = 30, 14 *a priori* groups) represented a preliminary step for investigating the distribution of environments in the study area in August 2015 and 2016. In other words*, a priori* grouping was required in advance of sub-environment classification using qualitative factors (i.e., topography, sediment texture, waves, flushing, vegetation, and biological activity) (Woo *et al*., 1997; Alcantara-Carrio *et al*., 2014).

RESULTS

The sediment distributions were classified into four sedimentary facies: Sand (S), muddy Sand (mS), sandy Mud (sM), and mud (M). The mean grain size in the barrier island system of the NRE ranged from 1.1 to 8.9 Φ (average: 3.9 Φ). Sand sediment generally dominated the seaward side of the barrier islands, while muddy sand sediment dominated the lagoon. Sandy mud and mud sediments were distributed in the tidal flat near the Noksan industrial district, on the west side of Eulsukdo Island, and in the channels near the dams (Figure 4a).

The characteristics of suspended sediments in the inlets and channel (based on four 12.5-hour anchoring surveys) during the spring tide were determined based on hydrodynamic parameters and suspended sediment concentrations at the inlets between Sinja-do and Doyo-deung (C) during summer 2015, between Jinu-do and Sinja-do (B) during summer 2016, and between Nulcha-do and Jinu-do (A) and at the channel mouth (D) near Maenggeummeori-deung during summer 2017. The calculated residual flow (R_f) veered seaward in the three layers (surface, middle, and bottom layer) at stations B and D. The R_f at stations A and C veered seaward in the surface and middle layers and landward in the bottom layer. Depth-integrated net suspended sediment loads (Q_S) for one tidal cycle at stations A, B, C, and D showed seaward movement of 498.6, 2318.6, 1698.4, and 278.7 kg/m, respectively (Figure 4b).

In the study of the brackish water zone environment (three lines), the average surface layer and lower layer water temperatures of lines A, B, and C were 12.4~29.2 and 11.6~25.7 °C, respectively, and the mean surface–bottom layer difference in April and July was 1.9 °C. The average surface layer and lower layer salinities of lines A, B, and C were 2.9~18.2 and 12.4~32.5 psu, respectively, and the mean surface–bottom layer difference in April and July was about 13.8 psu (Figure 4c).

In the seasonal variation in sedimentation along tidal flats (n = 29, three lines), deposition dominated the tidal flat along the JW and SJ lines, with net deposition rates of 10.09 and 12.38 mm/year, respectively. Erosion dominated over the course of 2 years on the tidal flat along the ES line, located on the eastern side of the system, at an annual erosion rate of −12.76 mm/year (Figure 4 (d)).

Data for landscape-based environmental classifications (n = 30, 14 *a priori* groups) were collected and analyzed for factors related to grain size and organic matter. Based on the results, the study area was divided into a mixed environment influenced by land and a marine environment influenced by the ocean. Using multivariate analysis, these two large environments were further divided into six sub-environments such that sub-environments 1 and 2 were in the mixed environment, and sub-environments 3, 4, 5, and 6 were in the marine environment (Figure 4e).

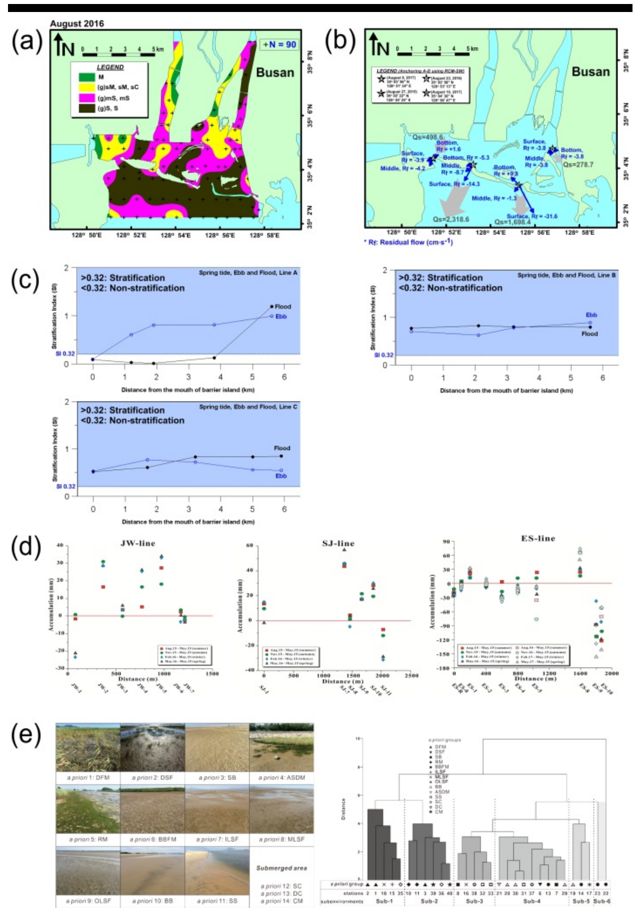

Figure 4. Pilot implementation of a marine environmental information system using marine observations (one to four times per year) in the Nakdong River Estuary, South Korea. The data include periodic observations of sediment distributions (n = 90) (M, mud; sM, sandy Mud; sC, sandy Clay; mS, muddy Sand; S, Sand; (g)-, slightly gravelly) (a); the characteristics of the suspended sediments in inlets and channel (n = 4) (Qs, suspended sediment load; R_f, residual flow) (b); data on the brackish water zone environment during ebb and flood (lines A, B, and C) (c); seasonal variations in sedimentation along tidal flats (n = 29) (three lines: JW, Jinu-do; SJ, Sinja-do; ES, Eulsuk-do) (d); Landscape classifications of sub-environments (n = 30, 14 *a priori* groups) (DFM, delta fringe marsh; DSF, delta sand flat; SB, sand bar; ASDM, artificial structure dyke marsh; RM, replacement marsh; BBFM, back-barrier fringe marsh; ILSF, MLSF, and OLSF, respectively, inner, middle, and outer lagoon sand flats; BB, barrier beach; SS, sand spit; SC, shallow channel; DC, deep channel; CM, channel margin) (e).

DISCUSSION

The differences in surface sediment distributions in the summers of 2015 and 2016 showed that sand sediments expanded into the back-barrier lagoon. The amount of rainfall and the average discharge flow from the dams in July 2015 and 2016 were 160.10 mm and 508.35 m^3/s, and 239.80 mm and 803.83 m^3/s, respectively (www.water.or.kr). The annual difference in surface sediment distribution should be dependent on the quantity of discharge flow from the Nakdong dams.

The four 12.5-hour anchoring surveys at the inlets and channel revealed that net suspended sediments were transported into the open sea during the tidal cycle in summer. Generally, the seasonal variations in sedimentation on the tidal flats indicated that in summer, deposition occurred with an inflow of sediments from dam discharges due to heavy rainfall, whereas in winter, erosion dominated due to waves. However, seasonal variations in sedimentation revealed the reverse cycles of sedimentation on the sand bar at the southern end of the tidal flat along the ES line.

In the stratification index analysis, the Nakdong River (line A) located at the bottom of the Noksan floodgate was classified as a "salt-water wedge estuary" with strong stratification in the ebb, and showed a "well mixed estuary" in which surface-bottom mixing occurred during the flood (Hansen and Rattray, 1966; Shaha and Cho, 2009). However, the Nakdong River (line B) on the east side of Eulsukdo Island and the right main stream of the Nakdong River (line C) showed a distinctive "salt-water wedge estuary" showing stratification during both the ebb and flood. There was little discharge from the Noksan Dam floodgate (line A) and the floodgate east of Eulsukdo Island. In addition, the topographic characteristics of the moat form (east of the Eulsukdo mud flat and in front of the water line on the right side of Eulsukdo Island) were expected to represent large changes in the waterside geological and water quality after full or partial opening.

The short-term sedimentation rates showed that the tidal flats of Jinu-do (JW line) and Sinja-do (SJ line) had net deposition rates of 10.09 and 12.38 mm/year, respectively. However, the tidal flat at the southern end of Eulsukdo Island (ES line) eroded at a rate of −12.76 mm/year.

Although the parameters related to grain size and organic matter used for the sub-environment classification were effective in identifying the major regulatory factors responsible for creating different environments, they could not be used to identify the ecological functions of the sub-environments in the NRE. To address these limitations, it is necessary to evaluate additional parameters. For example, in addition to physical factors, future analyses should include chemical and/or microfossil data (Figure 5).

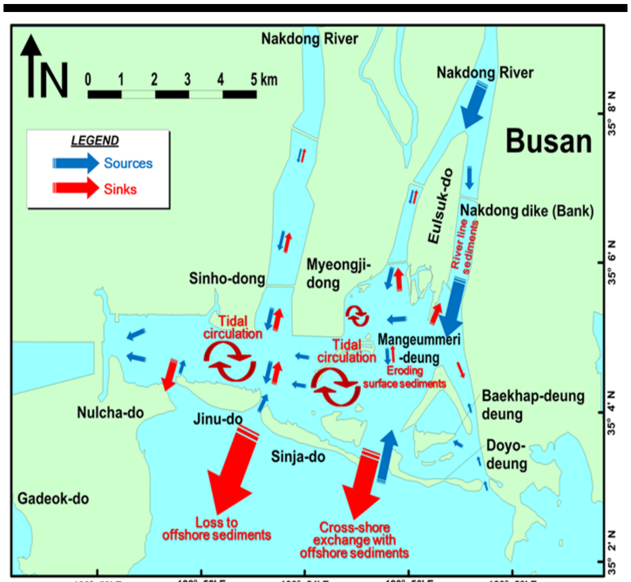

Figure 5. This map is diagram of sedimentary processes during the flood, ebb in the spring tidal current, modified from Woo *et al*. (2018) within the Nakdong River Estuary.

CONCLUSIONS

The acquired data and research findings reveal the real-time, multidimensional, multivariate, and spatiotemporal distribution variability characteristics of the NRE. The MEIS provides information to clarify land–sea interactions and the characteristics of the surrounding brackish water zone around the barrier islands, enabling the effective management of the estuary. Moreover, it is possible to use comparative data of the characteristics of environmental changes in this estuarine watershed to prepare the Nakdong River for the full or partial opening of the dams.

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