Sedimentary impacts of anthropogenic alterations on the Yeongsan Estuary, South Korea

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ABSTRACT

Over the last half-century, coastal zones within the Republic of Korea (S. Korea) have experienced a wide range of engineered coastal modifications including construction of seawalls, extensive land reclamation, and installation of estuarine dams. The Yeongsan Estuary has experienced all of these modifications and provides an ideal case study on how sedimentation changes within a macrotidal estuary in response to these alterations. Combined, these alterations have considerably modulated the timing and intensity of river discharge, prevented natural tidal exchange, modified the shoreline profile, and altered the transport of sediment and organic matter within the coastal zone. These impacts have been investigated using 30 gravity cores analyzed for 210Pb radioisotope geochronology, laser diffraction particle size analyses, δ13C and δ15N isotope ratio mass spectrometry, and X-radiography. Average sediment accumulation rates range from 0.9 ± 0.6 cm yr−1 to 10.0 ± 2.9 cm yr−1, with the highest rates proximal to the downstream side of the dam, and some areas determined to be either actively eroding or recently dredged. These results are supported by comparison of multiple bathymetric surveys, and CHIRP seismic data suggest an order of magnitude increase from average Holocene sediment accumulation rates. Side scan sonograms collected adjacent to the dam reveal distinctive scouring, transitioning to areas accumulating fine-grained sediments. Shifts in the organic matter source inputs are apparent in pre/post-dam sediments and reflect the occluding of tidal influence above the dam, resulting in increasingly terrestrial dominated signatures. Additionally, a time series of cores collected during periods of limited and high discharge analyzed for 7Be, indicates sediment deposition occurs episodically corresponding to high discharge dam releases. Our observations record a shift in depositional environments as a response to an extensive array of anthropogenic alterations. Ultimately, land reclamation and dam construction have severely altered the fate and transport of sediment within the estuarine system. As a consequence, sedimentation rates have increased dramatically and depositional events are primarily controlled by discharges from the estuarine dam.

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1. Introduction

Most of the world’s ports and coastal cities reside adjacent to estuaries, with approximately 65% of cities with population greater than 5 million located less than 10 m above sea level (McGranahan et al., 2007). Throughout the last century, rapid socioeconomic development has resulted in significant engineered alterations to coastal areas, and severe degradation of ecosystems (Lotze et al., 2006; Cooper, 2009; Wong et al., 2014). The industrial and urban development of estuaries has resulted in changes to shoreline configuration, fluvial discharge, tidal characteristics, and sediment dynamics (Byun et al., 2004; Crossland et al., 2005; Syvitski et al., 2005; Walling, 2006; Cuvilliez et al., 2009; Gao et al., 2012; Jackson, 2013; Wang et al., 2013; Williams et al., 2013; Liu et al., 2014; Pye and Blott, 2014). With 37% of the world’s population living within 100 km of the coast (Cohen et al., 1997), and a predicted rise in sea level of between 0.3 and 1.0 m within the next century (Church et al., 2014), it is anticipated that there will be an increase of engineered structures within estuaries globally. In order to predict the results of future anthropogenic alterations, we need to understand how systems that have already undergone comparable alterations have responded. The Republic of Korea provides an ideal natural laboratory to address such issues, because many of the watersheds and estuaries have been highly modified (Lee et al., 2011). Among the 463 estuaries identified in S. Korea, Lee et al. (2011) determined that approximately half are classified as closed estuaries due to an estuarine dam or sluice gate.

The construction of estuarine dams to impede saltwater intrusion and regulate discharge, along with vast emplacement of seawalls has considerably modified many coastal areas within the last century (Yoon and Woo, 2000; Choi et al., 2005; Yoon et al., 2007). The impacts of estuarine dams and/or reservoirs constructed in coastal zones on
sediment deposition have been investigated in numerous studies. Sedi-
mentation rates proximal to the Keum estuarine dam (S. Korea) were
reported to have increased as much as three times ($\sim 20$ cm yr$^{-1}$) due to hydrodynamic changes that resulted in a decrease
in overall current velocity (Kim et al., 2006). Within the Netherlands
Haringvliet Estuary, several coastal engineering projects and dam con-
struction resulted in increased sediment volume and a decrease in the
tidal prism (Tonis et al., 2002). Anthropogenic alterations to the
Nakdong Estuary (S. Korea) have also led to a similar reduction in the
tidal prism. Geomorphological changes due to seawall and estuarine
dam construction ultimately caused a shift in classification from a tide-
to wave-dominated estuary, resulting in a dramatic increase in sedi-
mentation rates below the dam and re-distribution of bottom types
and associated benthic habitats (Williams et al., 2013). Additionally,
several studies have documented changes in sediment transport dy-
namics due to coastal dam construction (Barusseau et al., 1998; Yoon
et al., 2007; Gao et al., 2012; Zamora et al., 2013). Management (dredg-
ing operations, etc.) and monitoring of estuarine sediment in macrotidal
systems, particularly in estuaries of Northern Europe (Mitchell and
Uncles, 2013), has been addressed and the need for further sediment ac-
cumulation research is apparent.

The Yeongsan Estuary (S. Korea) is a prime example of an estuary
that has undergone significant coastal construction within the last
century. Built to divert and impound fresh water for agricultural practices,
impede the intrusion of saltwater, and provide flood prevention, the
Yeongsan Estuarine Dam was constructed in 1981. As a result, approxi-
mately 98 km$^2$ of total estuarine area was eliminated above the dam
with the cessation of tidal exchange, creating the freshwater Yeongsan
Lake (Fig. 1). Prior to occlusion, tidally influenced environments
spanned approximately 63 km upstream from the dam (Lee et al.,
2009). Additionally, during land reclamation projects throughout the
1980s, tidal flats were filled and 90 km of seawalls/embankments
were added. With a current reservoir area of 34.3 km$^2$, the reduction
in intertidal area above the dam is estimated to be 63.2 km$^2$ (65%). Below the dam, land reclamation projects have reduced intertidal
zones by 16.5 km$^2$, resulting in a total reduction of nearly 80 km$^2$. Sea-
walls have also been constructed in the region south of the Yeongsan
Estuary including the Youngam seawall in 1991, and the Keumho seawall
in 1994, eliminating an additional 130 and 60 km$^2$ of intertidal zones
respectively (Kang, 1999).

Several studies have been conducted on the Yeongsan Estuary and
Lake examining the changes in tidal characteristics, water structure/
mixing, and biogeochemistry. In a multidisciplinary study of Yeongsan
Lake, Lee et al. (2009) showed significant anthropogenic organic com-
 pound loading and oxygen depletion due to thermal and haline stratifi-
cation, a reduction in fish diversity, and an increase in sediment depo-
sition based on bathymetric change analyses. Through observa-
tional data and numerical analysis, Kang (1999) reported an increase

![Fig. 1. Detailed study area map showing location of the Yeongsan Estuary within South Korea and all core sampling locations. Inset A identifies study location within South Korea. Detailed location of cores proximal to the Yeongsan Estuarine Dam (YED) is shown within Inset B (extent has been outlined). The location of discharge release at the floodgates has been indicated within Inset B. Cores are labeled according to respective environments, including Yeongsan Lake (YL 1–10), Inner Estuary (YE 1–11), Outer Estuary (YO 1–7), and Coastal (YC 1–2) cores. The total reclaimed area is represented by the change in shoreline pre-development (1963) to the current configuration (2013), such that the difference in area represents reclaimed intertidal zones (gray zones).]
in extreme high tide of 60 cm and a decrease in extreme low tide of 43 cm as a cumulative result of construction of the estuarine dam and seawalls. Furthermore, tidal current velocities decreased due to a reduction in tidal choking (Kang, 1999). Byun et al. (2004) also reported a significant increase in tidal amplitude and an advance in tidal phase due to the reduction in storage capacity associated with a shift towards a non-choked system. These alterations have severely impacted estuarine circulation by eliminating natural mixing of fresh and saltwater above the dams, which resulted in severe water quality degradation, and dramatically changed the sediment dynamics of the region (Lee et al., 2009).

Although these studies have provided insights into the hydrodynamic, biological, and chemical alterations, there remains a paucity of data investigating the historical changes within the recent stratigraphic record. While predictive or modeled shifts in sediment dynamics and historical bathymetric changes provide substantial information, evaluating the changes in sedimentary processes through core analyses remains crucial to characterize the impacts of human alterations to these systems.

This study aims to determine the effects of anthropogenic alterations on sedimentation within the Yeongsan Estuary. Specifically, we aim to determine 1) how environmental changes have impacted sedimentary organic matter signatures 2) the system response in terms of sediment distribution and accumulation, 3) the deposition of sediment associated with a large discharge, and 4) how current accumulation rates compare to average rates throughout the Holocene. The results herein provide a case study on how macrotidal estuaries respond to significant anthropogenic alterations. These findings are not only poignant regionally, as many estuaries in East Asia have recently and are continuing to undergo significant coastal construction, but have future global implications with continued industrialization in developing countries and predicted sea level rise (Church et al., 2014).

2. Regional setting

The Yeongsan Estuary is located within the city of Mokpo, with an approximate population of 250,000 and consists of the Yeongsan Lake, Inner Estuary, Outer Estuary, and Coastal zones (Fig. 1). The Yeongsan River has a drainage basin area of 3468 km² with a total length of 137 km, making it the sixth longest river in the country. The river debouches to the Yellow Sea through a relatively shallow (predominantly <50 m depth) intricate coastline of islands. The Inner Estuary is situated between the Muan and Yeongam peninsulas with an average depth and width of 19 m and 1.3 km, respectively for a length of 6.7 km. At the mouth of the estuary, the main channel splits around Goha Island opening to a series of islands separated by four main channels (Bukgu, Chunggu, Mokpogu, and Aphaedo) (Fig. 1). Wave height is typically suppressed within the estuary due to the orientation of the estuary and the many nearshore islands blocking the open sea (Byun et al., 2007). With an approximately 4.5 m tidal range, the estuary is classified as macrotidal, with primarily semidiurnal ebb dominated tides (Byun et al., 2004). The Yeongsan Lake spans 23.4 km in length from the estuarine dam to the Mongtan Bridge, decreasing in width from 1.2 to 0.6 km with an average depth of 10 m with two main tributaries, the Sampo and Yeongam Rivers, connecting from the east (Lee et al., 2009).

On the Korean peninsula, climatic conditions are dominated seasonally by monsoons. During winter months, strong north to northwesterly winds are accompanied by minimal precipitation. Conversely, summer months typically experience relatively weak south to southeasterly winds, heavy precipitation, and occasional typhoons (Chang, 2004). This seasonal variability in precipitation results in a predominance of freshwater releases from the dam during summer months. Discharge data from 1997 to 2013 reveals that nearly 80% of the discharge occurs between late June and early September (Fig. 2). However, the total annual discharge varies significantly and is highly dependent on annual precipitation (Fig. 3), resulting in large standard deviations in monthly averages, particularly in summer months (Fig. 2). Since 2000, on average the dam has been opened every 1.7 days during the summer months for 154 min. resulting in an average total discharge of 10.4 × 10⁶ m³ per dam release, and opened every 7.4 days during the dry season for 123 min. resulting in an average total discharge of 2.6 × 10⁶ m³ per dam release (Kang et al., 2009; Rhew and Lee, 2011).

3. Methods

3.1. Data collection/core processing

A total of 30 gravity cores were collected between May 15 and 16, 2012 using a 6.0 cm diameter core barrel with PVC liners and have been nominally assigned to either lake (YL 1–10), inner estuary (YE 1–11), outer estuary (YO 1–7), or coastal (YC 1–2) environments (Fig. 1; Table 1). Additionally, 10 cores were collected by a scientific diver using 7.2 cm diameter acrylic cores on June 7 and Aug. 5, 2013, respectively at core locations YE 1, 3, 7, 11 and YO 3, 6. Cores were sealed immediately upon recovery, and showed no signs of degradation from partial recovery or transportation. X-radiographs of diver cores were taken using a MinXray HF100 + Amorphous Silicon Imaging System 4030R X-ray unit at an energy level of 60 kV with an exposure time of 1/20 s. Subsamples were taken at 1 cm intervals, homogenized, and...
3.3. δ13C and δ15N

Sediment samples for bulk carbon and nitrogen stable isotope analyses were digested, HCl acidified, and analyzed via combustion with a Costech Elemental Analyzer at the Baylor University Stable Isotope Laboratory using USGS-40/41 as international standards for normalization. Standard deviations for standard reference materials were 0.01‰ and 0.02‰ for δ13C and δ15N, respectively. Standard delta notations of isotopic values are relative respectively to Vienna Pee Dee Belemnite and atmospheric N2 values.

3.4. Grainsize analyses

Samples were homogenized, sieved at 2 mm, sonicated with sodium hexametaphosphate dispersant, and analyzed for grainsize distribution using a Malvern Mastersizer 2000® laser particle diffraction meter at a calibrated level of obscurance. Sieved fractions were dried weighed for inclusion in the final distribution. Reported results are an average of triplicate measurements of sand, silt, and clay fractions.

3.5. Bathymetric data

Relative changes in seabed elevation were determined from bathymetric survey data provided by the Korean Hydrographic and Oceanographic Administration (KHOA) from 1983 to 1997. Using ESRI ArcGIS®, discrete measurements were made at 3- to 5-m vertical intervals of cores and surface grab samples (unpublished data) were used to calibrate backscatter intensities. High-resolution sub-bottom seismic data were collected with an Edgetech 3100 and SB-216S CHIRP towfish operating with a swept acoustic frequency range of 2–16 kHz. Post-processing of seismic data was conducted in Chesapeake Technology Inc. SonarWiz 5 software applying water-column blanking, sediment interface tracking and depth correction, and trace stacking.

3.6. Geophysical data

Side-scan sonar data were collected using a DSME E&R Ltd. T-150A SonarBeam at 400 kHz perpendicular to the axis of the estuary at 100 m line spacing using constant gain and range settings. Mosaic compilation was completed in Chesapeake Technology Inc. SonarWiz 5 utilizing nadir blanking and time variable gain. Grainsize data from surface intervals of cores and surface grab samples (unpublished data) were used to calibrate backscatter intensities.

4. Results

4.1. Geochronology

Examination of 210Pb-derived activity revealed 3 distinctive profiles that have been characterized herein as core types A, B, and C. Representative examples displaying typical 210Pb characteristics are shown in Figs. 5, 6, and 7. Sedimentation rates on a decadal timescale are assessed as valid. Vertical resolution. Considering the precision of available survey equipment, the accuracy of data on or below decimeter scales is contentious.
Core type A exhibits $^{210}\text{Pb}_{\text{tot}} > 2.0$ dpm g$^{-1}$ throughout the core, indicating activities are significantly above supported levels (Fig. 5). These 11 cores have been determined to have relatively high average sedimentation rates of $>4$ cm yr$^{-1}$, with values ranging from $4.1 \pm 1.2$ cm yr$^{-1}$ (YE 8) to $10.0 \pm 2.9$ cm yr$^{-1}$ (YE 5). Water contents are high (>50%) throughout, indicative of rapid sediment accumulation. Core type B displays relatively moderate average sediment accumulation rates, with $^{210}\text{Pb}_{\text{tot}}$ activities decreasing from approximately 2.0 to 1.0 dpm g$^{-1}$ at depth, reaching supported levels (Fig. 6). The 12 cores classified as type B represent a range in average accumulation rates from $0.9 \pm 0.6$ cm yr$^{-1}$ (YE 1) to $3.1 \pm 0.7$ cm yr$^{-1}$ (YO 3). Type B cores also showed a decrease in water content from approximately 60% at the surface to 35% at the base of the core, supporting the interpretation of relatively moderate accumulation rates. Cores of type C contain $^{210}\text{Pb}_{\text{tot}} < 1.0$ dpm g$^{-1}$ throughout, representing only supported activity (Fig. 7). The low $^{210}\text{Pb}_{\text{tot}}$ and water content values (<40%) throughout suggest the lack of sediment accumulation. However, an exception exists in the upper 8 cm of YO 7 with samples containing $^{210}\text{Pb}_{\text{tot}}$ activities of approximately 2.0 dpm g$^{-1}$ and water content of 53%.

Examination of the distribution of core type reveals a clustering of type A within the inner estuary and proximal outer estuary, type B cores dominating the upper lake region and areas near the dam, and type C cores occurring in varying locations throughout the system. Accordingly, the highest accumulation rates are within the inner estuary, averaging approximately 8 cm yr$^{-1}$ throughout, while relatively moderate accumulation rates are observed through the majority of Yeongsan Lake, averaging approximately 2 cm yr$^{-1}$ (Fig. 8). In order to understand the spatial distribution and variability in average sediment accumulation rates, interpolation of these data were conducted using a standard Kriging method (Fig. 8). While this method identifies trends, it is based solely on interpolation and it is presented as an interpretation. However, we believe that the spatial density of core locations is sufficient to provide an accurate portrayal, and consistency between this approach (Fig. 8) and bathymetric change analyses (Fig. 4) supports the reconstruction of accretion versus eroding regions.

4.2. Stable isotope signatures

Organic matter source was evaluated using stable isotopic analyses of $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$, with samples taken at surface and bottom intervals of 15 cores (Ex. Figs. 4, 5, and 6) and summarized as interval averages in Table 2. Signatures for $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ ranged from $-26.2\%$ to $-15.8\%$, and $4.7\%$ to $10.2\%$, respectively. Based on $^{210}\text{Pb}$ geochronology, isotopic values are interpreted as deposited pre-dam (<1981) if sampled from the bottom of core types B or C, and post-dam if sampled from the surface of core types A or B (Fig. 10). While a gradient in pre-dam $\delta^{13}\text{C}$ signatures exists from lake to coastal samples ($-22.3\%$ to $-15.8\%$), a notably higher range is observed in post-dam sediment ($-26.2\%$ to $-16.4\%$) (Fig. 10). Additionally, enrichment in $\delta^{15}\text{N}$ signature is apparent with pre-dam samples (4.7% to 6.5%) exhibiting a smaller and relatively depleted range compared to
Fig 5. Representative examples of core type A (Core locations are shown in Fig. 1). Left panel indicates relative grainsize percentage. Middle panel displays total $^{210}$Pb and unsupported $^{210}$Pb activities of $^{210}$Pb in dpm g$^{-1}$. Error bars for activity are indicated or occur within the range of the plot symbol. Regression line for $^{210}$Pb$_{us}$ and $R^2$ value are shown within plot. Samples chosen for $\delta^{13}C$ and $\delta^{15}N$ analyses are also indicated. Right panel shows water content percentage throughout each core. Note: depth scale is constant in Figs. 5, 6, and 7, with plotted data indicating depth of core.
Fig 6. Representative examples of core type B (Core locations are shown in Fig. 1). Left panel indicates relative grainsize percentage. Middle panel displays total ($^{210}$Pb$_{Tot}$) and unsupported ($^{210}$Pb$_{xs}$) activities of $^{210}$Pb in dpm g$^{-1}$. Error bars for activity are indicated or occur within the range of the plot symbol. Regression line for $^{210}$Pb$_{xs}$ and $R^2$ value are shown within plot. Samples chosen for $\delta^{13}$C and $\delta^{15}$N analyses are also indicated. Right panel shows water content percentage throughout each core. Note: depth scale is constant in Figs. 5, 6, and 7, with plotted data indicating depth of core.
Fig 7. Representative examples of core type C (core locations are shown in Fig. 1). Left panel indicates relative grainsize percentage. Middle panel displays total (\(^{210}\)Pb\(_{\text{Tot.}}\)) and unsupported (\(^{210}\)Pb\(_{\text{xs}}\) (YO 7 only) activities of \(^{210}\)Pb in dpm g\(^{-1}\). Error bars for activity are indicated or occur within the range of the plot symbol. Samples chosen for \(\delta^{13}C\) and \(\delta^{15}N\) analyses are also indicated. Right panel shows water content percentage throughout each core. Note: depth scale is constant in Figs. 5, 6, and 7, with plotted data indicating depth of core.
post-dam samples (5.3‰ to 10.2‰). Statistical analyses (heteroscedastic T-test) reveal there are significant shifts (p < .01) in δ¹³C and δ¹⁵N signatures of pre and post dam sediments within the lake and inner estuary. In the outer estuary, no significant differences for δ¹³C and δ¹⁵N are observed (p = 0.67 and p = 0.27, respectively).

4.3. Grain size profiles

Grain size profiles are shown as relative percent composition of sand, silt, and clay and exhibited relatively minor changes throughout individual cores, with only slight variation between cores regardless of depositional environment (Figs. 5, 6, and 7). The average relative grain size distribution for all cores is summarized in Table 1. The preponderance of samples are composed of fine silt and clay with minor amounts of sand present. Considering averaged data from all cores, the sediment composition data yields an average sand (6.2 ± 4.3%), silt (66.7 ± 4.1%), and clay (27.1 ± 5.4%) content, respectively (errors shown as 1σ).

4.4. Surficial sediment distribution

The surficial distribution of sediment adjacent to the dam has been investigated by side scan sonar mosaic analyses (Fig. 9). A range in backscatter intensity occurs throughout the survey, with the majority of the region displaying very low backscatter with several high backscatter targets distributed predominately in the inner estuary. Confirmed by grain size distributions of surficial sediment (YE 1–4, YL 10), the low backscatter represents unconsolidated fine-grained sediment. High backscatter targets observed within the survey area were identified visually as bedrock at low tide during subaerially exposure. In the central region of the estuary, numerous irregularly shaped, relatively high backscatter targets have been interpreted as coarser grain sediment.

4.5. High resolution seismic stratigraphy

The record of Holocene sedimentation has been evaluated through CHIRP seismic on a series of cross estuary transects intersecting with cores YE 3, 6, 7, 8, 10, and 11 (Figs. 1, 13). These profiles reveal a prominent reflector extending continuously through the survey at approximately 3 to 7 m sediment depth, with reflectors primarily indistinguishable below. Where identifiable, this reflector has been traced within Fig. 13. Above this point, an unconformable stratigraphic sequence with numerous continuous internal reflectors is observed throughout the inner estuary. While the thickness of the strata within this sequence varies, a strong correlation to the depth of the acoustic basement is apparent, suggesting control of antecedent topography (i.e. accumulation space) on sediment accumulation.

4.6. ⁷Be deposition and X-radiographs

To determine the timing of sediment deposition in relation to discharge, cores were collected and assayed for ⁷Be activity. In order to characterize the dry/low discharge season, 4 cores were collected (6/7/13) prior to the beginning of the summer monsoon. Although high discharge events may occur through Sept. (Fig. 2), to minimize time after a large
discharge event (7/6/13, Fig. 3), 6 subsequent cores were collected (8/5/13) before the end of the average high discharge/monsoon period. In locations with data from both sampling periods (YE 1, 3, 11 and YO 3), additional core results with pre-flooding data unavailable (YE 7 and YO 6) are also reported (Fig. 11).

Cores taken in June display relatively deep constant $^7$Be activities near detection limits between 0.06 and 0.25 dpm g$^{-1}$, suggesting sediment deposition prior to at least 2 half-lives ($\approx 100$ days). $^7$Be activities from cores taken in August are elevated in surface intervals (0.8 to 2 cm) predominate. Sediment texture is similar in cores with higher $^7$Be penetration depths (YE 7, 11, YO 3, 6), displaying coarser (1–3 cm) laminations interspersed with massive bedding.

### 5. Discussion

#### 5.1. Evidence of environmental change from organic matter isotopic signatures

There have been extensive studies utilizing stable isotopes as tracers for organic matter, specifically to delineate terrestrial versus marine sources, within coastal and estuarine sediments (Schelske and Hodell, 1995; Louchouarn et al., 1999; Zimmerman and Caneul, 2002; Bianchi, 2007; Brandenberger et al., 2011). In the Yeongsan Estuary and Lake, severe anthropogenic alteration to the system has resulted in a significant shift in stable isotopic signatures (Fig. 10).

To further assess these changes, the proportion of terrestrial organic matter (TOM) has been evaluated through a binary mixing model, applying end-member sources of $\delta^{13}$C to determine relative abundances. The terrestrial and marine end-member values have been respectively chosen based on the maximum depleted value found within the surface sediment of the lake ($-26.2\%$), and the most enriched value found offshore ($-15.8\%$). These values correspond with recognized signatures from terrigenous C3 plants and marine plankton (Bianchi, 2007).

The contribution from the terrigenous end-member ($\%$TOM) to the total organic carbon in sediment is determined by:

$$\%$TOM = \frac{\delta^{13}C_{X} - \delta^{13}C_{M}}{\delta^{13}C_{X} - \delta^{13}C_{M}}$$

where subscripts represent the sample ($X$), terrestrial end-member ($T$), and marine end-member ($M$) signatures. The $\%$TOM for all samples is summarized in Table 2. The proportion of TOM in pre-dam sediment ranges from 43–61% in the lake, 39–43% in the inner estuary, and 10–20% in the outer estuary. Post-dam sediment TOM ranges from 82–99% in the lake, 22–74% in the inner estuary, and 9–14% in the outer estuary. Changes in terrigenous input (Δ$\%$TOM) from surface to bottom of cores are shown to compare pre and post dam signatures (Table 2).

Notably, the Δ$\%$TOM is sufficiently small ($\approx 3.5$ to 7.4%) for core types A and C, indicating minor environmental changes, and providing corroborating evidence for core characterization.

Based on these calculations, there has been a significant increase in $\%$TOM ($\approx 30$–45%) in lake and inner estuary sediments since the construction of the estuarine dam (Fig. 10, Table 2). The elimination of marine phytoplankton, the primary source of relatively enriched $\delta^{13}$C, above the dam with the cessation of tidal mixing increased the relative abundance of TOM in lake sediments. Moreover, the influence of organic matter derived from the lake is apparent within surface sediment of the inner estuary, displaying high $\%$TOM in the majority of cores (YE 1, 3, 5) (Fig. 10). Combined, this suggests that reduced tidal inflow (lake) and increased flux of TOM (inner estuary) has resulted in increased proportions of TOM to lake and inner estuary sediments.

However, defining organic matter source based solely on $\delta^{13}$C has been shown to be problematic (Louchouarn et al., 1999; Gordon and Goñi, 2003; Bianchi, 2007; Bianchi and Caneul, 2011). First, endmembers may vary with changing environmental conditions. Second, contributions from additional sources such as terrigenous soils, C4 salt marsh plants, or freshwater phytoplankton could alter $\delta^{13}$C signatures. Expansion of the model herein to include soil and biomarker data (lignin phenols and/or lipids), and completed profiles of elemental and molecular analyses would further elucidate organic matter sources and the transition from historical to current conditions.

Similarly, $\delta^{15}$N values show a marked shift in lake and inner estuary samples after impoundment (Figs. 10). Typically, a shift from higher relative contribution of marine/estuarine phytoplankton to terrigenous vascular plants results in a depletion of $\delta^{15}$N; however, post-dam sediment reveals enrichment. Several studies have shown that enriched $\delta^{15}$N signatures are caused by isotopically heavy nitrogen loading from agricultural runoff (fertilizers) and/or sewage waste (Heaton, 1986; Macko and Ostrom, 1994), or from recycling/regeneration under anaerobic conditions (Struck et al., 2000; Zimmerman and Caneul, 2002; Bratton et al., 2003). Recently, severe oxygen depletion due to eutrophication has been observed within Yeongsan Lake (Smith et al., 2006; Park et al., 2008; Lee et al., 2009). Therefore, with the introduction of highly fertilized agricultural plots and sewage waste input, the enriched $\delta^{15}$N signatures are interpreted as a combination of these processes.
5.2. Sediment accumulation and distribution

The cumulative effects of appreciably reducing tidal current velocities, altering river discharge characteristics, and hardening shorelines have drastically altered sediment accumulation and distribution within the Yeongsan Estuary and Lake. With water and sediment flux restricted to the dam, the effects on sediment distribution are apparent within side scan sonograms (Fig. 9). Flow velocities of approximately 1.5 m s\(^{-1}\) recorded 1.8 km from the dam during moderate discharge events (Shin et al., 2014) support the interpretation of the prominent high backscatter area extending approximately 1 km on each side of the dam as a zone of intense scouring. Indurated clays obtained from this area (Core YE 2 and a surficial grab) suggest exposure of early to mid Holocene deposits (Nahm et al., 2008). On the edges of the scoured zone, the gradation in backscatter is interpreted as a transition from erosion to accumulation of fine-grained sediment.

Throughout the estuary and lake, the loss of intertidal zones resulted in a substantial reduction of accommodation space. Apparent from geochronological and bathymetric change analyses, this resulted in the inner estuary accreting sediment at high rates since the construction of the dam (Figs. 4, 8). Previously dominated by tidal processes, the lake was excluded from macrotidal influence and estuarine mixing post dam. Contribution of sediment from the Sampo and Yeongam tributaries has resulted in relatively moderate accumulation rates (compared to inner estuary) in upper portions of the lake. Increased accumulation due to trapping of sediment upstream of dams has been widely documented (Kummu et al., 2010; Gupta et al., 2012; Ran et al., 2013; Vukovic et al., 2014), and it is emphasized that this phenomenon is occurring in the Yeongsan Lake. Holistically, due to anthropogenic activities, modern accumulation rates within the Yeongsan Estuary and Lake are considerably higher than rates reported in many natural estuarine systems (Santschi et al., 2001; Pekar et al., 2004; Lu and Matsumoto, 2005; Álvarez-Iglesias et al., 2007; Osterman and Smith, 2012).

Results from subsurface seismic analyses reveal an unconformity apparent throughout the inner estuary, which has been interpreted as the Holocene–Pleistocene unconformity surface (Fig. 13). The stratigraphic sequence above this surface is interpreted as Holocene estuarine fill (H.E.F.) (Fig. 13). The thickness and age of these strata correspond well to units identified as deposited during the Holocene marine transgression within the Yeongsan Estuary, which unconformably overly a paleosol determined to be exposed during the Last Glacial Maximum (Nahm et al., 2008). Additionally, the depth of the Holocene–late
Pleistocene boundary and the thickness of this stratigraphic sequence (<10 m) are consistent with other studies within the region (Park et al., 1991; Khim et al., 2000; Choi et al., 2002, 2012; Lim and Park, 2003; Lim et al., 2004; Kwon, 2012).

With rising sea levels, many of the world’s estuaries formed between 5 and 10 ka (Wolanski and Chappell, 1996; Long et al., 1998; Kench, 1999; Lario et al., 2002; Rodriguez et al., 2005). Relative sea level rise rates within the region have been estimated to be approximately 0.5–2 mm yr⁻¹ for at least the last millennia (Park, 1983; Bloom and Park, 1985; Park and Yi, 1995; Yoo and Park, 2000; Chang and Choi, 2001). Using these local sea level curves, the initiation of estuarine conditions to our study area can be conservatively estimated at 6 ka. While modern (post dam) sediment accumulation rates have been determined herein, it is clear that sediment deposited at these rates represents only a small fraction of the total estuarine fill throughout the Holocene (e.g. core penetration depths, Fig. 13). However, considering the variable thickness of the H.E.F., we can conclude the average Holocene sedimentation rates in the estuary to be approximately 0.5–1.5 mm yr⁻¹. These rates are consistent with an estuary in equilibrium with relative sea level rise, and are typical of reported values throughout the Holocene (Park et al., 1991, 1995; Lario et al., 2002; Klingbeil and Sommerfeld, 2005; Frouin et al., 2007; Schneider et al., 2010). Therefore, this indicates at least an order of magnitude increase from Holocene averages to modern accumulation rates, suggesting the rates reported in this study are not sustainable and are distinctively a recent phenomenon as a result of anthropogenic alteration.

5.3. Episodic sedimentation

Elevated ⁷Be activities in surface intervals and laminations in X-radiographs are indicative of event driven sedimentation (Figs. 11, 12) (Sommerfield et al., 1999; Mullenbach and Nittouer, 2000, 2006; Carlin and Delapenna, 2014). Combined with a lack of visible bioturbation (Fig. 12), this suggests that deviations in ²¹⁰Pbₑₑₑ profiles may represent temporal variability in sediment deposition (Fig. 5). The highly variable and non-rhythmic nature of the lamination thickness suggests tidal processes are not the primary deposition control; however, tidal advection likely plays a role in the distribution of sediment. Episodic sedimentation is not necessarily an impact of anthropogenic alteration; however, the timing and intensity of discharge are markedly different after emplacement of an estuarine dam. The typical hydrographic profile of a flooding event in a natural system displays a normal distribution curve, with the majority of sediment deposition occurring on the falling limb with decreasing flow velocity. A relatively short, high intensity discharge pulse from a dam differs in that the build up and falling stages have been eliminated, resulting in an extremely rapid introduction of sediment to a quiescent environment.

If a constant supply of sediment is deposited and undisturbed (i.e. limited or no physical or biological mixing), exponential decay of ⁷Be activity with depth is expected. However, our data display relatively constant activity throughout surface intervals suggesting sediment was deposited synchronously (Fig. 11). Comparing the thickness of this interval to decadally averaged annual accumulation rates (Table 1) reveals that a singular event may represent a significant fraction of the annual rate. Therefore, assuming a direct correlation to sediment accumulation in the estuary, the amount of sediment deposited annually should reflect discharge (Fig. 3). However, this assumption does not account for sediment supplied to the system from other sources, such as advection from offshore. Considering the high sediment accumulation rates in the central portion of the outer estuary, this process is likely a contributing factor. Additionally, this is supported by isotopic data with δ¹⁵N significantly lower in the outer estuary and core YE 11, with intermediate values of the inner estuary, suggesting a combination of sources.

Relative to average values, the low total discharge in the summer of 2013 seems insufficient to produce the deposition recorded by ⁷Be activities (Figs. 3, 11). This implies that the amount of sediment deposited is not strictly a function of total discharge. Although the vast majority of discharges release <30 x 10⁶ m³ per event, the event occurring on 7/6/13 of 167 x 10⁶ m³ accounts for nearly half of the total summer discharge and represents the second highest discharge event recorded from 1997 to 2013 (Fig. 3). Over this time period, there were 18 discharge events exceeding 100 x 10⁶ m³, with the largest event occurring in 2002 (288 x 10⁶ m³) (Fig. 3). This suggests that the magnitude of discharge events may be equally important as the total annual discharge when considering sediment deposition. Hence, the sediment observed with elevated ⁷Be activities is interpreted as primarily sourced from the 7/6/13 event.

Several other factors could also impact sediment deposition on an annual basis. The concentration of suspended sediment in the
water column prior to opening floodgates, and the erodibility of the bed adjacent to the dam would impact sediment availability. To summarize, the amount deposited in any given year is likely dependent on total amount of discharge, quantity and volume of individual events, and suspended sediment concentration prior to discharge.

6. Conclusions

Anthropogenic alteration to the Yeongsan Estuary has dramatically changed the shoreline geometry, accumulation rates, depositional environments, and distribution of organic matter. The primary modifications to the system that have resulted in these changes include
construction of an estuarine dam and massive land reclamation projects. Additionally, construction of seawalls has hardened shorelines and restricted overbank deposition. Due to the loss of intertidal zones, the accommodation space was significantly reduced resulting in rapid accumulation rates and an increase in sediment trapping efficiency. The average accumulation rates derived from this study indicate that rates have increased over average Holocene by at least an order of magnitude, with most areas displaying more than a 20× increase. Sediment delivery mechanisms, including the timing and intensity of discharge, have also been modified from a natural system. The high flow velocities associated with discharge have resulted in scouring adjacent to the dam, and episodic sedimentation associated with discharge is apparent. The distribution of organic matter throughout the system shifted in accordance with the construction of the estuarine dam. Organic matter source signature in pre and post-dam lakes and inner estuary sediments displays an increase in %TOM, reflecting the elimination of natural estuarine circulation and the influence of discharge, respectively.

Significant environmental changes have occurred throughout the Anthropocene, and many are represented within the Yeongsan Estuary. It is predicted that coastal engineering will continue to rapidly increase globally over the next century. Impacts on estuarine systems, such as those observed in this study, are likely to be magnified with increasing coastal population, industrialization, and rising eustatic sea level. Continued observation is necessary for increased understanding of how multiple feedback mechanisms drive natural responses to anthropogenic alterations. These results provide advancement in the knowledge of how estuarine sedimentation processes respond to severe coastal

Fig 12. Representative X-radiographs for cores shown in Fig. 11. Depth of 7Be penetration is indicated (also shown in Fig. 11). 7Be depths were allowed slight depth adjustment (<1 cm) to coincide with observed bedding features to compensate for sampling procedure error.

Fig 13. High resolution CHIRP seismic subsurface profiles from within the inner estuary. Profile locations are indicated in Fig. 1, and maintain consistent scales at a vertical exaggeration of approximately 10:1. A prominent reflector identified throughout the survey has been traced, and all sediment above this point has been interpreted as Holocene estuarine fill (H.E.F.). Cores YE 3, 6, 7, 8, 10, and 11 are indicated with appropriate penetration depths. All seismic profiles are displayed as viewing upstream.
construction within estuaries, and can be used to advise and develop future estuarine management strategies throughout the world.

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