TIME SERIES ANALYSES OF CHANGES IN SURFACE AREA OF SOUTH KOREAN ESTUARIES FROM 1985-2015: DEVELOPING NEW TOOLS AND PROTOCOLS USING GLOBAL SURFACE WATER DATASETS WITHIN GOOGLE EARTH ENGINE AND ARCGIS

A Thesis

by

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ABSTRACT

Estuaries play key roles in both marine and fluvial ecological health, as they house some of the largest biodiversity in the world, provide important marine habitat, including nursery grounds for both fin and shellfish, and act as filters and buffers between saltwater and freshwater. They are also important for geologic stability, as they stabilize shorelines and protect coastal areas from large tidal events, storm surge and coastal flooding. However, many estuaries as well as drainage basins, globally, have been heavily altered over time, due to the expansion of urban areas, flood water controls, freshwater retention, storm surge and tsunami mitigation and the implementation of intensified agricultural practices. Given the variety of estuarine types and settings as well as the high degree of coastal modification, it can be difficult to examine changes over time. One way many researchers study estuaries is through aerial images and datasets. This project will use a Global Surface Water Dataset (GSWD) and display it in both Google Earth Engine and ArcGIS in order to delineate estuaries and compare their changes in surface area across a time series of images (1985-2015) in South Korea. Within South Korea, there are 463 identified estuaries, 49% of these estuaries have been closed with estuarine dams. In addition, the vast majority all of the Korean estuaries (both with and without estuarine dams) have been modified by land reclamation and seawalls. Natural morphodynamic feedbacks to these alterations have led to further alteration of the systems. To quantify these changes across the time series, Geospatial Methodology will be developed and implemented, including clipping the GSW dataset to South Korea, buffering shoreline datasets, using stream datasets to intersect with the GSW dataset to locate major estuaries, and examining the change in size of individual estuaries. This project will

establish a set of tools that can be used for estuarine delineation and quantification of change detection within these estuaries.

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1. INTRODUCTION

1.1 Estuaries and Their Importance

Throughout recent history, human populations have migrated towards the coast, and in turn, estuaries. This is due to their access to the open sea, being cultural and economic hubs, high rates of biological productivity, and being the confluence point of rivers, which allow access to inland navigation (Sweet, 1971). An estuary is a partially enclosed coastal body of brackish water with one or more rivers or streams flowing into it, a free connection to the open sea and a tidal fluctuation (Perillo, 1995). Estuaries form a transition zone between river environments and marine environments (Perillo, 1995). They are subject both to marine influences—such as tides, waves, and the influx of saline water—and to fluvial influences—such as inflows of fresh water and sediment, which can be seen in Figure 1 (Perillo, 1995; Hume at al., 1988). The inflows of

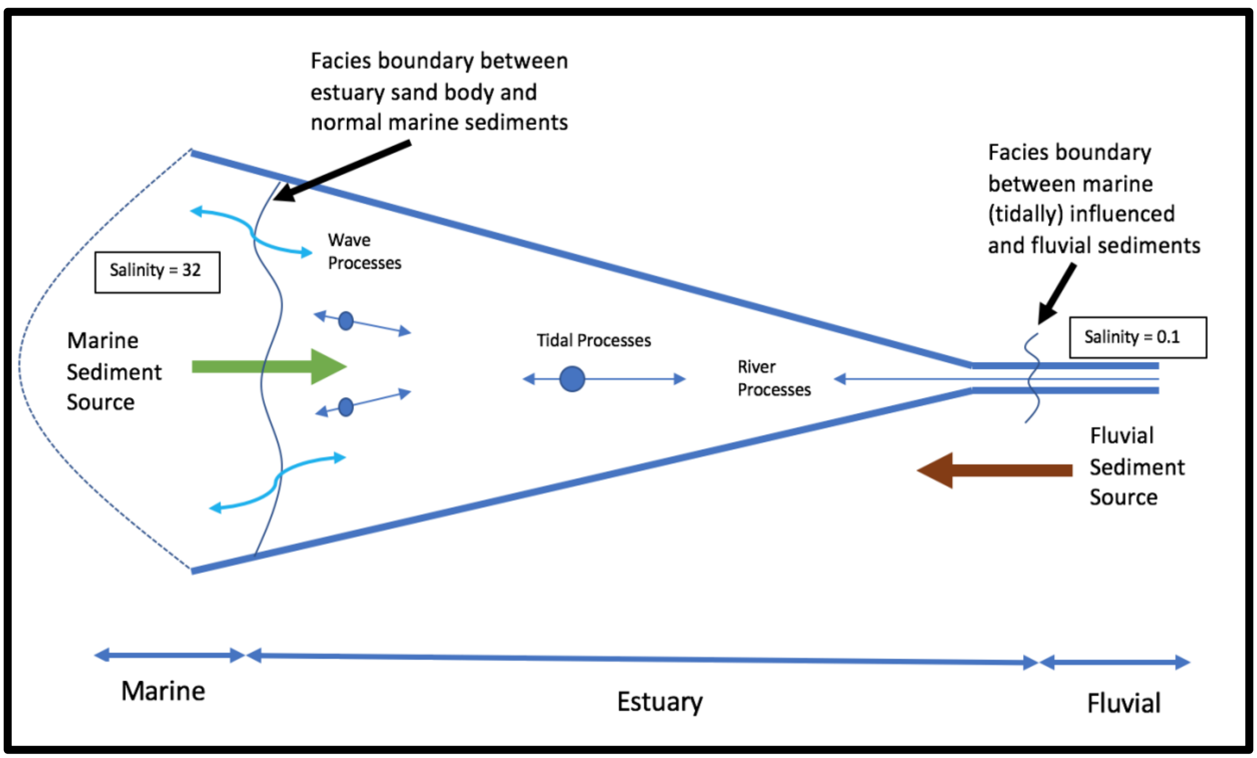


Figure 1: Basic diagram depicting estuary processes and dominating forces

both sea water and fresh water provide high levels of nutrients both in the water column and in sediment, making estuaries major filters for nutrients, as well as among the most productive natural habitats in the world (Kennedy, 2013; Sweet, 1971). Estuaries provide habitat for a wide variety of seabirds, fish, shellfish, and both marine and aquatic mammals (Ashe, 1982; Beck et al., 2001). The banks of many estuaries are amongst the most heavily populated areas of the world, with about 60% of the world's population living along estuaries and the coast (Hume et al., 1988). As a result, estuaries suffer degradation by many factors, including elevated sedimentation resulting from soil erosion and deforestation (Sherk et al., 1975), overgrazing, and other aggressive agricultural practices (Kirby-Smith et al., 1979); overfishing; drainage and filling of wetlands (Kennish, 2002); eutrophication due to excessive nutrients from sewage and animal wastes (Bricker et al., 1999); pollutants including heavy metals, polychlorinated biphenyls, radionuclides and hydrocarbons from sewage inputs (Savage et al., 2002); and volume loss and/or freshwater input loss due to diking or damming for flood control or water diversion (Kennish, 2002). This makes identifying changes and protecting estuaries a very important issue.

1.2 Project Purpose and Hypothesis

One way to differentiate and identify estuaries is to identify them through maps and areal images. Although identifying these estuaries may be easy, examining size and area changes over time with just aerial images can be quite difficult. The purpose of this project is to develop automated tools to delineate estuaries and quantify their change across a time series of imagery. Estuaries are in a state of constant flux (Lotze, 2006). The sizes of an individual estuary can change through feedback from a wide variety of processes and factors. To address this question, this study will test the hypothesis: Between 1985 and 2015, due to anthropogenic alterations, there has been a net decrease in the size of estuaries in South Korea. This hypothesis will be tested and validated by developing algorithms to be used in Google Earth Engine and ArcGIS to both delineate estuaries and quantify their surface areas. By applying these algorithms to the time series of data, this hypothesis will be quantitatively tested.

2. BACKGROUND AND REGIONAL SETTING

2.1 South Korea and the Korean Peninsula

Although this projects' methodology can be used to help determine area changes for global estuaries, this specific project will address the delineation and examination of change of South Korean estuaries. Also known as the Republic of Korea, South Korea is mostly surrounded by water and has 2,413 kilometers of coast line along three seas (Wells et al., 1990). To the west is the Yellow Sea, to the south is the East China Sea, and to the east is Ulleung-do and Liancourt Rocks in the East Sea, also known as the Sea of Japan (Wells et al., 1990). Geographically, South Korea's land mass is approximately 100,032 square kilometers, with an additional 290 square kilometers occupied by water and in turn, estuaries (Wells et al., 1990). Among the 463 estuaries identified in South Korea, Lee et al., (2011) determined that approximately half are classified as closed estuaries due to an estuarine dam or sluice gate built to address the threat of sea level rise or meet other anthropogenic needs (Figure 2).

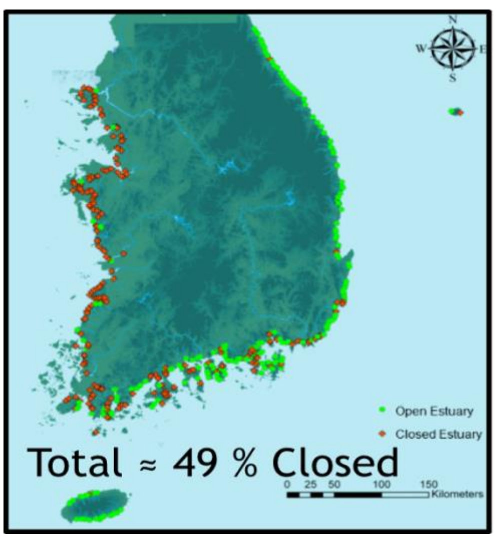
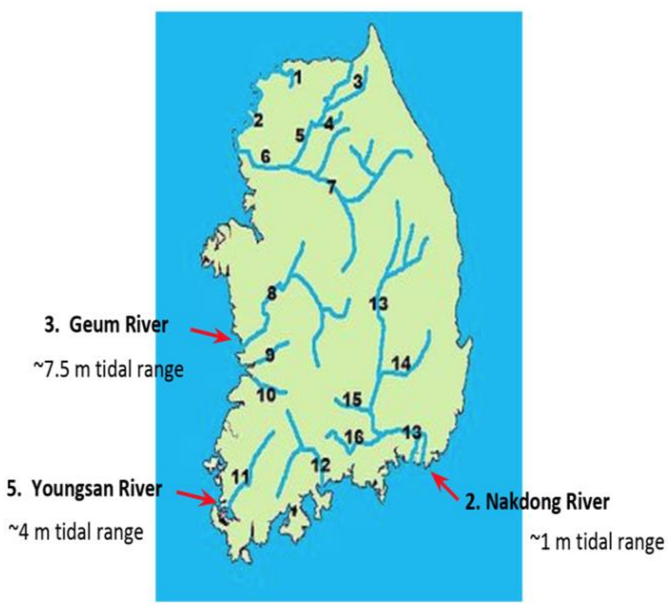


Figure 2: Locations of estuaries in South Korea
(Adapted from: "Estuary classification based on the characteristics of geomorphological features, natural habitat distributions and land uses" by: Lee K.-H., Rho, B.-H., Cho H.-J., Lee. C.-H., 2011. *Journal of the Korean Society for Oceanography*, 16, pp. 53-69.)

Unlike Japan or the northern provinces of China, the Korean Peninsula is tectonically stable (Chough, 2015). There are no active volcanoes (aside from Baekdu Mountain on the border between North Korea and China, most recently active in 1903), and there have been no strong earthquakes in recent history (Chough, 2015). The Korean peninsula also has many rivers and streams, as seen in Figure 3. The Nakdong River, South Korea's longest river, is 521 kilometers long (Park and Lee, 2002); the Han River, which flows through Seoul, is 514 kilometers long (Chang, 2008); and the Geum River is 401 kilometers long (Ryu et al,. 2011). Other major rivers systems include the Imjin, which flows through both North Korea and South Korea and forms an estuary with the Han River (Peng et al., 2014); the Bukhan, a tributary of the Han that also flows out of North Korea (Chang, 2008); and the Somjin. The major rivers flow South to North or East to West and empty into the Yellow Sea or the Korea Strait, respectively. They tend to be broad and shallow and to have wide seasonal variations in water flow (Wells et al., 1990).



River Name	Watershed Area (Km^2)	Length (Km)	Openness
Hangang	35770	494	Open estuary
Imjingang	8897	244	
Yeseonggang	3916	NA	
Sacheon(cheon)	351	30	
Gogneungcheon	261	46	
Nakdonggang	★ 23394	510	Closed estuary
Seonakdongang	285	26	
Geumgang	★ 9912	398	Closed estuary
Seomjingang	4960	224	Open estuary
Yeongsangang	★ 3468	137	Closed estuary
Anseongcheon	1656	60	Closed estuary
Sapgyocheon	1650	59	
Mangyeunggang	1504	81	Closed estuary
Dongjingang	1124	51	
Wangpicheon	514	61	Open estuary
Tamjingang	509	55	Open estuary
Yangyangnamdaecheon	474	55	Open estuary
Samcheogosipcheon	394	56	Open estuary
Yeongdeogosipcheon	375	55	Open estuary
Suncheondongcheon	367	36	Open estuary
Gagogcheon	265	42	Open estuary
Gangneungnamdaecheon	259	33	Open estuary
Watancheon	245	25	Closed estuary
Ungcheoncheon	235	39	Closed estuary
Jujincheon	229	29	Open estuary
Hoeyagang	218	42	Open estuary

'GANG' in English means "river". "CHEON" in English means "small river".

Figure 3: Major rivers of the Korean Peninsula. Left shows spatial locations. Right shows major river names and characteristics (Adapted from: "Shifts in depositional environments as a natural response to anthropogenic alterations: Nakdong Estuary, South Korea" by Williams, J. R., Dellapenna, T. M., & Lee, G., 2013. *Marine Geology*, 343, pp. 47-61.)

2.2 Types of Estuaries

Estuaries can be classified in a variety of ways, including: 1) by their geological/geomorphological characteristics (Perillo, 1995), 2) by degree of water column stratification (Hall and Kenny, 2007), and 3) by tidal range (Uncles et al., 2002). In this project, we will focus primarily on the geological/geomorphic classification, which includes five major types of estuaries, which are: 1) coastal plain/flooded incised valley, 2) bar-built, 3) tectonic, 4) rias and 5) fjords.

Coastal plain estuaries form generally during transgressions, within drowned incised river valleys and fluvial channels (Perillo, 1995). The width-to-depth ratio of these estuaries is typically large, appearing wedge-shaped (in cross-section) in the inner part and broadening and deepening seaward. Water depths rarely exceed 30 meters (Hume et al., 2007). Coastal Plain estuaries are the most common type of estuary in temperate climates. Bar-built estuaries are characterized by barrier spits or islands that form parallel to the coastline and separate the estuary from the ocean (Perillo, 1995). Barrier islands are formed by the accumulation of sand delivered by longshore drift (Perillo, 1995). Bar built estuaries are found along micro to meso-tidal, wave dominated coastalines, mainly found along passive continental margins (Perillo, 1995). Tectonic estuaries are found along tectonically active continental margins and are associated with tectonic features (Perillo, 1995). An example is San Francisco Bay, which resides within a fault-formed basin along the San Andres Fault. Rias are typically defined as a rocky coastline where an estuary has formed by the partial submergence of an unglaciated river valley (Evans and Prego, 2003; Richthofen, 1886). Typically, rias have a dendritic, treelike outline inherited from the dendritic drainage pattern of the flooded river valley (Evans and Prego, 2003). Fjords are estuaries that form within steep walled, U-shaped, glacially carved valleys, which have been flooded with seawater (Perillo, 1995). These estuaries typically have steep, bedrock sides, bedrock outcrops from within, and submarine sills created by recessional moraines (Perillo, 1995). Fjords are shallowest at the mouth, where terminal glacial moraines or rock bars form sills that restrict water flow, and in the upper reaches of the estuary, where depths can exceed 300 meters (Hume et al., 2007). The most common estuary type in South Korea are rias, found primarily along the western and southern coastlines of the country and include the Nakdong, Yeongsan, Saemangeum and the Han River Estuaries.

2.3 Major Anthropogenic Effects on Estuaries

On the Korean Peninsula and throughout much of East Asia, traditional agricultural practices include upland agricultural fields and terraced rice farming, which utilize local water resources through irrigation and drainage canals (Crawford and Lee, 2003). These are forms of elevated agricultural practices, which can help fields from being flooded and help organize fields into sectors based on production (Crawford and Lee, 2003). Additionally, coastal construction of estuarine dams to impede saltwater intrusion, and extensive seawalls in land reclamation and river divergence projects have considerably modified the shoreline within the last century (Yoon et al., 2007). Together, this has resulted in significant engineering of the drainage system in most watersheds, altering both net transport of sediment and freshwater from these systems and modulating the timing of the discharge (Yoon et al., 2007; Choi et al., 2005). As a result, the sediment dynamics and ecosystems within the estuaries into which these rivers flow have been significantly altered.

Several studies have shown the impacts on estuarine sedimentation after the emplacement of dams and/or reservoirs near the coast (Williams et al., 2013 Williams et al., 2014). After the construction of a dams in the Nakdong Estuary on the southern coast of South Korea, the sedimentation rate in the estuary, below the dam, increased by a factor of 10, new barrier islands formed across the mouths of the estuarine tributaries (Williams et al., 2013), and this increased accumulation of fine-grained sediments occurred due to a stronger flood dominated tide and a decrease in overall current velocity (Lee et al., 2006). After the construction of the Yeongsan estuarine dam, Williams et al., (2014) found that sedimentation rates below the dam, within the estuary also increased by up to a factor of 10, resulting from the reduction in the tidal prism after the installation of the dam.

2.4 Estuarine Dams used in this Study

Within this project, many major dams were explored and found to have a significant effect on the surrounding ecosystem. The spatial locations of these dams are found in Figure 4. These major dams are as follows:

- **Saemangeum Dam:** The Saemangeum Seawall, located on the southwest coast of the Korean peninsula, is the world's longest man-made dyke, measuring 33 kilometers (Min et al., 2012). It extends between two headlands and separates the Yellow Sea and the former Saemangeum estuary (Min et al., 2012). Major construction was completed in April 2006, with the seawall 500 meters (1,600 ft) longer than the Afsluitdijk in the IJsselmeer, the Netherlands, previously the longest seawall-dyke in the world (Min et al., 2012).
- **Yeongsan Dams:** Built to divert and impound fresh water for agricultural practices, impede the intrusion of saltwater and provide flood prevention, the Yeongsan Estuarine Dams were constructed in 1981. As a result, approximately 98 km^2 of total estuarine area was eliminated above the dam with the cessation of tidal exchange, creating the freshwater Yeongsan Lake (Williams et al., 2014). Prior to occlusion, tidally influenced environments spanned

approximately 63 km upstream from the dam (Lee et al., 2009). The dam is 19.5 m high and spans a distance of over 2.5 km between the Mokpo peninsula and the Yeongam peninsula.

- **Geum River Dam:** Water quality conditions for nutrients have deteriorated considerably since the dam construction in 1994, with the reservoir water degraded more severely than the estuarine water (Jeong et al., 2014). Many other major dams on the Geum River are far upstream, out of the study area.
- **Noksan Dam and Nakdong Dam:** The construction of two estuarine dams, Noksan Dam and Nakdong Dam (1934 and 1983) as well as numerous others have taken place on the Nakdong River (Willaims et al., 2013).
- **Ungcheoncheon Dam:** Built in 1998 (found on Google Earth). No other information could be found.
- **Anseongcheon Dam:** Built before 1985 (found on Google Earth). No other information could be found.
- **Sapgyocheon Dam:** Built before 1985 (found on Google Earth). No other information could be found.

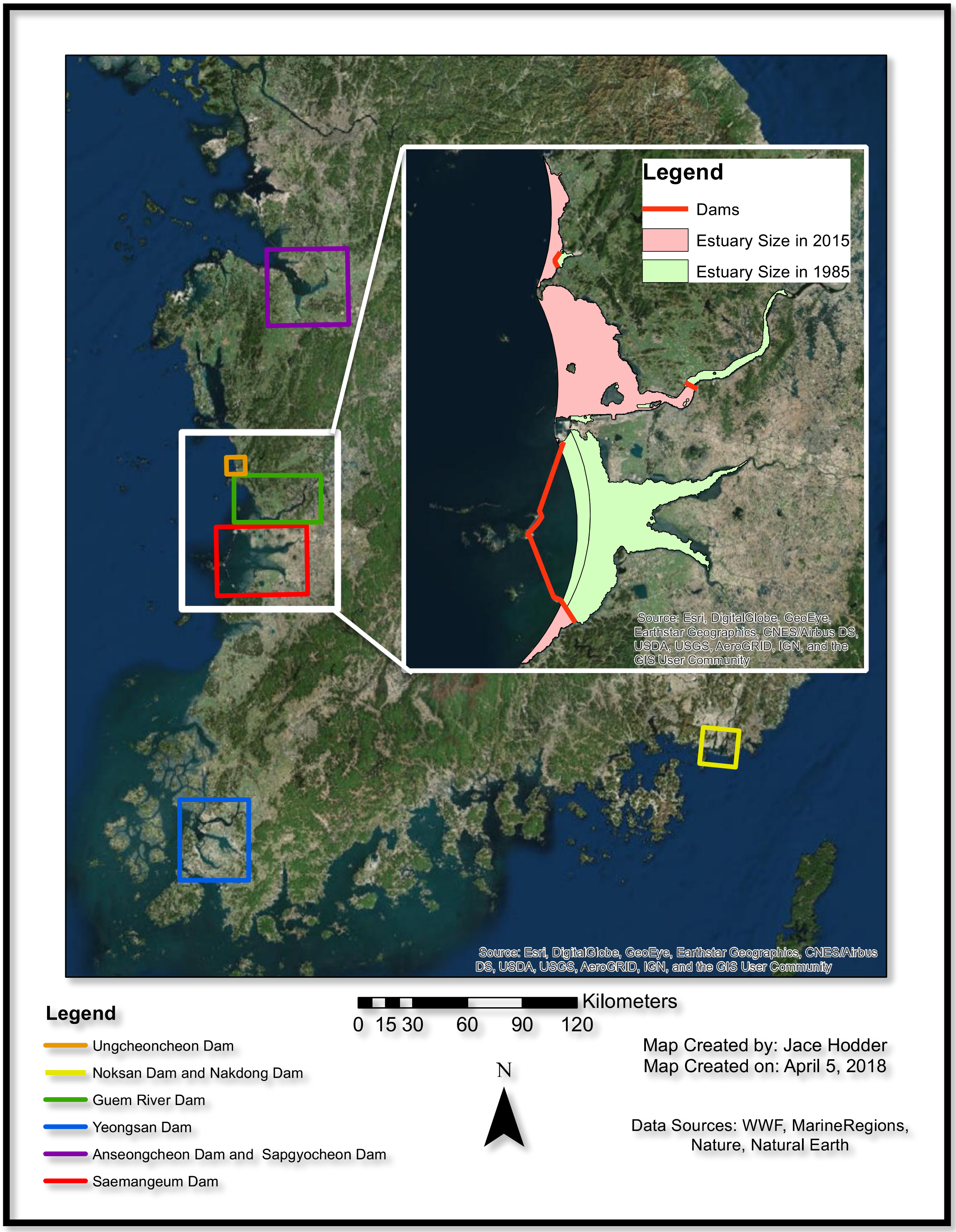


Figure 4: Locations of all Selected Dams and Changes in Surface Area in the Saemangeum Dam (Bottom), Geum River Dam (Middle) and Ungcheoncheon Dam (Top)

2.5 Tools and Datasets

This project will utilize Google Earth Engine (GEE) and ArcGIS to analyze the Global Surface Water Dataset (GSWD), provided by Pekel et al. (2016). Additional datasets used to facilitate this analysis include an Economic Exclusion Zone Dataset (EEZ), the Natural Earth Global Coastline dataset, and hydrological data and maps based on SHuttle Elevation Derivatives Dataset (HydroSHEDS).

As stated by Gorelick et al., (2017), Google Earth Engine (GEE) combines a multi-petabyte catalog of satellite imagery and geospatial datasets with planetary-scale analysis capabilities and makes it available for scientists, researchers, and developers to detect changes, map trends, and quantify differences on the Earth's surface. The user-friendly front-end provides a workbench environment which allows interactive data and algorithm development and exploration as well as provides a convenient mechanism for scientists to share data, visualizations and analytic algorithms via URLs (Gorelick et al., 2017). The software uses Javascript to create variables, run functions, and display images; because everything is run on Google servers, any computer with an Internet connection has the capacity to use this tool. This free-to-use software is the foundation of this project, as it is very powerful in creating and running algorithms in real time on large raster datasets. The other tool used for this study is ArcGIS, which is a geographic information system for working with maps and geographic information (Longley et al., 2005). ArcGIS will be mainly used for vector-based tools and functions not yet available in Google Earth Engine, and to create maps and figures for later sections.

The GSWD will be the primary data set used in this project. This raster dataset gives global surface water for the years from 1984-2015, with a very high resolution of 30 meters. This data was created by combining millions of Landsat images and classifying them as water or land using an “expert system” elaborated on in Pekel et al., (2016). The final dataset has over 40,00 reference points, with a 1% false water detection (Pekel et al., 2016). It will also indicate if waters are seasonal, permanent, or nonexistent for any of those given years. Because of the intricacy and extremely large size of this dataset, Pekel et al., (2016) decided to share it via GEE, as it allowed the datasets to be broken up by years as well as water type. The methodology in Pekel et al., (2016) will provide the foundation for displaying data and navigation through the GSWD in GEE. Other datasets that will be used are a Global Coastline dataset, a South Korean Economic Exclusion Zone (EEZ) dataset, as well as the newly created HydroSHEDS. The HydroSHEDS is a dataset created by the World Wildlife Federation, among many other stakeholders. The HydroSHEDS dataset provides hydrographic information in a consistent and comprehensive format for regional and global-scale applications (WWF, 2017). The goal of developing the dataset was to generate key data layers to support regional and global watershed analyses, hydrological modeling, and freshwater conservation planning at a quality, resolution and extent that has previously been unachievable (WWF, 2017). The EEZ dataset is provided by the Marine Regions project and is used to clip out only areas within the EEZ zone of South Korea (Hoel, 2009; VLIZ, 2014). The Global Coastline was downloaded from Natural Earth and is found in the Physical Vector Data Themes section (Natural Earth, 2018). This project uses the 1:10,000,000 scale dataset, as it is the most refined (Patterson, 2012). A buffered version of this dataset was used to capture only those portions of the GSWD that are near the coast.

3. METHODOLOGY

Figure 4 shows a basic flow chart for each of the steps described below, with the code used found in Appendix A:

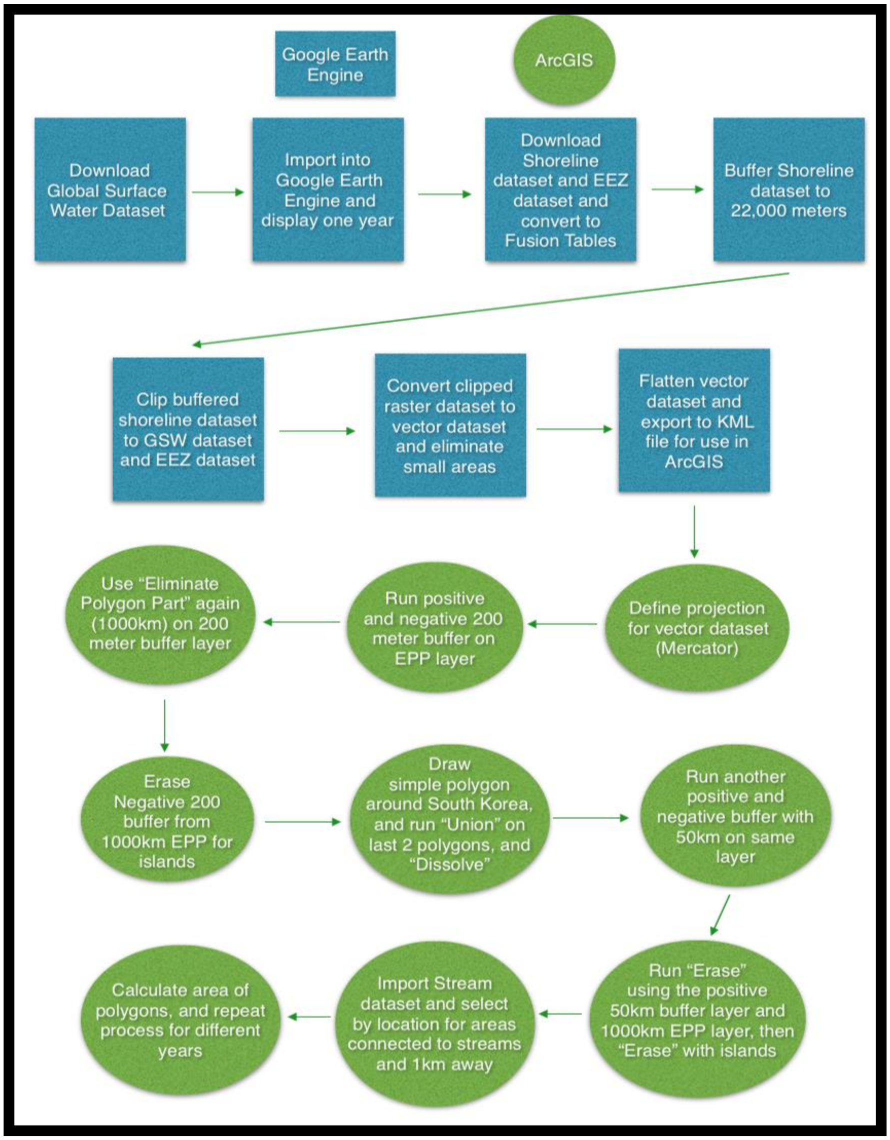


Figure 5: Flow chart of major steps in project methodology

3.1 Google Earth Engine

1. Data Access: The GSWD (1984-2015) developers (Pekel et al., 2016) have loaded this dataset into GEE and made it freely available to other researchers on the GEE platform. It can also be downloaded from (https://global-surface-water.appspot.com/download).

2. Data Organization: One year (2010) of the GSWD was chosen to test the workflow. This involved creating a new variable that displayed only one year, instead of the entire dataset.

3. Downloading Shoreline Dataset and EEZ Dataset: The Global Shoreline dataset was downloaded and converted to Fusion Table for GEE compatibility. These fusion tables are one of the preferred formats for storing vector data in GEE. Shape Escape is used for this conversion process. Similar to the previous step, a Global EEZ Dataset is downloaded to provide administrative boundaries for South Korea and its EEZ in 2014. This dataset will be used to restrict analysis to South Korea and its EEZ. This is also converted to a Fusion Table in Shape Escape, and the link generated is used in the code.

4. Buffer Shoreline Dataset: First, the removal of areas far from the coast helped narrow the study area. As only the proximal coastline will be important for the estuary studies, inland areas were eliminated. This step used buffer and clip commands to keep only areas within 22,000 meters of the coastline. The shoreline dataset that was downloaded in Step 3 was buffered with the 22,000 meters' value and this dataset will serve as the extent for the portion of the GSWD used for analysis. The value of 22,000 meters was chosen as some of the largest estuaries are considered to extend about this far inland, so this average will be used to help quantify the edges of the estuaries.

5. Clip Shoreline Dataset to EEZ and GSWD: The Shoreline dataset was clipped to the EEZ dataset to restrict its extent to South Korean waters. Finally, the geometry of this dataset for nearshore South Korean waters was used to clip the Global Surface Water dataset. This new dataset, “clippedImage”, gave surface waters that are in the proximal vicinity of the coastline in South Korea, limiting the scope of estuarine size change analyses to the area of interest to test the hypothesis. After this step, the “clippedImage” output was edited to limit it to only permanent waters.

6. Convert Raster to Vector and Eliminate Small Areas: In order for the generated datasets to be usable in ArcGIS for delineating estuarine areas, the raster dataset for our “clippedImage” (Step 5) was converted to a vector dataset, with a “scale” (horizontal resolution) of 100 meters. During this step, smaller areas were deleted so that only larger areas will be visible for estuary identification. This was done with a threshold of pixels, and any areas smaller than this threshold was deleted from the newly created datasets, “gswVectors”. This variable will give a vector dataset for boundaries of the surface waters in South Korea.

7. Flatten and Export Vector Dataset: After all of the datasets have been created, the final step within GEE was to export the “gswVectors” dataset so that it can be used in ArcGIS, where more numerically based models and methods will be run to delineate estuarine zones and calculate their areas. Before the “gswVectors” dataset can be exported, it must be “flattened”. This was done with a new variable “gswVectorsFlat,” The “gswVectorsFlat” was exported to the designated GoogleDrive as a “kml" file.

3.2 ArcGIS

8. Convert to KML and Project: Within ArcMaps, the “Kml to Layer” tool used to convert the exported dataset to a layer that can be displayed in ArcGIS. Before any analysis can be done, a projection was made, as the “gswVectors” shapefile did not have a projection. This was accomplished using the “Define Projection” tool and used the Mercator 1984 (World) projection system. After the layer has been projected, analysis began.

9. Buffer Positive and Negative 200m on Vector: A buffer was run with a 200 meter distance. Then, another buffer was run, with a distance of negative 200 meters, in order to go back to the original size, and delete small inclusions at polygon margins.

10. Eliminate Polygon Part with 1000km Threshold: The next tool that was used was the “Eliminate Polygon Part” tool that is located in the “Generalization” folder in the toolbox. This tool aided in filling potential “holes” in the permanent water dataset created by small areas of land (islands) or temporary water. Using the “Eliminate Polygon Part” tool with a tolerance of 1000 km, it deleted all but the largest island areas (areas with no connection to the mainland). Islands are eliminated because they interfere with the large buffers used to identify coastal bends (Step 14).

11. Erase to Find Islands: An erase function was run with the 1000 EPP layer (Step 10) and the negative 200 meter buffer layer (Step 9), in order to locate islands, which were then erased from the final layer.

12. Draw Large Polygon to Extend Vector: In order for later buffer process to function properly, a very large polygon was drawn around the coast of South Korea, extending a few thousand kilometers out.

13. Union and Dissolve Large Polygon: A “union” was run with the newly created large polygon (Step 12) and the previously created layer (Step 10). After this union, the attribute table of the newly created output was edited to add a new field with value of “1” for every record. Next, a “Dissolve” was run on the union output using the newly added field.

14. Buffer Positive and Negative 50 km: Two more buffers were run on the layer created in Step 13. The first will be a negative 50 km, and the other will be a positive 50 km buffer, a very similar process done in Mitropoulos et al., (2005). Within the project by Mitropoulos et al., (2005), the concept of epsilon-convexity is discussed in terms of detecting bends along cartographic lines. Here, the sequence of positive and negative buffers reproduces the effect of rolling a circle of diameter epsilon along the coastline; coastal bends with widths smaller than the epsilon are cut off (Mitropoulos' et al., 2005). Therefore, by using an epsilon value (here, buffer distance) equal or greater twice the width of the widest estuary it is possible to create a layer that removes all coastal bends of that size or smaller. Mitropoulos' et al., (2005) compared a coastline from which bends had been removed using this epsilon convex area approach to a manually generalized coastline and found methodology very promising for generalizing coastlines.

15. Erase to find Major Inlets: Once appropriate simplified coastlines were created, the "Erase" tool was used again. This tool erased the simplified version (Step 14) of the vector dataset from the original 1000 km EPP vector dataset (Step 10), leaving only the deeper bends, or the major estuaries.

16. Erase Islands and Divide up Polygons: Another erase was also run, with the newly created layer in Step 15 and the located islands layer created in Step 11. Also, the "Multipart to Singlepart" tool was used to subdivide the coastal bend polygons (potential estuaries).

17. Import HydroSHEDS: To make sure the polygons created are estuaries, a global stream dataset was downloaded from the World Wildlife Federation's HydroSHEDS database to find only those coastal inlets that intersect (with a tolerance of 1 km) with the global stream and river dataset (WWF, 2017).

18. Select Major Streams: The "Select by Attribute" tool was used and select streams with an "UPCELL" count of 1000. UPCELL's are the number of cells upstream and are used to quantify size in this dataset. In the HYDROSheds technical document, is was stated that a network of main rivers was calculated at 3 arc-second resolution and that main rivers were defined as those having an upstream catchment area of more than 1000 cells (approximately 8 km^2 at the equator). This means each UPCELL is approximately 8 m^2 (WWF, 2017).

19. Select Major Polygons that Intersect: This was done by using the "Select by Location" tool and selecting the polygons that intersected with the streams, and also used a distance of 1 km. This found which potential estuaries actually serve as the outlet of a river or stream.

20. Fix Problem Areas: As some of the individual water polygons may change over time, some which were connected may become disconnected or vice versa. These are areas where narrow straights or channels separate the mainland from islands. Due to the spatial resolution of the methods, these islands may, in some instances, appear to become connected with the mainland. In areas where there is a high level of confidence that the islands did not in fact become so connected, the data was corrected to make clear that they remained as islands. Based on the geographic location, polygons which may have been missed in some years were manually selected and re-exported.

21. Trace Dams and Delete Areas Landward: In order to truly see the effects of dams on estuaries, the dams were traced and any areas that were on the landward side of the dams were deleted which was accomplished with the "Erase" tool. As these areas no longer have a connection to the sea, they became "lakes", not "estuaries". This process demonstrated how the estuaries were eliminated upon installation of the dam.

22. Repeat: The process was repeated using different years in the GSWD. With future implementation usable for world estuary identification and area comparison, this methodology is an extremely important part of this study.

4. RESULTS

The GSWD was analyzed to identify potential estuaries along the South Korean coast using the methodology described above. Areas are reported in square km with precision to the hundredths decimal place, which is reflective of the 100-meter resolution of the vectorized GSWD (minimized vectorized area of 0.01 km^2). This study is primarily to establish and test methods, consequently, where estuarine dams are discussed, rather than using all ~225 estuaries with dams in Korea, only the seven largest estuarine systems are considered.

4.1 Results for Major Estuaries Changes due to Land Reclamation

The nation-wide surface area changes in coastal waters and estuaries, with various corrections, are shown in Table 1. Column 1 contains Coastal Waters and Embayments and includes all coastal waters, including both coastal embayments as well as estuaries. Overall, the trend shows that, after 1990, that there has been a steady decrease in overall coastal water area, with a notable decline after 2005 (Table 1; Fig. 6). To detect and sub-divide estuaries, i.e. those coastal embayments associated with river mouths or fluvial inputs, the coastal embayments that intersect of rivers were identified and the total area identified as estuaries was subtracted from Column 1, producing Table 1, Column 2. Upon inspection, it was revealed that the automated Rivers insect tool missed a number of rivers, requiring a manual identification and selection process. Column 3 shows the results of both the automated as well as manual selection of estuaries. The GSWD does not differentiate between saltwater and freshwater, consequently, it does not differentiate between water above and below estuarine dams. Consequently, estuarine dams were manually delineated and all waters above the dams that were formerly estuarine were manually removed. Column 3 shows the total area of estuaries, not considering estuarine dams. The 1985 area, of 5342.59 km^2 is our best estimation of the total estuary area prior to the installation of estuarine dams, using the available data sets, and will be referred to as 1985 Total Estuarine Area (1985-TEA). It should be noted, the 1985-TEA does not account for areas lost to land reclamation prior to 1985 but provides a reasonable estimate of changes due to installations of estuarine dams. Column 5 shows the area of estuarine loss, was calculated by subtracting the total area of estuary for each year from the 1985-TEA with the areas above the estuarine dams included. Column 6 shows the percent change between the 1985, including the areas above the estuarine dam from Column 5. Note, using this technique, by 1985, there was already a loss of 4.42% of the area of estuary due to estuarine dam construction. This also shows that by 2015, construction of estuarine dams and land reclamation resulted in the loss of 15.14% of Korea's estuaries, with 10.72% loss since 1985. Graphical comparisons can also be seen in Figure 6.

Table 1: Changes in Estuary Area Since 1985 Using Various Corrections

Column Number	**1**	**2**	**3**	**4**	**5**	**6**
Area (km^2)	**All coastal waters and coastal embayments (n=258)**	**Total area of estuaries with river intersect and search distance of 1 km (automated selection only) (n=30)**	**Total area of estuaries with river intersect and search distance of 1km (automated plus manual selection) (n=29)**	**Total area of estuaries with areas above dam removed (km^2) (n=29 with emphasis on 7 selected sites)**	**Estuarine Area Change**	**Percent Change**
2015	9214.52	4934.79	5012.90	4533.97	-808.62	-15.14%
2010	9403.92	5168.99	5168.99	463.68	-738.91	-13.83%
2005	9590.00	5207.00	5270.00	5033.99	-308.6	-5.78%
2000	9662.90	5204.59	5247.78	5018.40	-324.19	-6.07%
1995	9617.61	5097.53	5312.53	5079.89	-262.7	-4.92%
1990	9685.99	5012.09	5298.29	5085.00	-257.59	-4.82%
1985	9547.41	4974.72	5342.59	5106.64	-235.95	-4.42%

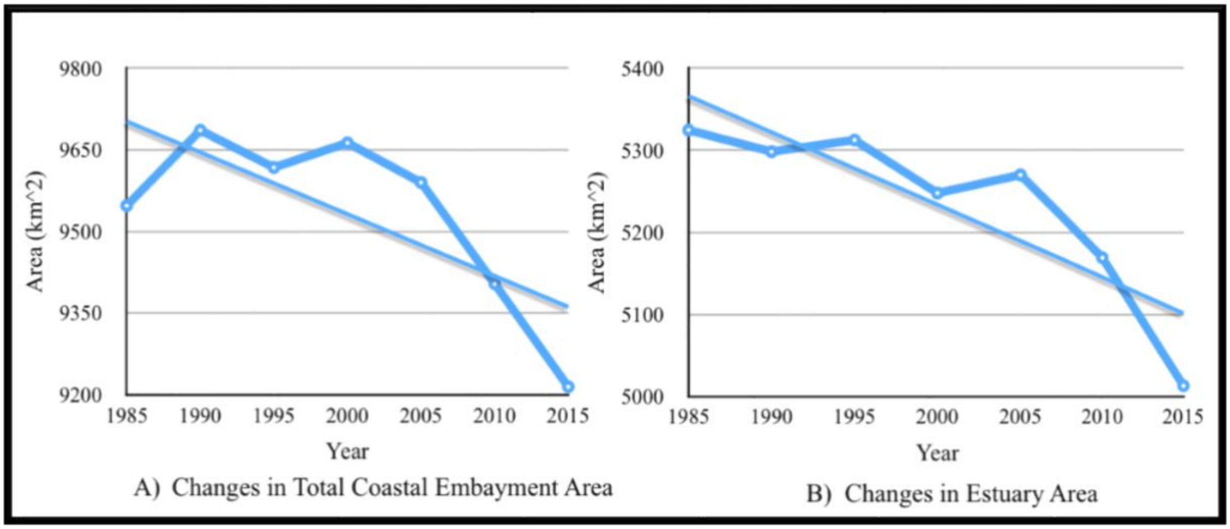


Figure 6: A) Changes in Total Coastal Embayment Area since 1985, shows all estuaries and coastal inlets since 1985 and B) Changes Estuary Area since 1985, shows total change in estuarine areas, including the removal of all areas below estuarine dams for the seven largest

4.2 Results for Major Estuaries Changes Due to Dams

When the dams were installed in these estuaries the portion above the dam became a freshwater lake. Consequently, the final results of this section show the changes in estuary surface area for the seven estuaries considered, with all water landward of the dams deleted, as they are no longer a part of the estuary. The total area of estuaries with areas above the dams removed for the seven largest estuaries is shown in Column 4 of Table 1. The comparisons of the results of removing the portions of the former estuaries that are now converted to lakes to the overall nation-wide coastal embayments and estuarine areas are shown in Column 5 of Table 1. Although not every dam is included in this analysis, many major dams were chosen based on a study conducted by Williams et al., (2013). These dams were chosen based on their size and spatial locations, which can be found in Figure 4.

Table 2 summarizes the changes in surface area of selected estuaries and well as percent change in surface area. Saemangeum Dam extends across the mouth of Saemangeum Bay, which was the estuary for the Mangyeong River and Dongjin River. The Saemangeum Dam is the largest sea dike in the world, making it also the largest estuarine dam in South Korea, and attributed to the 68.7% of the total loss of estuary surface area for the estuaries examined (Table 2; Fig. 4). The second largest area of impact is from the Anseongcheon and Sapgyocheon Dams, found on a tributary of the Han River. Although these dams were constructed prior to 1985, there was an 11.95% change in estuarine surface area, representing a 13.01% change for all estuaries considered in the study (Table 2; Fig. 7). The Yeongsan Dam is 9.7 river km upstream from the mouth of Yeongsan River and was installed in 1981, four years prior to the time series used in this study. Consequently, there was only a 3.65% change in estuarine area between 1985 and 2015, representing a 2.18% of the total change (Table 2; Fig. 7). The Geum River Dam, which sits 22.5 km up the Geum estuary, was installed in 1994, and resulted in a loss of 9.27% of its estuary and represents 4.82% of all of the change observed in this study (Table 2; Fig. 4). The Noksan Dam was installed in 1930 and Nakdong Dam was installed in 1990, both of which both sit on the Nakdong River. Since 1985, this system has seen a total of 4.92% change in area and represents 8.01% of the total change in this study (Table 2; Fig. 7). The Ungcheoncheon Dam extends across the mouth of what had been Ungcheoncheon Bay. Although the estuary is relatively small, the entire bay was closed. Although the dam was installed prior to 1985, land reclamation resulted in 8.01% of within the estuary, however, this change represents less than 1% overall change in all systems investigated in this study (Table 2, Fig. 4). Figure 8 shows the visual representations of trends of area change of each estuary to help demonstrate the effects of the dams.

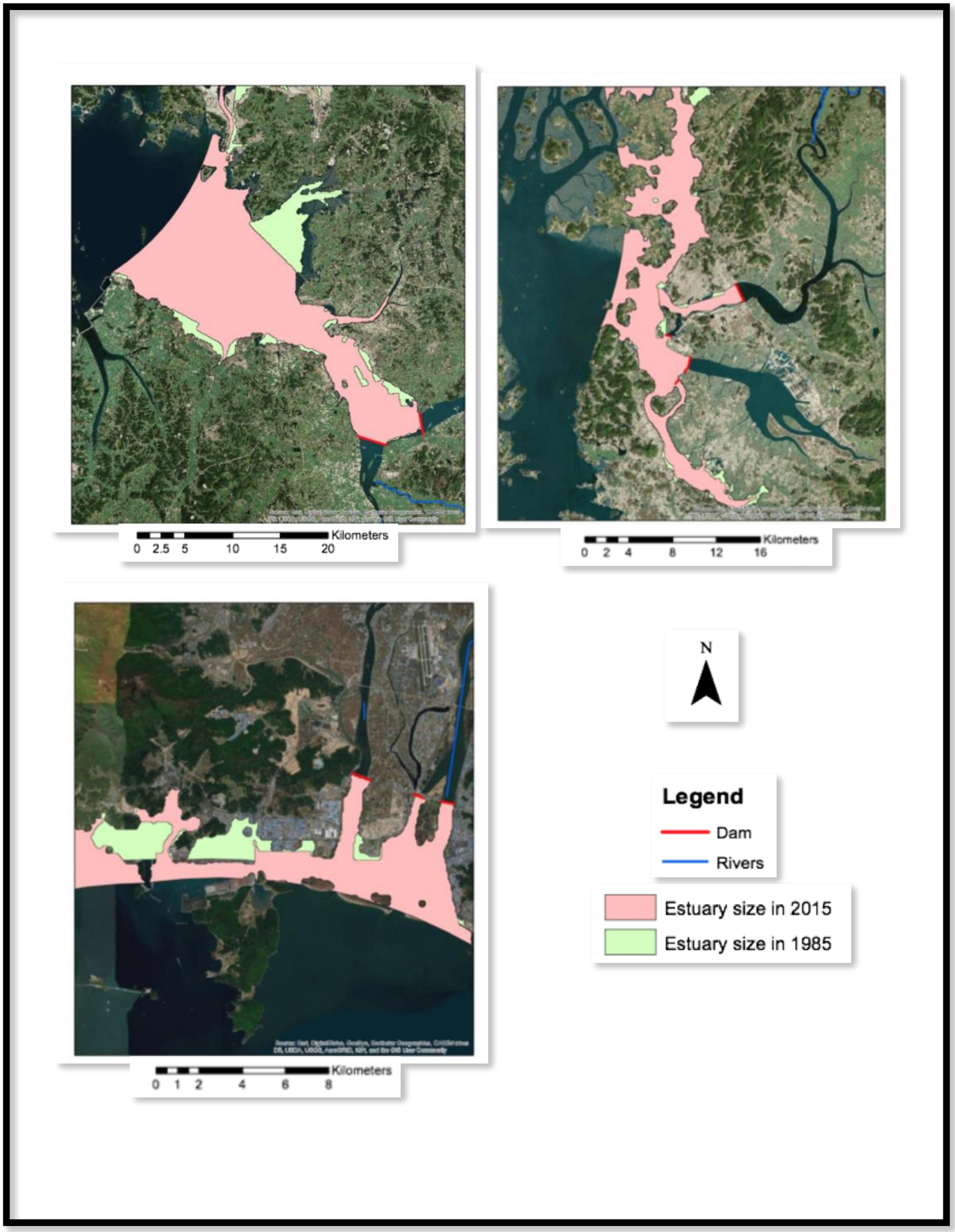


Figure 7: Shows changes in Surface Area in the Anseongcheon Dam and the Sapgyocheon Dam (Top Left), Yeongsan River Dam (Top Right), Noksan Dam and the Nakdong Dam (Bottom Left)

Table 2: Shows changes in surface area of selected estuaries and well as percent change in surface area

Area in Square Kilometers (km^2)	Saemangeum Dam	Anseongcheon Dam and Sapgyocheon Dam	Yeongsan Dam	Geum River Dam	Noksan Dam and Nakdong Dam	Ungcheon cheon Dam
2015	25.14	548.99	329.57	269.86	46.89	45.21
2010	25.19	551.41	375.21	268.33	45.22	44.80
2005	424.90	605.31	353.57	267.63	49.29	45.99
2000	410.58	610.63	332.15	269.27	47.26	45.69
1995	413.18	655.96	321.26	270.79	47.16	49.21
1990	421.02	631.95	349.45	310.59	50.24	47.23
1985	418.60	623.53	342.09	297.51	49.32	49.15
Area Below Dams	25.14	548.99	329.57	298.86	46.89	45.21
Total Loss (km^2)	393.46	74.54	12.52	27.62	2.43	3.94
Percent Loss	93.99%	11.95%	3.65%	9.27%	4.92%	8.01%
Percentage of Total Loss Nationwide	68.70%	13.01%	2.18%	4.82%	< 1%	< 1%

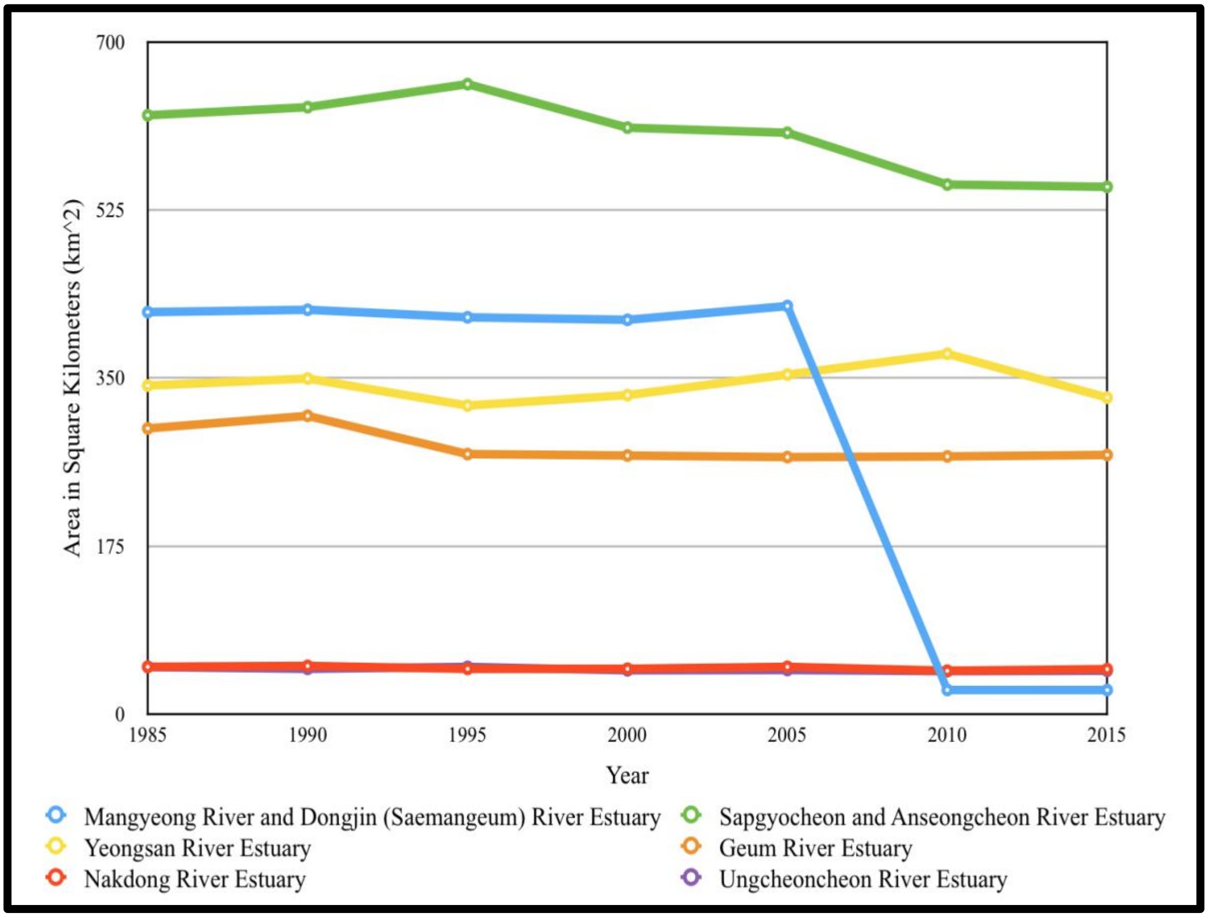


Figure 8: Trends of area change in selected individual South Korean Estuaries

5. DISCUSSION

Analyses of the changes in the estuary surface area for the estuaries studied in South Korea between 1985 to 2015 reveals that, overall, a total loss of 808.62 km^2 of South Korea's estuaries in seen, which attributes to a loss of 15.14%, with 10.72% loss since 1985 (Table 1). This study further reveals that within the selected dammed estuaries, there have been significant decreases in surface area, as shown in Table 2. This table also takes into account land reclamation, which converted estuarine and tidal flat areas into land for urban development (high rise districts), industrial complexes, or agriculture. Within Table 2, approximately 60 km^2 (11.36%) of estuary loss was attributed not to dam construction but to other changes (likely anthropogenic) that occurred in remaining estuary areas after damming. This shows that these selected dams contribute to 88.63% of the change in surface area of these selected estuaries. Notably, where the dam was installed in the estuary had a significant control on the impact of the estuary. For example, the Saemangeum Dam was constructed as an arc extending offshore of the mouth of the former estuary. Because of its sheer size, it contributes 68.7% of the total loss in surface area of the selected study areas. Other major changes to large estuaries in South Korea can be found in Figure 9, which shows changes in surface area in bar graphs for 1985 and 2015.

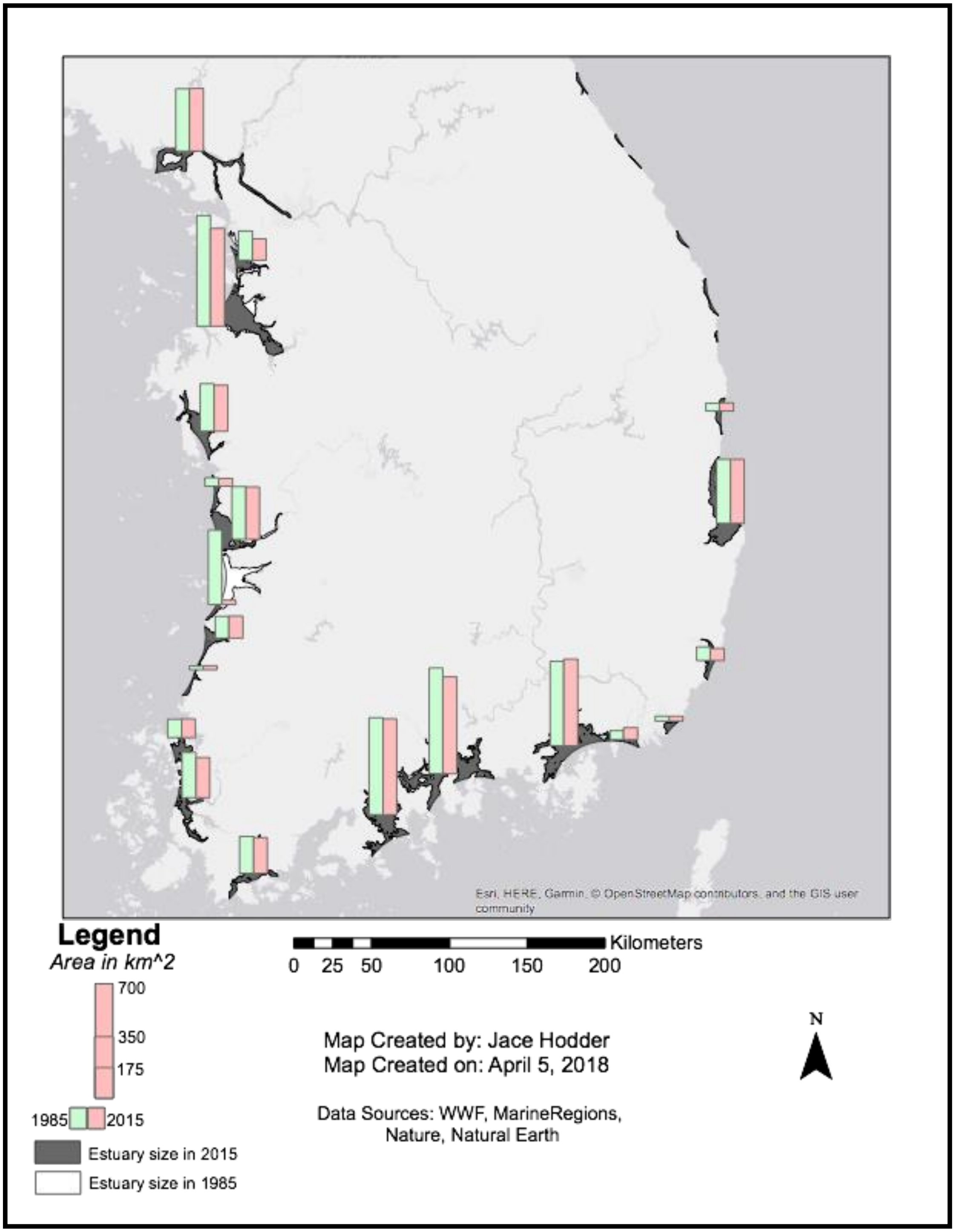


Figure 9: Changes in surface areas of all major estuaries in South Korea using bar graphs

Tönis et al., (2002) conducted a study of the impact of estuarine dams in the Netherlands, where many major coastal engineering projects (e.g. closure of tidal inlets in the Delta Coast, major land reclamation) have taken place in the past and several more are still being considered for the future. Tönis et al., (2002) focuses on the morphological development of one of the inlets in the southeast part of the Netherlands: the Haringvliet estuary. This estuary was closed in 1970; the closure triggered a large-scale adaptation of the morphology of the estuary. The study revealed that after major dams were constructed, sedimentation rate increased dramatically, and estuary size decreased by 15% (Tönis et al., 2002). This decrease in surface area is similar to that observed for many estuaries in this project.

As stated previously, Williams et al., (2014) conducted a study in the effects of damming on the Yeongsan Estuary, which was also covered in this project. They found that the Yeongsan estuary had a loss of about 98 km^2 of overall size after dams were constructed (Williams et al., 2014). This includes losses upstream as well as downstream of the dams. This project showed about a 12 km^2 loss in estuary size of the same estuary, which is a significant difference. The major difference in these numbers is due to the study timeline. Williams' et al., (2014) study was conducted from 1963 to 2013, which includes data from before and after the dam's construction. Our study only had data after the construction of the dam, and this discrepancy can prompt a more in-depth analysis of this and other estuaries. This may also be due to Williams' et al., (2014) study including the entire Yeongsan River, while our study included only coastal areas (within 22 km of the coast), not the entire river basin.

There have also been a few studies directed towards the effects of land reclamation on estuary size and health. One in particular, Wang et al., (2014), examined the importance of land reclamation as well as the serious environmental problems that follow. The article states that reclamation is one potential solution for the increasing demand of new land for living and development (Wang et at., 2014). However, it was shown that land reclamation had brought about serious impact on China's coastal ecosystems and their services, including: reduction of coastal estuary area by slightly over 50%, significant coastal landscape fragmentation and loss of biodiversity, destruction of habitats for fish and feeding grounds for shorebirds, decline of bird species and fisheries resources, reduced water purification ability from narrowing and even disappearance of gulfs and bays, increased water pollution and frequent harmful algal blooms (Wang et at., 2014). This study has shown that land reclamation has the potential to help build new lands for growth populations but can also severely affect the surrounding environment. The study done by Wang et at., (2014) has many parallels to this study, the largest being both show significant decreases in estuary and coastal area size with the implementation of land reclamation.

The impact of elevated sedimentation on the estuarine ecosystem also needs to be addressed. It is well established that elevated sedimentation rates impact both the abundance and diversity of benthic communities (e.g. Nassar, 2011; Chou and Loh, 2004). Field and laboratory experiments by Norkko et al., (2002), Cummings et al., (2003), Hewitt et al., (2003) and Thrush et al., (2003a&b), summarized by Thrush et al., (2004) reveal that a critical threshold of episodic deposition of 2 cm of deposition in an estuary will quickly create anaerobic conditions within the seabed, resulting in the death of the resident faunal community. The benthic and pelagic coupling within an estuary or shallow water coastal system is central to the nutrient cycling and overall productivity of the system and an interruption from of this coupling resulting from elevated sedimentation rates can have dramatic impacts on the entire ecosystem (Eyre and Ferguson, 2005). Studies of the impact of the Nakdong (Williams et al., 2013), the Yeongsan (Williams et al., 2014) and the Geum estuaries (Dellapenna et al., in prep) reveal that the areas below the dam were dramatically impacted by the dam, with sedimentation rates elevated 10-20 times pre-dam rates and converting substrates from sand dominated to mud dominated and vice versa. Sedimentation rates in these systems ranged from 1.5 to 10 cm/year, suggesting that nearly all portions of the estuary below the estuarine dam fall at or are significantly higher than the 2 cm threshold, suggesting that the entire benthic habitat below the estuarine dam in each of these systems has been drastically impacted and that the benthic-pelagic coupling has been interrupted, likely dramatically impacting the entire estuarine ecosystem. This suggests that the impact of the installation of estuarine dams has an impact far greater than just the loss of estuarine habitat and that these dams have likely impacted the entire estuarine systems associated with the dams.

6. FUTURE STUDIES AND IMPLEMENTATION

With this project, there are many opportunities for future work and implementation. Many different choices were made when creating the methodology for this project, and the potential for improvements and changes may result in various new findings.

6.1 Explore Other Tolerance Numbers and Location

The first thing that could be built upon would be to try different tolerances for estuary identification. Changing the numbers for the many buffers ran, “large” river lengths and search distances as well as what can be considered a “large” estuary may lead to different results, and these numbers can be tailored to any scale based on the study area. Examining all 250 estuarial dams and closed off estuaries may also show more complete trends, as locating all estuarine dams could be the next step in this project. Looking at other countries such as China, Australia and even the United States can help find differences in the methodology and can help show estuary changes around the world.

6.2 Examine Other Study Areas, Time Scales and Datasets

Another future study that can be done would be to examine individual estuaries to see how dams have affected them. As this project was done on a county wide level, some detail can be left out on individual estuaries. Examining the largest estuaries, such as Saemangeum Estuary, can be an entire project in itself. Examining every year of the GSWD may also yield more complete data and trends, which can build upon a very detailed study. Within the GSWD, looking at both seasonal and permanent water rather than just permanent water, as well as ground truthing the water extent for the GSWD to see how well it corresponds with shoreline positions under different tidal datums should be implemented into future projects. One can also input other datasets such as urbanization and agricultural datasets and see how the changes in these datasets may affect the estuary sizes. This kind of correlation study can help give concrete results for specific areas and can show what kind of anthropogenic change can have the largest effect on estuaries, aside from damming.

6.3 Look into Other Tools and Programs

Looking into other tools and programs for estuary identification is also another step that can be taken. As GEE is a fairly new program, there are still functions that have yet to be implemented into the program; as time progresses, more and more analysis can be done in GEE instead of having to export and work in ArcGIS. Also, creating a model in ArcGIS can greatly speed up the work flow of a project such as this one, as it requires the same methods for various years. Creating this model can help make sure all the steps taken in different years are exactly the same, limiting the chance for errors between datasets.

7. CONCLUSION

Most of the world's ports and coastal cities reside adjacent to estuaries. As seen in many studies, estuaries are very important systems that act as buffers between fresh and saltwater and provide significant ecosystem functioning. However, throughout the last century, rapid socioeconomic development has resulted in significant engineered alterations to coastal areas, and severe degradation of estuaries. This project tested whether South Korean estuaries have decreased in overall surface areas using GEE and ArcGIS. Using the methodology of this project and its many programs and datasets, this hypothesis was proven true. South Korean estuaries have decreased over time, with notable periods such as 2000-2015 seeing the most change, as these were the years when major dams were constructed. There were also portions of the coast where water area fluctuates up and down from 1985-1995. This may be due to waters becoming seasonal or permanent, data resolution, or could be because of heavily rainfalls and wet seasons. Results also showed land reclamation to cause significant change in South Korean estuaries; however, the most notable changes were seen in areas that have been dammed. A 15.14% decrease in South Korean estuary size was shown after damming projects in South Korea, with more in-depth results seen in selected estuaries. Every damming project studied showed a decrease in surface area of the estuary, even if only a few percent. Some estuaries lost a majority of their size, such as the former Saemangeum Estuary, which lost over 90% of its total size after being dammed off. These selected estuaries and dams were chosen from a previous study and are the largest in South Korea.

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 sea levels. Continued observation is necessary for increased understanding of how anthropogenic feedback characteristics can drive changes in natural ecosystems. Finally, although many studies have been conducted on this topic, not many have found concrete numbers of estuary surface area changes over time, especially in damming cases. This project serves as a starting point for many more projects to be built off of it, as continued research on this subject can be used to advise and develop future estuarine management strategies.

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APPENDIX A

```
// Add Global Surface Water Dataset
var gsw = ee.ImageCollection('JRC/GSW1_0/YearlyHistory');
print(gsw);
var temporalFiltered = gsw.filterDate('Selected Year');
print('temporalFiltered', temporalFiltered);

// Import Shoreline Dataset (10m resolution)
var Land10 = ee.FeatureCollection('ft:1Q1KXW9lFhh4tUTT84iG9DMFcIufnxa_F41daJqTQ');

// Import EEZ Dataset
var eez_land = ee.FeatureCollection('ft:1AjjyHs7G1-
G_jMxM05FJpWRMipAfWBO5PN6KTNCH');
var countryCode = 'KOR';
var countryEez = eez_land.filter(ee.Filter.eq('ISO_3digit', countryCode));
var countryCoast = Land10.filterBounds(countryEez);

// Buffer Shoreline Dataset
var fc_buff = function(feature) {
  var buffer = feature.buffer(22000);
  return buffer;
}
var bufferedCoast = Land10.map(fc_buff);

// Clip GSW and Buffer and (EEZ)
var bufferedCountryCoast = countryCoast.map(fc_buff);

var ic_clip = function(image) {
  var clip = (image.clip(countryEez)).clip(bufferedCountryCoast);
  return clip;
}
var clippedImage = temporalFiltered.map(ic_clip);

//Mask so only permnant waters are visable
var imagemasker = function(image) {
  var mask = image.eq(3);
  var masked = image.updateMask(mask);
  return masked;
}

// Update the composite mask with the water mask.
var maskedClipped = clippedImage.map(imagemasker);
Map.addLayer(maskedClipped, {}, 'masked');
```

```
//Convert GSW Raster (clipped) to Vector Polygons
//Part 1 (zoned)
var image_zoner = function(image) {
  var zoned = image.gte(2).add(image.gte(3));
  zoned = zoned.updateMask(zoned.neq(0));
  return zoned;
}

var gswzoned = clippedImage.map(image_zoner);
print (gswzoned);

//Part 2 (vector and erase small areas)
var area_threshold = 25000

var image_zoneVectorize = function(zoned) {
  var vectored = zoned.addBands(zoned).reduceToVectors({
    geometry: countryEez,
    crs: zoned.projection(),
    maxPixels: 1e10,
    scale: 100,
    geometryType: 'polygon',
    eightConnected: false,
    labelProperty: 'zone',
    reducer: ee.Reducer.sum()
}).filterMetadata("sum","greater_than", area_threshold);
return vectored;
}

// Make a display image for the vectors, add it to the map.
var feature_displayer = function(feature) {
  var imagedFeature = ee.Image(0).updateMask(0).paint(feature, '000000', 2);
  return imagedFeature;
}

var gswVectors = maskedClipped.map(image_zoneVectorize);
print (gswVectors);

var displayVectors = gswVectors.map(feature_displayer);
Map.addLayer(displayVectors, {}, 'vector');

var gswZones = clippedImage.map(image_zoner);
Map.addLayer(gswZones, {min: 1, max: 2, palette: ['0000FF', '00FF00']}, 'raster');

//Flatten gswVectors for export
var gswVectorsFlat = gswVectors.flatten()
```

```
//Export gswVectors
Export.table.toDrive({
  collection: gswVectorsFlat,
  description:'gswVectorsPermanentSelectedYear',
  fileFormat: 'KML'
});
```