Spatiotemporal Variation in Suspended Sediment Concentrations and Related Factors of Coastal Waters Based on Multispatial Satellite Data in Gyeonggi Bay, Korea

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ABSTRACT

The variations in suspended sediment concentration (SSC) in turbid coastal waters around Gyeonggi Bay, Korea were analyzed using multiresolution ocean-color satellite imagery. Geostationary Ocean Color Imager (GOCI) and Landsat-7 Enhanced Thematic Mapper Plus (ETM+) images were atmospherically corrected, and an empirical algorithm was employed to generate maps of SSCs in the study area and investigate daily and annual variabilities in coastal water turbidity. SSC values were highest around 6 hours before high tide and around low tide, and the maximum values had strong positive relations with the tidal range near the sand ridge and channel ($R^2$ values of 0.74 and 0.72, respectively), which implies that the main driver of the diurnal variability in SSC is resuspension of bottom sediment by tides in areas of shallow water. Annually, the maximum SSC value near the sand ridge was about 400 g m$^{-3}$, showing remarkable variation over tidal cycles, whereas it was about 10 g m$^{-3}$ in the open sea, with little variation. The SSC around the sand ridge was higher in winter than in summer, mainly because of stronger resuspension resulting from winds during the NW monsoon in winter. The SSC around the Han River estuary was higher in summer than in winter because of the river discharge, which indicates that suspended sediments supplied by the Han River do not significantly affect SSC variation in the open ocean. This study revealed that application of the high temporal resolution of GOCI, combined with the high spatial resolution of Landsat-7 ETM+, can be useful for monitoring short- and long-term variations in SSC in Korean coastal waters.

ADDITIONAL INDEX WORDS: Coastal water turbidity, GOCI, Landsat-7 ETM+, time series variability, Gyeonggi Bay.

INTRODUCTION

Estuaries are transition regions between inland waters and open ocean. Suspended sediment (SS) transport in an estuary is affected by the conditions at the end of the estuarine transition zone and changes brought about by winds, tides, and river discharge (Krone, 1975). Recent studies have shown that estuarine regions and coastal environments are increasingly affected by human activities and climate change, as evidenced by variations in suspended sediment concentration (SSC) and chlorophyll concentration (Brando et al., 2006; Rodriguez-Guzman and Gilbes-Santaella, 2009). In particular, SS at lower trophic levels serves as a vital source of energy for bacteria, phytoplankton, and zooplankton (Hakanson, Gyllehammar, and Brolin, 2004). In coastal waters, high SSC results from terrestrial inputs and resuspension of bottom sediment (He et al., 2013; McCave, 1984; Velegrakis et al., 1997). Variations in SSC in coastal areas play a major role in erosion and deposition processes, biomass primary production, and transport of nutrients, micropollutants, and heavy metals (Lewis et al., 1990; Morel and Antoine, 1994; Platt et al., 1988; Sathyendranaath et al., 1989, 1991; Volpe, Silvestri, and Marani, 2011). Local-scale field studies of changes in SSC are inadequate for showing spatial or temporal variation; therefore, to complement field observations, researchers have used ocean-color satellite imagery, such as that provided by the sea-viewing wide field-of-view sensor, the medium resolution imaging spectrometer, and the moderate resolution imaging spectroradiometer (MODIS). Variations in SSC can be enough for resolving diurnal variations in turbid coastal waters because of their low-temporal resolution with respect to ocean dynamics.

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A geostationary ocean-color satellite can supplement polar-orbiting satellite imagery and provide high-frequency observations of the environment over large geographic regions, permitting temporal resolution of dynamic processes at a timescale of hours to days (IOCCG Staff, 1998). The Geostationary Ocean Color Imager (GOCI), the first geostationary ocean-color satellite, was launched in 2010. J.K. Choi et al. (2012) and Choi et al. (2014) estimated the hourly variation in SSC along the west coast of Korea using GOCI images, and He et al. (2013) studied the diurnal dynamics of SS in Hangzhou Bay, China, using GOCI and buoy data. Despite its advantage of high temporal resolution, most studies using GOCI data have focused on expansive areas because of the low spatial resolution (about 500 × 500 m) of the data, as opposed to examining river inputs that discharge large amounts of sediment into coastal areas. Understanding the distribution and movement of SS between rivers and coastal waters is essential to improve monitoring and ensure the preservation of coastal environments. Most ocean-color sensors, including MODIS and GOCI, have demonstrated insufficient spatial resolution regarding detailed variation in estuarine SSC, prompting the use of low-temporal-resolution but high-spatial-resolution satellite imagery, such as Landsat or Satellite pour l’Observation de la Terre (SPOT) data. Doxaran et al. (2002) and Doxaran, Castaing, and Lavender (2006) estimated turbidity in the Gironde estuary of SW France using Landsat Enhanced Thematic Mapper Plus (ETM+) and SPOT images, which showed detailed variation in SSC in the coastal area. Landsat data have been used to map SS for more than 25 years (Kritikos, Yorinks, and Smith, 1974; Mertes, Smith, and Adams, 1993; Rouse and Coleman, 1976). M.S. Lee et al. (2011), Miller et al. (2011), and Volpe, Silvestri, and Marani (2011) revealed small-scale spatial gradients in SSCs using Landsat ETM+ or Advanced Spaceborne Thermal Emission and Reflection Radiometer in coastal areas. However, the temporal resolution of the imagery is insufficient to observe tidal cycles in dynamic coastal waters or short-term episodic events, even in cloud-free conditions. Vanhellemont, Neukermans, and Ruddick (2014) analyzed the synergetic merging of the high-frequency but spatially, spectrally, and radiometrically coarse data from Spinning Enhanced Visible and Infrared Imager with the low-frequency but high-quality data from MODIS Aqua, and they observed spatial variability of SS using the synergy image. At present, there is only one ocean-color sensor on a geostationary satellite: the Korean GOCI. GOCI images, combined with these high-spatial-resolution synchronous orbit satellite images, would be useful for effectively resolving dynamic SS variation in coastal areas with respect to estuarine processes. To date, the integration of high-temporal-resolution geostationary ocean-color images and high-spatial-resolution polar orbit satellite images to study the coupling of SSC between ocean dynamics and river inputs has received little attention.

The intention of the research was to analyze and quantify the variation in SSC. To pursue the research, the diurnal, monthly, and seasonal dynamics variations of SSC in the turbid coastal waters from GOCI and Landsat ETM+ images were observed, and the diurnal SSC variation of GOCI was elucidated using hydrodynamic modeling. The main factors (such as tide, wind, and river discharge) that affect SSC variation were identified. In particular, Landsat ETM+ images were used for monitoring the seasonal SSC variation in the narrow Han River estuary.

Study Area

Gyeonggi Bay, located on the midwestern coast of the Korean Peninsula, is one of the most extensively developed bays (Figure 1a). It is a semienclosed bay (Figure 1b) that is characterized by shallow water (<40 m) (Figure 1c), a large tidal range (4–8 m), strong tidal currents (1–2 m s⁻¹), a semidiurnal tide (Lee, Yoo, and Park, 1992), and a large sediment supply (12.42 × 10⁶ tons/y) from the Han River (Kim...
Table 1. Characteristics of GOCI and Landsat-7 ETM+.

<table>
<thead>
<tr>
<th></th>
<th>GOCI</th>
<th>Landsat-7 ETM+</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Band</strong></td>
<td><strong>Spectral Resolution (μm)</strong></td>
<td><strong>Spatial Resolution (m)</strong></td>
</tr>
<tr>
<td>1</td>
<td>0.402–0.420</td>
<td>500 × 500</td>
</tr>
<tr>
<td>2</td>
<td>0.433–0.453</td>
<td>500 × 500</td>
</tr>
<tr>
<td>3</td>
<td>0.480–0.500</td>
<td>500 × 500</td>
</tr>
<tr>
<td>4</td>
<td>0.545–0.565</td>
<td>500 × 500</td>
</tr>
<tr>
<td>5</td>
<td>0.650–0.670</td>
<td>500 × 500</td>
</tr>
<tr>
<td>6</td>
<td>0.670–0.690</td>
<td>500 × 500</td>
</tr>
<tr>
<td>7</td>
<td>0.735–0.755</td>
<td>500 × 500</td>
</tr>
<tr>
<td>8</td>
<td>0.845–0.885</td>
<td>500 × 500</td>
</tr>
<tr>
<td><strong>Temporal resolution</strong></td>
<td>1 hour (8 times per day)</td>
<td>16 days</td>
</tr>
<tr>
<td><strong>Swath</strong></td>
<td>2500 × 2500 km</td>
<td>16 days</td>
</tr>
</tbody>
</table>

and Lim, 2009). The tidal currents run from the NE to the SW, which creates a sand ridge in the direction of the current (Lee et al., 2009). Meteorological data for Gyeonggi Bay obtained over a 30-year period (1971–2000) indicate that the average annual precipitation amounts to 1344.2 mm, occurring mostly between June and August (KMA, 2001). Monsoons from the NW are observed in the winter season (Ahn and Kim, 2010). The coastal area around the bay is a macrotidal environment that connects the Yeomha and Seokmo Channels (Figure 1b). H.J. Lee et al. (2013) concluded that Yeomha Channel plays a predominant role in supplying Han River-derived SS to the estuary. It is a direct link to the Ganghwa tidal flat. Another major channel, the Seokmo Channel, contributes little to the estuarine mud repository, particularly the Ganghwa tidal flats. The Yeomha Channel has a total length of 42 km, a width of 350 to 1000 m, and a depth of 2 to 10 m in the central channel (Oh, 1995). The Seokmo Channel has a total length of 15.9 km and a width of 1400 m (N.Y. Choi et al., 2012). Since 1992, various development projects brought on by rapid industrialization, such as the construction of Incheon Bridge and Yeongjongdo International Airport and the reclamation projects in Songdo, have transformed the submarine topology and seawater flow characteristics of Gyeonggi Bay (Lee and Woo, 2011). As a result of the reclamation, a variety of environmental problems, such as artificial coastline changes, decreasing fishery productivity, intertidal topography change, and distribution changes in salt marshes (Y.K. Lee et al., 2011), most of which have been associated with sedimentary processes, have arisen continually. However, little information useful to understanding the sedimentary processes has been made available (H.J. Lee et al., 2013). Although previous researchers have studied seawater flow and sediment transport in Gyeonggi Bay using field survey data (Choi and Kwon, 1998; Kim et al., 2009; Lee, Yoo, and Park, 1992; H.J. Lee et al., 2013; Oh and Bang, 2003), these studies were limited to certain areas, such as Yeomha, the Seokmo channels, and the Ganghwa tidal flat. Choi and Kwon (1998) explained from in situ data that the seasonal variation in transparency seems to be affected mainly by resuspension of solids from the bottom of the SE Yellow Sea. Lee, Yoo, and Park (1992) evaluated the surface sediment distribution and the mineral and chemical compositions of the intertidal surface of Gyeonggi Bay using in situ data. Kim et al. (2009) surveyed the current characteristics near the Yeomha and Seokmo Channels using field data. However, they could not explain the sediment transport process from the estuary of the Han River to the bay, and an integrated study of SS transport from river to bay has not been completed. To understand sediment transport in Gyeonggi Bay, the interactions among each part, including the Han River, the tidal flat, the sand ridge, and the open sea, should be considered.

METHODS

This section describes the characteristics of the data and the methods used in this study. A modified management unit of the North Sea mathematical models (MUMM) algorithm and a cosine approximation (COST) model, along with a near-infrared (NIR)–shortwave infrared (SWIR) method, were employed to correct the satellite images atmospherically. For generating the SSC map, SSC algorithms were developed by an empirical algorithm using in situ data.

Data

The GOCI satellite sensor, launched 27 June 2010, records observations eight times a day at hourly intervals from 0915 to 1645 local time (from 0930 to 1630 in Gyeonggi Bay) and has a spatial resolution of 500 × 500 m (Ryu et al., 2012). It has six visible and two NIR spectral bands (centered at 412, 443, 490, 555, 660, 680, 745, and 865 nm), with high signal-to-noise ratios, enabling accurate retrieval of SSC and other ocean-color information. GOCI observation covers an area of about 2500 × 500 km, centered on 130° E and 36° N, overlapping the coasts of eastern China, the Korean Peninsula, and Japan. Landsat-7 ETM+ images have three spectral bands in the visible spectrum, one band in the NIR spectrum, and two bands in the SWIR spectrum, with a 30-m spatial resolution and a 16-day revisit period (U.S. Geological Survey, 2004). Table 1 summarizes the characteristics of the two satellite sensors used in this study. The GOCI data, including the study area, are acquired at half-past the hour, whereas the acquisition time of Landsat data is about 1100 local time. A total of 626 cloud-free GOCI images acquired during 1 year (from 1 January to 31 December 2012) were used for mapping SSC. In particular, images obtained 7 and 16 January 2012, showing the flood- and ebb-tide conditions, respectively, were used to examine the daily variations in SSC relating to tidal effects. GOCI images with <20° sun elevation angles were removed because low sun elevation
angles < 20°, according to Ding and Gordon (1994), used as a basis for all operational ocean-color atmospheric correction algorithms are no longer valid. To examine the seasonal variations in SSC and compare the atmospheric correction result of GOCI with the Landsat imagery, seven images were used (Table 2). Landsat-7 ETM+ images can possibly show the SSC variation, even if the Landsat-7 ETM+ images have scan line corrector off lines. Six Landsat-7 ETM+ images were also employed to monitor the relationship between seasonal SSC variation and its influencing factors, including river discharge and wind effects. Four Landsat-7 ETM+ images were used to validate atmospheric correction compared with atmospherically corrected GOCI images. The Landsat-7 ETM+ image acquired 6 March 2015 was not suitable to be used for monitoring seasonal SSC variation with the other Landsat images because of a large difference in tidal condition at the acquisition time. Tides at the Incheon station were used, and the diurnal tidal range was calculated. The corresponding river discharge in the estuary was expressed as the sum of the Han River discharge and the Imjin River discharge (Han River Flood Control Office, 2012). GIS for Ocean Research (GFOR) data, created using digital and electronic navigation charts, were used to determine water depths in the study area (Korea Institute of Ocean Science & Technology, GIS for Ocean Research, 2012). Wind speed data were measured and provided by the Korea Meteorological Administration (2012).

### Atmospheric Correction

Atmospheric correction was applied to the satellite images. A modified MUMM algorithm (B. Lee et al., 2013) was used for the GOCI images, and a COST model, along with a NIR–SWIR method, was used for the Landsat-7 ETM+ images. The MUMM algorithm proposed by Ruddick, Ovidio, and Rijkeboer (2000) was not suitable for application to high-turbidity water. Therefore, B. Lee et al. (2013) modified the MUMM algorithm to apply atmospheric correction for high-turbidity water. The modified MUMM algorithm uses two ratios corresponding to aerosol reflectance (a) and water-leaving reflectance (α), which is the water-leaving radiance divided by the downwelling irradiance at the surface at two NIR wavelengths, 745 and 865 nm. The validity of the modified MUMM algorithm when applied to GOCI data was verified by Choi et al. (2014) for turbid areas; they compared the GOCI-derived remote sensing reflectance ($R_{rs}$) obtained from the modified MUMM algorithm with in situ $R_{rs}$ data and showed a very high correlation ($R^2 = 0.927$). The COST model, developed by Chavez (1996), for Landsat-7 ETM+ images is an image-based absolute correction method that uses only the cosine of the sun zenith angle (cos(TZ)) as an acceptable parameter for approximating the effects of absorption by atmospheric gases and Rayleigh scattering (Mahiny and Turner, 2007). Although most atmospheric effects comprise Rayleigh scattering in this area, removal of aerosol scattering is necessary. The COST model is unable to remove aerosol scattering completely. Thus, the NIR–SWIR bands were added to account for aerosol scattering, in conjunction with the COST model. NIR–SWIR atmospheric correction algorithms have been described in numerous studies (Gordon, 1997; Gordon and Wang, 1994; Wang and Shi, 2005; Wang, Son, and Shi, 2009). In this study, a reflectance value in the clear water area that was regarded as reflectance by aerosol scattering was selected in the NIR and SWIR bands, because the reflectance at NIR and SWIR wavelengths was assumed to be nearly zero in clear water areas. The $R_{rs}$ values of band 3 (660 nm) for Landsat-7 ETM+ were calculated after removal of the aerosol contribution obtained by extrapolating those of NIR and SWIR bands. Then, Landsat-7 ETM+ pixels were averaged to 500 × 500 m for comparison with GOCI data.

### SSC Map Generation

SSC maps can be constructed by applying the empirical algorithm proposed by Choi et al. (2014) to the GOCI data. The algorithm was developed based on GOCI band 5 (centered at 660 nm) and was used to quantify the SSC distribution in highly turbid waters through tests near the Mokpo coastal zone and Gyeonggi Bay based on the relationship between the in situ SSC and the $R_{rs}$ at 660 nm measured by spectroradiometer:

$$\text{SSC(GOCI)} = 1.545e^{179.53R_{rs}(660)}, \quad R^2 = 0.9209 \quad (1)$$

Although the spectral responses of the two sensors have similar spectral locations near 660 nm (Figure 2), an algorithm for Landsat-7 ETM+ was needed because Landsat has a broader spectral window. Equation (1) was suitable for only GOCI band 5. Therefore, the SSC algorithm for generating the Landsat-7 ETM+-derived SSC map was developed using the same field data used for Equation (1):

$$\text{SSC(Landsat)} = 1.5119e^{179.85R_{rs}(660)}, \quad R^2 = 0.9205 \quad (2)$$

GOCI-derived SSC values in the study area have been well validated by comparisons with in situ measurements (Choi et al., 2014). Therefore, the Landsat-derived SSC maps in this study could be validated by examining the relationships with GOCI-derived SSC maps at similar acquisition times (1100 Korean standard time, or KST).

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**Table 2. List of Landsat images used to generate the SSC map.**

<table>
<thead>
<tr>
<th>No.</th>
<th>Date</th>
<th>Tide Condition</th>
<th>Tidal Height (cm)</th>
<th>River Discharge (m³/s)</th>
<th>Note</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2012.01.25</td>
<td>Ebb</td>
<td>97</td>
<td>187.84</td>
<td>Atmospheric correction</td>
</tr>
<tr>
<td>2</td>
<td>2012.08.04</td>
<td>Ebb</td>
<td>243</td>
<td>332.13</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>2015.11.17</td>
<td>Ebb</td>
<td>395</td>
<td>273.38</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>2012.09.05</td>
<td>Ebb</td>
<td>358</td>
<td>2754.20</td>
<td>Atmospheric correction</td>
</tr>
<tr>
<td>5</td>
<td>2015.02.02</td>
<td>Flood</td>
<td>128</td>
<td>168.58</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>2015.08.13</td>
<td>Flood</td>
<td>210</td>
<td>282.61</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>2015.03.06</td>
<td>Ebb</td>
<td>87</td>
<td>166.33</td>
<td>Atmospheric correction</td>
</tr>
</tbody>
</table>

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The pixel values of 29 points (Figure 1b) in the GOCI images were used to monitor the annual variation in SSC and to compare with tide and water depth data. These points had various water depth values from 5 to 50 m. To analyze the relationship between SSC and tide, times before and after high tide were calculated. A zero value means high-tide conditions; minus and plus values indicate hours before and after high tide, respectively. In addition, to understand SSC variation affected by tidal range (Figure 1a), 12 averaged 3 × 3-pixel areas were selected. In this study, the 6 hours before high tide (i.e. ebb condition) were considered, because those times were distinctive in average SSC value and tidal range. SSC data were separated into two groups, summer season (June–September) and winter season (January–April, November, and December). May and October data (spring and fall) were not used, because there were no significant changes.

RESULTS

This section shows daily and monthly SSC variations and explains the environmental factors controlling the variation in SSC.

Comparison between GOCI and Landsat-7 ETM+ Data

To monitor seasonal SSC variation in the Han River estuary using Landsat imagery in place of GOCI, four Landsat ETM+ images were used. The atmospheric correction result of the Landsat imagery was compared with the GOCI image verified by Choi et al. (2014). Figures 3a, c, e, and g illustrate the relationship between \( R_{rs} \) in GOCI band 5 and that in Landsat-7 ETM+ band 3; red color (z-scale bar) corresponds to the highest pixel density. An underestimation of Landsat-7 ETM+-derived \( R_{rs} \) was shown in clear waters (\( R_{rs} < 0.01 \)), whereas in turbid waters (\( R_{rs} > 0.02 \)), the Landsat-7 ETM+-derived \( R_{rs} \) values showed good agreement with those derived from GOCI. The \( R_{rs} \) values showed a linear fit with slopes (coefficient \( a \)) of 0.6333, 0.6133, 0.4246, and 0.4620 and intercepts (coefficient \( b \)) of 0.0028, 0.0025, 0.0076, and 0.0080. Overall, values were in good agreement based on the determination coefficient (\( R^2 \)) (>0.60) of the best-fitted linear relationship. The Landsat ETM+-derived \( R_{rs} \) values in the turbidity area were generally slightly larger than the GOCI-derived \( R_{rs} \) values. Some data dispersion in the high-turbidity area was also apparent because of an adjacency effect near the land of the GOCI image. According to Dancey and Reidy (2011), if the \( R^2 \) values of two variables are from 0.1 to 0.3, 0.4 to 0.6, and 0.7 to 0.9, they are considered to have weak, moderate, and strong correlations, respectively. Thus, the GOCI-derived \( R_{rs} \) values were in good agreement with the Landsat ETM+-derived \( R_{rs} \) values in this study.

The \( R_{rs} \) data were then used to generate SSC maps of the study area. Figures 3b, d, f, and h illustrate the relationship between SSCs based on GOCI data and on Landsat-7 ETM+ data, again showing a good agreement in terms of \( R^2 \) values.
The overall SSC showed a linear fit with slopes (coefficient a) of 0.2365, 0.2912, 0.3843, and 0.3071 and intercepts (coefficient b) of 5.2181, 6.2360, 12.4157, and 18.6508. Overall, the values were in good agreement based on the determination coefficient ($R^2$) of the best-fitted linear relationship. However, the red circles in Figures 3f and h indicate points associated with a weak relationship between GOCI-derived and Landsat-7 ETM+-derived SSC data. For these points, the SSC values of Landsat-7 ETM+ data were higher than those of GOCI data. The points correspond to highly turbid water pixels near land, which have high $R_{ss}$ values.

**Daily and Monthly Variability in SSCs Based on GOCI Data**

GOCI-derived SSC maps were used to monitor daily variations in SSC. Figures 4a–k show maps of the SSC derived from GOCI band 5 data acquired 7 and 16 January 2012, together with the tidal status at the Incheon station (Figures 4f and m) (Korea Hydrographic and Oceanographic Agency, 2010). A change in color from blue to red indicates a change from low to high SSC values. Figures 4a–e show flood conditions, and Figures 4g–m show ebb conditions. In all images, SSC values were high ($>80$ g m$^{-3}$) around the tongue-shaped sand ridge area (red rectangle in Figure 4a). Around the time of low tide (1430 and 1530 KST), turbidity in the region was remarkably lower (Figures 4e and f). This was attributed to the settlement of suspended particulates during the transition from flood to ebb tide (and vice versa) and the resulting lull in the tidal current. Although SSC values were not observed near the Han River estuary because of the low spatial resolution of the GOCI, SSC values gradually decreased under high-tide conditions, most likely because of the input of water from the open ocean. In contrast, SSC increased during ebb tides due to the resuspension of bottom sediment as the tidal current was strengthened. As expected, the highest concentrations occurred during maximum tidal current, both for flood and for ebb.

To elucidate the pattern of SSC variation in the study area, SSCs with data obtained from hydrodynamic modeling were compared (Lee et al., 2015). This model was a modified version of the Princeton ocean model, which is used widely in studies of coastal water circulation (Blumberg and Mellor, 1987). Figure 5 shows the hydrodynamic modeling results acquired using data from 7 January 2012, which were used to show flood conditions. Tidal velocity was high around the sand ridge (red rectangle in Figure 5a), where the water was shallow under the entire daily tidal cycle, which may have led to strong resuspension and resulted in the highest SSC being in that area (as in Figure 4). However, tidal velocity was generally low in the open ocean; deep water which may be the reason for the lower SSC values in the open ocean. After low water, the tidal flow (Figure 5c) turned toward the land and the tidal energy gradually increased, causing decreased SSC values. The tidal model supported the results from the GOCI-based diurnal variability analyses. Thus, SSC decreased under flood conditions because of the dilution of turbid waters by clear open ocean waters, but values were still higher around the sand ridge than in the open ocean because of resuspension processes.

To monitor the monthly variation in SSC in 2012, 29 points were selected over the study area (Figure 1b). Figure 6a shows the GOCI-derived SSC and water depths acquired from GFOR data for each point. The water depth in the shallow area, mainly near the sand ridge, was about 20 m, whereas it was more than 40 m deep in the open ocean. High SSC values were evident in the shallow area near the sand ridge, whereas SSC values in the deep areas were low. Figures 6b and c show the monthly SSC variation at points 3 and 17 during 2012. In July, the GOCI imagery was affected by cloud cover because of the rainy season; therefore, Figures 6b and c do not include data for July. The SSC values at point 3, far from the sand ridge and from land (about 130 km from land), with deep water ($>45$ m), were low throughout the year; the maximum SSC was about 5 g m$^{-3}$ in February, and the monthly SSC values changed little over 12 months (Figure 6c). Lower SSC values were observed in summer (from July to September), but there was little change over the year. The SSC values for point 17, in shallow water (approximately 10 m) on the sand ridge, were higher in winter than in summer. The maximum SSC measured was $300$ g m$^{-3}$ in March, while the maximum SSC between May and September was about $10$ g m$^{-3}$. Thus, SSC at point 17 changed less in summer than in winter (Figure 6c). The SSC varied greatly over the year, with lower values in summer than in winter, but with the same pattern of seasonal variation as the open area, with low SSC values in summer and high SSC values in winter.

**Environmental Factors Controlling the Variation in SSCs**

Various factors, including tides, wind, and river discharge, affect the spatiotemporal dynamics of SSC. Figures 7a and b show the relationship between GOCI-derived SSC values and tidal variation. Figure 7a shows the averaged SSC variation from point 1 to point 3 (deep water areas) (Figure 1b) by time before and after high water. The figure shows little variation in SSC in response to tidal conditions. Figure 7b shows the averaged SSC variation from point 15 to point 17 (shallow water areas) (Figure 1b) by time before and after high water. SSC values decreased up to 0 hours after high tide (i.e. low tide) and then increased. Thus, SSC in the shallows clearly shows minima under high-water conditions and maxima under low-water conditions. This implies that tidal conditions strongly affect the variation in SSC in shallow areas as a result of the degree of resuspension of bottom sediment.

To estimate the relationship between SSC variation and tidal range, 12 subareas indicated by the six blue boxes, three green boxes, and three red boxes in Figure 1, which are located on the sand ridge, channel, and open sea, respectively, were selected. Figures 8a–c show the relationship between GOCI-derived 3 x 3-pixel averaged SSC values at each subarea 6 hours before high tide (i.e. around low tide), when the sea surface SSC is the highest and tidal range on the same date of GOCI acquisition in the winter season in the sand ridge, channel, and open sea areas. In the sand ridge and channel areas, SSC values were higher when tidal range was larger, showing obvious positive relationships between SSC and tidal range ($R^2 = 0.74$ and 0.72, respectively), which implies that large tidal ranges induce high
SSC at the sea surface by causing more resuspension of bottom sediment. At the sand ridge, the maximum and minimum SSC values at 900 cm of tidal range were about 80 and 40 g m$^{-3}$, respectively, whereas the maximum and minimum SSC values at 700 cm of tidal range were about 25 and 15 g m$^{-3}$, respectively (Figure 8a). In the channel, the maximum and minimum SSC values at 900 cm of tidal range were about 75 and 65 g m$^{-3}$, whereas those at 700 cm of tidal range were about...
7 and 10 g m\(^{-3}\) (Figure 8b). In the open sea, no notable relationship between SSC and tidal range was shown \((R^2 = 0.05)\) (Figure 8c). In the summer season, a good relationship was shown in the sand ridge area \((R^2 = 0.40)\), but there was no relationship in the channel or the open sea area \((R^2 = 0.11\) and 0.04, respectively).

To investigate the seasonal SSC variation, Landsat ETM+ images were used, because GOCI images are not suitable in the
narrow Han River estuary. Figures 9a and b show the GOCI-derived and Landsat-derived SSC images. The GOCI images were not suitable for monitoring the SSC in the narrow Han River estuary because of masking of the images, whereas the Landsat images revealed the SSC variation in the narrow estuary. Therefore, Landsat images were used to monitor the seasonal SSC variation in the estuary of the Han River. Figures 10a–f show the seasonal variation in Landsat ETM+-derived SSC values in winter (Figures 10a, c, and e) and summer (Figures 10b, d, and f). Table 2 shows a list of images and river discharge values. SSC values in winter were high near the open ocean and the sand ridge, whereas in summer they were high near the inland area (Han River estuary). These results have a pattern similar to the monthly SSC variation in the GOCI images. Although the GOCI images did not include the narrow Han River estuary, GOCI-derived SSC in the winter season was high in the shallow water area but low in deep water areas. In general, SS input by the river is higher in the wet season (i.e., large discharge) than in the dry season (i.e., low discharge) (Heckin, 1995). In this area, the wet season with high discharge is from June to August and the dry season with low discharge is from September to December. There was a higher amount of river discharge in the summer season than in the winter season. Although the river discharge was high in summer, the SSC values were low in the open ocean and sand ridge areas (Figures 10b, d, and f). This implies that river discharge affects only the areas around the Han River estuary. In general, most of the sediment from the river is not transported to the deep sea (Liang, Li, and Lee, 2007). The study results showed a pattern similar to the results of Liang, Li, and Lee (2007), which also indicated that the river does not affect the deep sea. However, river discharge was low in the winter season even though SSC values were high in the open ocean, possibly because of the NW

![Figure 6](image_url)

**Figure 6.** (a) Comparison between water depths and SSCs. (b) and (c) Monthly variation in GOCI-derived SSCs at points 3 and 17.

![Figure 7](image_url)

**Figure 7.** Relationship between averaged SSCs and the tide effect (a) from point 1 to point 5 and (b) from point 13 to point 19. The x- and y-axes indicate the time before and after high water and the averaged SSC derived from GOCI images, respectively.
monsoon rather than river discharge. Figures 11a and b show a rose diagram of wind in the winter and summer seasons, respectively. Wind speeds in Gyeonggi Bay were higher in the winter season than in the summer season (Figure 11a). SSC values in the winter season were higher in the open ocean and sand ridge areas, which are unaffected by river discharge, than in the Han River estuary. In conclusion, this study indicates that the main factor in SSC values is tidal resuspension in shallow areas. In particular, both tide and wind affect the sand ridge, whereas river discharge affects only the Han River estuary. Both tide and wind affect particle movement on the sea bottom, resulting in SSC variation.

**DISCUSSION**

To understand the time series variation in SSC in the turbid coastal water, an SSC map was generated using GOCI and Landsat-7 ETM+ data. To generate the SSC map, atmospheric correction of the Landsat ETM+ images was performed using the COST model, along with the NIR–SWIR method. Overall, $R_{ss}$ and SSC values showed a good relationship between GOCI and Landsat ETM+ ($R^2 > 0.6$ and 0.5, respectively), but the scatter and the bias at higher SSC, i.e., uncertainties, could be rather high. Empirical algorithms based on the red band are simple and easy to implement. In addition, the relationships between the SSC and the $R_{ss}$ values are more specific geographically, showing good correlation in general. Thus, the empirical algorithm developed by Choi et al. (2014) was used. It works well for low- to moderate-turbidity values (Dogliotti et al., 2015); however, when SSC is very high, such as along the east coast of west China, $R_{ss}$ values can be saturated and the simple empirical algorithm may not be effective. In that case, other algorithms, such as semianalytical algorithms, physical approaches, or two-band empirical algorithms, may be useful for generating a more accurate SSC map. The high spatial resolutions of Landsat sensors proved to be useful for detecting detailed SSC near land, but they were not well suited to detecting daily variations in SSC. Thus, GOCI data, combined with Landsat imagery, provide a means to monitor detailed local variations in coastal water turbidity. As mentioned earlier, although the sensors used have different band characteristics and acquisition times, the results of atmospheric correction and the SSC values for each image can be determined for monitoring sediment variation in estuaries.

Daily and monthly variations in GOCI-derived SSC were analyzed. The SSC in daily GOCI images showed variation with tide conditions. In the high-tide condition, SSC decreased as a result of water input from the open sea. In the ebb-tide condition, it increased by the resuspension of bottom sediment. In general, erosion, sedimentation, and resuspension of bottom sediment are closely related with the shear stress induced by the current. In the monthly SSC variation, the SSC in the shallow water on the sand ridge was higher in winter than in summer. The results suggest that bottom sediments in the shallow areas over the sand ridge and near land can easily be resuspended, affecting SSC variation at the sea surface. In Gyeonggi Bay, high SSC values occur in areas of strong shear stress, which leads to strong resuspension (Park, 2012). Thus, examinations of the bottom surface sediment characteristics and bottom shear stress are needed to reveal the relationship between the degree of resuspension and the bottom shear stress in the study area.

Additional studies are needed to complement this result. The flow of the Han River influences the Ganghwa tidal flat, rather than the open sea (Y.K. Lee et al., 2011; H.J. Lee et al., 2013). However, to interpret the results based on satellite images; sedimentological interpretation, including net SS transport; residual flow; and so on, is necessary. Bottom surface sediment characteristics in the study area are required to analyze the sediment transport processes. Satellite-based observations can be applied to sea surface variation and reflect variation below the sea surface. In general, the modes of sediment transport are related mainly to the textural characteristics of sediments and local hydrodynamic conditions (Dyer, 1986; Kim et al., 1989). Park (2012) reported that the SS in Gyeonggi Bay was made up mostly of sand particles and that SS was transported by strong
current velocity and shear stress from in situ and modeling data from 2007 to 2009. Although particle size on the bottom is coarse grained, high current velocities and shear stresses resulting from tides and wind can promote particle resuspension. Precise bottom surface characteristics, such as grain size, shear stress values, and vertical current velocities, are needed.

**CONCLUSIONS**

To evaluate sediment dynamics and erosion–sedimentation patterns in a coastal region, preliminary SS transport observations in Gyeonggi Bay, including the estuary of the Han River, were performed in this study. For this study, time-
series variations in SSC in Korean coastal waters were analyzed using GOCI images combined with Landsat-7 ETM+ images to elucidate sediment movement in the study area and to examine the possibility that multispatial resolution satellite data can be integrated with sediment transport processes in the estuary. SSC maps were generated by applying an empirical algorithm and were used for monitoring the daily, annual, and seasonal variations in SSC from the coast to the open ocean. The relationships between SSC and environmental factors such as water depth, tidal cycle, and river discharge.
were then examined to identify the main factors affecting SSC variation. The conclusions drawn from this study follow.

The results of atmospheric correction of GOCI and Landsat-7 ETM+ images showed good agreement for generation of SSC maps in the turbid area. Although Landsat-7 ETM+ data are less suitable than GOCI data to monitor SSC variation, Landsat-7 ETM+ results were similar to those obtained using GOCI data. Atmospheric correction of only Landsat-7 ETM+ images was performed in this study, but many Landsat ETM+ and Operational Land Imager (OLI) images should be analyzed in the future. In particular, Landsat-8 OLI images offer higher radiometric quality than Landsat-7 ETM+ images and could be used to monitor SSC variation. If Landsat-8 OLI images could be acquired in combination with Landsat-7 ETM+ images, many SSC maps under various tidal conditions could be generated. Moreover, to verify the results of atmospheric correction, many field data, such as $R_{rs}$ and SSCs, need to be collected on the Landsat passing day because the revisit time of Landsat is longer than that of GOCI.

Examination of the diurnal variation in SSC showed that tide is a main factor in generating high SSC because of the resuspension of bottom sediments. High tidal velocity led to high SSC values around the sand ridge as a result of strong resuspension. In the case of monthly SSC variation, SSC values in deep-water open seas did not exceed 10 g m$^{-3}$, whereas the maximum SSC near the sand ridge was about 400 g m$^{-3}$. SSC variation was high throughout the year around the sand ridge, but values changed less over the same period in the open ocean. Seasonally, river discharge affects only the Han River estuary, but the high winds characteristic of the NW monsoon result in resuspension in shallow marine areas. These effects resulted in higher SSC values in winter than in summer. The results show that tide is the main driver of diurnal spatial and temporal variability in SSC but that bathymetry and wind speed also have an effect. At the sand ridge and in the channel, SSC showed a good relationship with tidal range ($R^2 = 0.74$ and 0.72, respectively). In particular, a large tidal range generated a high SSC, possibly because of strong resuspension. In the 900-cm tidal range, SSC showed a range of 40 to 80 g m$^{-3}$, whereas SSC in the 700-cm tidal range showed a narrow range of 7 to 25 g m$^{-3}$. Both tide and wind speed affect the sand ridge area, whereas river discharge affects SSC values only near land. Oh and Bang (2003) revealed that the surface sediment movement in Gyeonggi Bay is influenced mainly by tide, which is in accordance with the results of this study.

Analysis of images generated by fusion of GOCI and Landsat-7/8 ETM+/OLI images (Vanhellemont, Neukermans, and Ruddick, 2014) would also be valuable to elucidate the relationship between SSC and sediment processes in estuaries. By fusing 7/8 ETM+/OLI images, eight high-spatial-resolution images per day could be obtained to analyze dynamic local SSC variation. Nevertheless, to verify the quality of the fused images, many field data for land and open ocean would be needed. The results of this study could be combined with appropriate geological analyses to examine the dynamics of sediment movement along the west coast of the Korean Peninsula, which would help to elucidate the sediment transfer process and thus changes in the coastal environment.

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LITERATURE CITED


