Interactive Visualization for Coastal Science Communication: A Case Study of Grayland Plains

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Abstract

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Scientific data are indispensable for guiding climate-crisis decisions, yet the underlying information is often too complex for policymakers or the public to grasp without skilled mediation. Effective visualization can translate those complexities into persuasive, evidence-based narratives. Landscape architecture, with its foundation in aesthetic design, environmental science, and community engagement, can act as an intermediary at the science-policy interface. Coupled with emerging web technologies, it can deliver dynamic, spatial–temporal views of environmental change that resonate far beyond specialist circles.

This thesis explores coastal-science communication through a landscape-architecture lens, employing an interactive, web-based medium. Drawing on visualization theory, it proposes a three-stage visualization framework: Define—Develop—Refine. This framework guides an iterative production process that includes defining the visualization audience and goal, obtaining data and exploring efficient tools, developing web-based interactive visualization and evaluating through interviewing audience representatives.

The theoretical framework is applied to a case study on coastal research in the Grayland Plains on the Pacific coast of Washington state, demonstrating how visualization strategies can enhance the communication of complex coastal processes. The resulting prototype, an interactive 3D web visualization can be viewed at: https://little-x.github.io/visCRLC/. The thesis generates new insights for landscape architects to communicate coastal science with novel tools, fostering a deeper connection between scientific research and public understanding.

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1. Landscape Architecture and Data Visualization in Climate Science-Policy interface

Scientific data are indispensable for guiding climate-crisis decisions, yet the underlying information is often too complex for policymakers or the public to grasp without specialized numeracy, vocabulary, expertise and level of interest (McInerny et al. 2014). Effective visualization can translate those complexities into persuasive, evidence-based narratives. Landscape architecture, with its foundation in aesthetic design, environmental science, and community engagement, can act as an intermediary at the science-policy interface. Coupled with emerging web technologies, it can deliver dynamic, spatial–temporal views of environmental change that resonate far beyond specialist circles.

This thesis explores coastal-science communication through a landscape-architecture lens, employing an interactive, web-based medium. Drawing on visualization theory, it proposes a three-stage visualization framework: Define—Develop—Refine. The Define phase establishes the target audience and communication objectives; the Develop phase encompasses data acquisition, tool selection, and prototype construction; and the Refine phase incorporates stakeholder feedback to improve clarity, usability, and interpretability.

Although two semi-structured interviews have yielded valuable insights for the Refine phase, this work represents only the first cycle of an ongoing design iteration. Future iterations will require broader participant testing and quantitative usability assessments to validate and extend the findings presented here.

1.1. Science-Policy Interface

Climate change has been studied by scientists for over a century (Rosen 2021), and has become an essential consideration in forward-looking policy development. Given its large scale, long temporal dimension, and inherent uncertainty, rigorous scientific research—supported by extensive data and evidence—is essential for understanding the relationships between climate change, human activities, and future scenarios. For policy making, it demands clear support for reliable decisions, while scientific information is one factor that can shape policy, alongside with economic, social and political considerations (Harold et al. 2016).

Despite this reliance, evidence-informed decision making is often impeded by fundamental differences between the nature of science and policy: 1) Depth and width. While science research typically pursues deep, narrowly focused questions, policy making need to synthesize knowledge spanning multiple disciplines to arrive at comprehensive solution (Gluckman, Bardsley, and Kaiser 2021). 2) Uncertainty and definiteness. Science research is an long-term pursuit of the truth with uncertainty and unquantifiability remained, while policymakers expect for clear and definitive scientific evidence to ground policies on (Bremer and Glavovic 2013). 3) Epistemic complexity. Science research is built on extensive theories with restriction between theory and practice, while policy requires a convincing and practical conclusion. 4) Communication channels. Science research relies on paper-based publication, which limits accessibility for non-expert audiences, while complex graphs and domain-specific jargon further hinder lay understanding. These inconsistencies compromise the effectiveness of science communication to policymakers, hamper the science promotion and poses threat to policy-impacting communities.

The concept of a science-policy interface has emerged to bridge these gaps. Typically initiated by research organizations in collaboration with communication specialists, such interfaces aim to tailor scientific evidence to the needs of decision-makers. Effective implementations start from identifying demand side and policy dynamics, recognizing policy questions, clarifying required evidence, assessing knowledge gap, and communication of the uncertainties, caveats and reliability of evidence (Gluckman, Bardsley, and Kaiser 2021).

Intergovernmental Panel on Climate Change (IPCC) is an example holding the science-policy interface for climate change. In IPCC's plenary sessions, the primary target audiences of the communications efforts are governments and policymakers at all levels. Wider audiences are diverse, ranging across non-governmental organizations, the education sector, business and the public (IPCC 2016). Another example is Integrated Coastal Management (ICM), with its effort to create political settings where informs coastal communities for the management of coastal commons (Bremer and Glavovic 2013).

Science-policy interface actively utilizes a wide range of tools for effective communication, such as written reports, newsletters and visualization. When producing a visualization, however, scientific analysis and artistic design involve distinctly different cognitive styles (Dibiase 1990). Although many scientists have well-developed visual sense, they generally lack formal training in communication—an issue that has hindered climate-related outreach. Climate visualization has unfortunately been largely neglected (McMahon, Stauffacher, and Knutti 2015). Overcoming this shortfall requires integrating principles of visual design, narrative structure, and user-centered interactivity to ensure that complex climate data can support informed and inclusive policy decisions, which will be explored in the following chapters.

1.2. Visualization as an Effective Communication Tool in Science-Policy Interface

Visualizations are visual representations of information (Padilla et al. 2018). In climate science-policy interface, the information can be scientific knowledge including climate model, historical records, and environmental data, or political information such as zoning, parcels and legal boundaries.

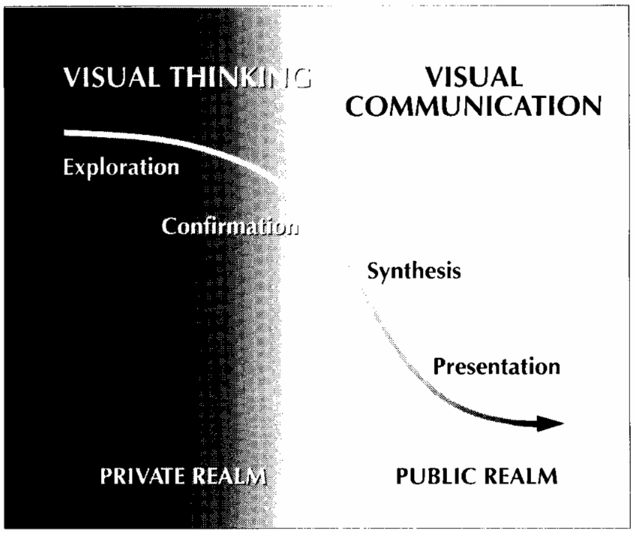


Figure 1 The Range of Functions of Visual Methods in an Idealized Research Sequence (Dibiase 1990)

The amount of data for science communication is usually intense, and discovering meaningful patterns in large datasets is a common challenge in many fields (Walker et al. 2020). Due to human cognitive style, visual representation of data is an effective way to explore the data pattern and generate understanding for intangible subject matter due to the scale, complexity or abstraction (McInerny et al. 2014).

Communication success, however, depends on more than the data themselves. It hinges on four interacting factors—user, task, domain, and resources—a relationship formalized in early adaptive-visualization research (Domik and Gutkauf 1994). This study introduces a “user modeling” method, to define the audience in multiple aspect such as color perception or even motor skills. User modeling can also be based on an audience’s occupation and cognitive style for assigning visualization tasks. Visualization misalignment with the task, or conceptual question (Padilla et al. 2018) will causes inefficient information convey.

Cognitive theory offers further guidance. Dual-process models posit a fast, intuitive “Type 1” system and a slower, analytical “Type 2” system (Evans and Stanovich 2013). Graphics that cue only intuition can mislead, whereas overly intricate plots may swamp working memory. By balancing salient visual cues with on-demand detail, designers can server both intuitive and rational modes of thought (Padilla et al. 2018).

Additionally, in a study evaluating policy-makers reading climate-related figures (IPCC, n.d.), no association was found between the ranked importance of the figures and the ranked ease of comprehension. Non-specialists made intuitive judgements based on visual characteristics of this figure, rather than a deeper understanding of the content (Harold et al. 2020). This suggests the need to manage visual complexity (Rosenholtz, Li, and Nakano 2007) to help improve audience’s comprehension by concentrating on information, without compromising informational complexity (Harold et al. 2020).

To meet these cognitive and communicative demands of visualization, professional designers and communication specialists are involved in the science-policy interface to address the key visualization issues in graphical representation, technical implementation, multidisciplinary collaboration and user-center design (McInerny et al. 2014). These approaches help reduce visual complexity, frame scenario storylines (Mastrandrea et al., n.d.), address transdisciplinary problems, and ultimately promote scientific knowledge dissemination for policy making.

An example of the visualization at the science-policy interface is “IPCC Summary for Policymakers (SPM)”, a synthesis report in PDF format that can be freely downloaded from IPCC website, highlighting the significant historical trend and future projection in temperature, CO2 emissions and sea level changes. These graphics provide government with the highly complex knowledge synthesizing from an “amalgamation of millions of gigabytes of data, as well as thousands of published findings” (McMahon, Stauffacher, and Knutti 2015). The content in the report is presented by clear visualization formats such as charts, hexagon tile maps, choropleth maps and pictogram visualization, along with detailed textual explanation to ensure unbiased interpretation. However, while SPM are aimed at policy maker, these figures are likely for experts in government and have been criticized for being inaccessible to non-experts (Harold 2017).

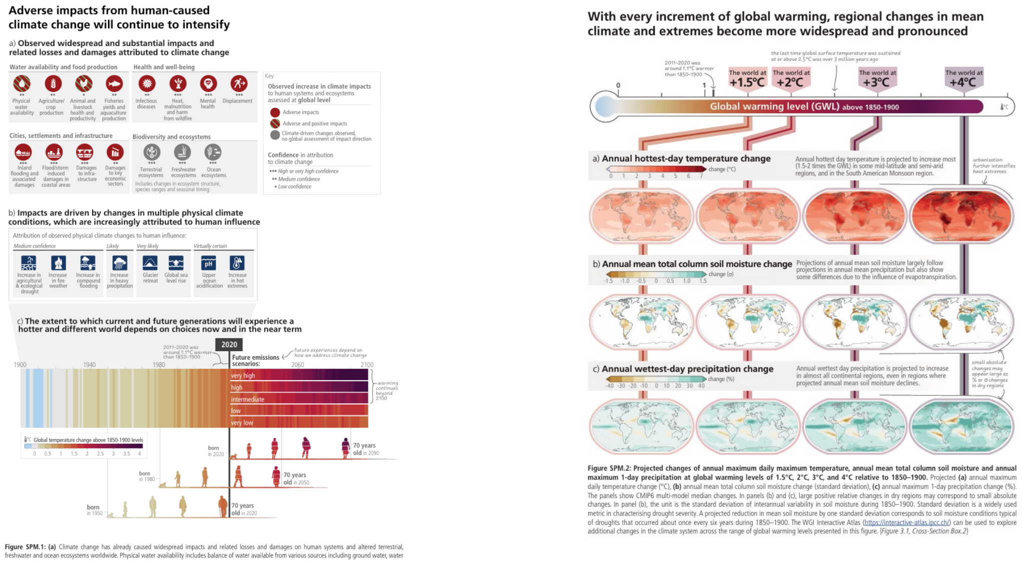


Figure 2 Visualization Examples from IPCC SPM (Calvin et al. 2023)

Landscape architecture contributes to science communication with complementary expertise: three-dimension spatial form and artistic graphic design. In the project North Willapa Bay Shoreline Erosion and Dune Restoration Graphics (Balderas Guzman et al. 2025). Maps are used to visualize a large-scale spatial pattern such as matter movement, ecological implementation distribution, and jurisdiction boundary; Perspective cross sections with iconography to convey ecological feature like specific species and human experience of a place: a critical perspective to view coastal space as, for residents, a lived place (Tuan 1977; Bott, Cantrill, and Myers 2003). Largely welcomed by a broad range of stakeholders: coastal scientists, engineers, state, local and tribal agencies and residents, these graphics are used for grant application, legislative outreach, and supporting other Pacific Northwest coastal communities.

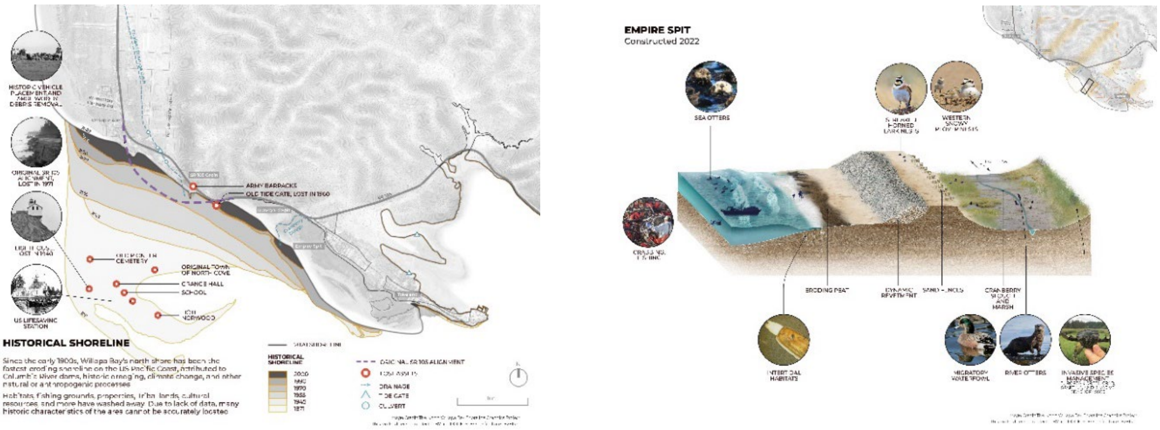


Figure 3 North Willapa Bay Shoreline Erosion and Dune Restoration Graphics (Balderas Guzman et al. 2025)

However, most existing coastal-decision visual tools remain 2-D GIS dashboards that assume technical fluency and favor top-down plan views (US Department of Commerce, n.d.). Reaching a broader constituency therefore requires interdisciplinary insights to better align scientific evidence with the values, constraints, and cognitive habits of coastal stakeholders and explore alternative forms of visualization.

1.3. Previous Scholarship on Data Visualization

As a tool of interdisciplinary communication, data visualization is researched in a broad range of study fields, with various focuses. In general, research can be grouped into three complementary strands based on production process:

1) Visualization technique. Facing the increasing amount of data, data management and visualization tool development is usually studied by computer science and human computer interaction scholars (Johansson, Neset, and Linnér 2010; Lam et al. 2012) , managing the algorithm to transform numerous data into graphics in an accessible manner.

2) Cognitive interpretation and evaluation. To improve the visual efficiency and complexity from the perspective of human perception, psychological and communication scientists (Harold et al. 2017) investigate how visual attribute—layout, color, annotation and interactivity—affect perceptual efficiency through surveys and experiments.

3) Design guidelines. Design recommendations and suggestions are released based on cognitive evaluation. Controlled experiments and user studies yield principles and heuristics for effective representation.

Table 1 Climate Visualization Research Focuses in Reviewed Studies

Focus Areas	**Representative Studies**
Visualization techniques	Al-Kodmany (1999); Nocke et al. (2008); Goudine et al. (2020); Dean et al. (2022); Canepa et al. (2023); Steed et al. (2014); Steed et al. (2020); Dykes (1997); Spiegelhalter et al. (2011); Portman (2014)
Cognitive interpretation and evaluation	Johansson et al. (2010); McMahon et al. (2015); Herring et al. (2017); Daron et al. (2015); Altinay and Williams (2019); Bazzurri (2024); Harold et al. (Harold et al. 2020)
Design guideline	Harold et al. (2016; 2017);

Taken together, these strands demonstrate that effective visualization research must couple robust technical methods with evidence-based design guidelines and empirical cognition studies to advance both theory and practice. Across the literature, evaluation instruments typically combine self-report surveys with comprehension tasks, probing multiple dimensions of user response.

Table 2 Visualization Evaluation Metric

Study	**Illustrative evaluation metrics**
McMahon, Stauffacher & Knutti (2015)	graph salience; scientific literacy; content knowledge; graph-comprehension scores
Daron et al. (2015)	interpretation accuracy; confidence in climate-change message; perceptual clarity; relative preference
Johansson, Neset & Linnér (2010)	perceived novelty and aesthetics; insight into dataset; impact on engagement, lifestyle reflection, and professional interest

Visualization grows as technology supports more visual effects. Traditionally, visualizations are in the form of a static picture, which are limited to the variables and spatial and temporal scales for which they were created (Herring et al. 2017). As display media advances along with technologies develop, there are increasing possibilities to present a visualization on interactive media. Interactive data visualizations can make large and complex datasets easier to access and explore, which contributes to knowledge discovery, hypothesis formation and improved understanding (Walker et al. 2020). For example, Herring et al. (2017) found that using an interactive data visualization tool for exploring local climate risks significantly changed the participants' attitudes towards climate change.

As the context of this thesis, environmental communication (Hansen and Machin 2013) is an evolving discipline gaining in interest, especially as tools such as crowdsourcing and social media constitute everyday interactions and local activism takes on global challenges, such as changing behaviors to mitigate climate change (Sheppard 2012). Under the background of a tremendous amount of misleading information and scattered efforts to promote environmental awareness, studies increase in relevant domain to support science communication regarding environmental changes, present insight from the past, and pose influence on the future.

Within climate-related disciplines, both domain experts and visualization specialists are investigating visualization methods for communicating climate processes. Climate researchers usually utilized standard visualization tools, such as Microsoft Office software and script-based systems (e.g. R, Python, and MATLAB) in typical 2D form, while visualization researchers are developing techniques for visualizing weather and climate data. (Nocke et al. 2008). Applications extend well beyond meteorology. Civil engineers employ bathymetric data visualization to inform coastal management strategies (Durap 2024). Architects and planners experiment with immersive representation of environmental data to support decisions at urban and regional scales (Portman 2014), and marine scientists develop interactive visual interface for domain-specific data such as ocean temperature and salinity data collected by buoyancy gliders in the Gulf of Mexico (Hsu et al. 2020).

Furthermore, in coastal science-policy communication, landscape architects utilize comprehensive analytical and design tools, such as GIS and 3D modeling, to communicate coastal hazard scenarios in flood prone areas (Yang 2016). This approach enables effective processing, analysis, and representation of diverse environmental data, thereby facilitating stakeholder engagement and promoting climate awareness. Positioned at the nexus of science, design and public communication, landscape architects are well-suited to explore the potential of visual tools to bridge the gap between scientific data and public understanding. In doing so, they help foster a more informed, inclusive and actionable decision-making process in coastal policy contexts.

1.4. Multi-faceted Data in Coastal Science-Policy Interface

Communication necessitates science data and policy data to conduct a comprehensive analysis and achieve a convincing conclusion. To start with, it is essential to know what data constitutes the common interest of coastal scientists and policymakers.

1.4.1. Scientific Data in Coastal Contexts

Kehrer and Hauser (2013) categorized multi-faceted scientific data according to their spatial-temporal dimensions, attribute variates, data sources, simulation runs and models. This thesis mainly discusses coastal science data with a focus on geospatial and remote sensing data, ecological data, geology and oceanographic data from multiple sources.

1.4.2. Policy-Related Data in Coastal Management

Changing coastal environments influence policy making at zoning, land-use planning and insurance. In this term, policy data includes regulatory frameworks, legal boundaries, public engagement data, and socioeconomic data.

1.4.3. Challenges in Data Acquisition

Data deficiency in various ways constitute reasons of limits sharing of coastal science, including poor quality data and analysis, incomplete data, incompatible data, inability to properly understand scientific documents, and the embarrassing release of “sensitive data” (McConney et al. 2016).

1.5. Tools of Interactive Data Visualization

This section reviews the computational platforms used to couple data with visual elements—particularly those that support interactive features and immersive 3-D scenes. Data visualization tools may be broadly grouped into three classes: spreadsheets, software and programming libraries (Srivastava 2023). Although spreadsheets remain valuable for exploratory charting, only the latter two categories offer the geospatial and real-time rendering capabilities required for web-based coastal visualization. Accordingly, this thesis concentrates on specialized software and open-source libraries, which together enable the mapping, interaction logic, and performance optimizations demanded by 3D, browser-delivered experiences.

Table 3. Popular Interactive Visualization tools

Tool	Brief	Strength	Weakness
3D GIS (ESRI, n.d.)	Geological Information System (GIS) in 3D	Compatible with traditional 2D GIS; Accurate geospatial data; Accurate Elevation display	High computational resources; Limited compatibility with web application
D3.js (Bostock, Ogievetsky, and Heer 2011)	A JavaScript library to build data visualization in web applications.	High flexibility in chart types; focus on web standard	Steep learning curve; Demands programming language
Datawrapper (Datawrapper, n.d.)	A data visualization website specifically for charts, maps and tables	No programming needed; Neat graphic templates; Support color-blind palette check	Limited options for data sources (Shakeel et al. 2022);
Tableau	A data visualization software specifically for business analysis	Convenient drag-and-drop data import operation; strong community	Limited function in free version; Potentially expensive
Three.js	A JavaScript library to create 3D scenes in web applications.	Compatible with common 3D modeling software through glTF file	Require 3D modeling and rendering knowledge;
Procedural-gl.js (Procedual GL JS Team, n.d.)	A library for creating 3D map experiences on the web, written in JavaScript and WebGL. Built on top of Three.js	Annotation on 3D map; Support multimodal map tiles; Support elevation data for 3D terrain	Complex when handling imported 3D model;

1.6. Objectives and Research Questions

While conventional scientific visualizations often prioritize precision and technical completeness, they may not always serve the communication needs of non-expert policymakers navigating complex coastal challenges. Landscape architecture, with its emphasis on environmental knowledge, visual storytelling and stakeholder communication, offers a complementary skillset for enhancing visualization at the coastal science-policy interface.

The overarching objective of this thesis is to evaluate how 3D interactive visualization can strengthen communication at the science-policy interface for coastal resilience. This aim is pursued through three questions:

1) In what specific ways do widely used (2D, static) scientific visualizations fail to meet the information needs of non-expert decision-makers?
2) How can a web-based, 3D interactive visualization improves comprehension of spatial-temporal shoreline data and support dialogue among scientists, policymakers and the public?
3) How do audiences in different decision-making contexts perceive the same visualization?

These questions frame the thesis inquiry as both exploratory and practice-led, focusing on the potential of 3D interactive visualization to bridge data and decision-making.

2. Methodology: Visualization Framework for Coastal Science Communication

From the perspective of landscape architecture discipline, this thesis adopts an interdisciplinary methodology that weaves together scientific data processing, visualization design, and science communication theory. These components are organized within a three-phase visualization framework, Define—Develop—Refine, which structures the development of an interactive 3D web-based visualization for coastal science-policy communication.

This framework is demonstrated through a case study of shoreline changes in the Grayland Plains on the Pacific coast of Washington state. The case study serves as both a practical demonstration and a methodological exploration, examining how landscape design-based thinking and digital tools can enhance the communication of scientific information in policy-relevant settings.

The approach is primarily exploratory and design-based. It is informed by literature review, data collection, experiment with software toolchains, and iterative digital prototyping. In combination, these steps test how interactive visualization can strengthen communication between coastal scientists, decision-makers, and the broader public.

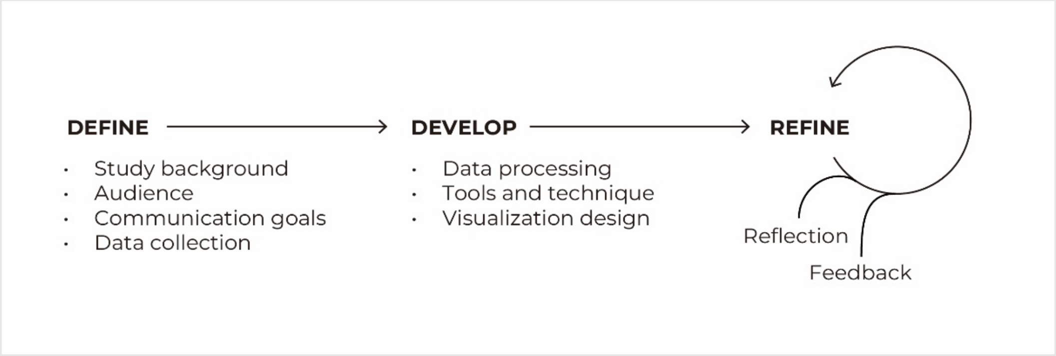


Figure 4. Visualization Framework

2.1. Define: Visualization Goals, Context and Audience

2.1.1. Case Study

The publication Historical evolution of the Columbia River littoral cell (CRLC) (Kaminsky et al. 2010) is chosen as a case study for visualization analysis and re-creation practice. The paper synthesizes shoreline positions and bathymetric surveys spanning more than a century to quantify shoreline change rate along the CRLC, which extends across southwest Washington and northwest Oregon. Three factors motivated its choice: 1) Policy relevance. The findings bear directly on management issues such as legal shoreline delineation, land-use regulation, hazard zoning, and property-insurance assessment—making the dataset ideal for exploring science–policy communication. 2) Rich, multivariate data. The publication provides well-documented spatial-temporal datasets (historical shorelines, bathymetric volumes, and change-rate metrics) suitable for developing and testing interactive visual encodings; and 3) Scholarly prominence. The CRLC has been a focal region for coastal-process research, ensuring that reinterpretations of its data will resonate with an established scientific audience and contribute to an active body of literature.

Data and visualization in this study demonstrates historical shoreline positions, bathymetric volumes and change rates from 1870 to 2000 in CRLC. While these graphics are well-suited for expert interpretation, they pose barriers to broader engagement for non-technical audiences. The original visualizations include time-sequence plan views of bathymetric volume changes annotated by compartment (Figure 6, Left), bar charts showing shoreline change rates by group (Figure 6, Right), and line charts of historical shoreface profile changes. Even when these chart types are prevailing and require “relatively little cognitive effort” for comprehension (Mesters 2010), the data unfamiliarity adds to their understanding challenges. Most of the visualization requires domain knowledge such as shoreline morphology and GIS mapping conventions to be immediately understood.

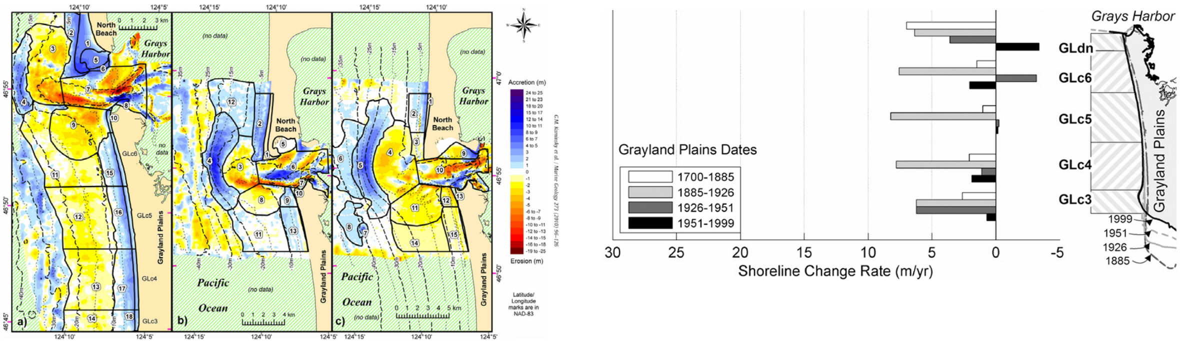


Figure 5. Visualization in *Historical evolution of the Columbia River littoral cell* (Kaminsky et al. 2010).

Left: Bathymetric Change Mouth of Grays Harbor and Adjacent Coast

Right: Block-averaged Shoreline Changes Rates at Grayland Plains

From a science communication perspective, several design choices in the original visualizations contribute to their inaccessibility. 1) The complexity and inconsistency of spatial overlays (i.e. overlapping compartment boundaries on bathymetric maps); 2) Visual clutter arises from unclear or unnecessary visual elements (i.e. diagonal hatch fills for indicating shoreline groups); and 3) unconventional chart layout (i.e. horizontal bar charts where positive change is mapped left and negative to the right on the shoreline change rate chart).

These design characteristics highlight the gap between expert-focused data presentation and broader public or policy-oriented communication, underscoring the need for visualization strategies that prioritize clarity, intuitive interaction, and narrative cohesion.

2.1.2. Audience and Goals of Visualization

This thesis prototypes an interactive visualization centered on Grayland Plains (Figure 6) between Grays Harbor on its north and Willapa Bay on its south, a sub-cell of the Columbia River Littoral Cell. Over the past century, both estuary mouths are significantly transformed by human development and the accompanying large-scale engineered modifications (GeoEngineers, Inc. 2015), such as jetty and dam construction (Kaminsky et al. 2010), navigation channel dredging project (GeoEngineers, Inc. 2015), and water irrigation (Sherwood et al. 1990). Overall, the Grayland Plains shoreline is net erosional in around two centuries but net accretional in recent 50 years (USGS 2013), with localized dramatic retreat. For instance, Willapa Bay North shore continues to experience the fastest erosion rate on the US Pacific Coast. Shoreline retreat poses huge social and ecological impact such as infrastructure relocation, properties and wildlife habitats loss (Talebi et al. 2017).

This site was chosen for two primary reasons: First, ongoing collaborations between the University of Washington College of Built Environments and regional partners have yielded extensive data and active communication with local stakeholders, ensuring that design assumptions rest on real information needs. Second, compared to the entire littoral cell, the sub-cell's limited spatial extent reduces data-processing and rendering costs.

Figure 6. Study Region: Grayland Plains

The notional audience mirrors the stakeholder network identified in the UW Geonarrative project for adjacent Westport. It includes practitioners at multiple governance scales—Washington Department of Ecology, U.S. Army Corps of Engineers, Washington State Parks, the City of Westport, Shoalwater Bay Indian Tribe, Willapa Erosion Control Action Now organization (WECAN), and the Westport-by-the-Sea condominium association. While the visualization is not formally tested with stakeholders, the design is informed by their potential interests and decision-making responsibilities. By bridging historical shoreline changes with multimodal data—such as physical disturbance timeline, property loss and biodiversity variance—the visualization can inform policy areas ranging from habitat-protection zoning to coastal-development restrictions and restoration initiatives (Karasik et al. 2023).

Grayland Plains—locally known as South Beach—are highly vulnerable to ongoing beach erosion, sedimentation, storm surge and sea level rise (Hutchison and Abramson 2021). The Shoreline Master Program was adopted in 1972 guiding the uses of shorelines, in terms of Activities and Development, Natural System, Shoreline Environment and Administration (Abramson et al. 2019). Hazard-mitigation efforts—including vertical evacuation structures, tsunami-evacuation mapping, and shoreline stabilization—aim to prepare the community for earthquakes, tsunamis, and post-disaster recovery (Mattheis and Hutchison 2021; Hutchison and Abramson 2021). In North Cove alone, more than 3,000 acres of upland, 30 public buildings, and 640 parcels have eroded away since the 1880s, forcing the Coast Guard lighthouse to relocate twice (Talebi et al. 2017). Such dramatic losses have spurred government agencies to experiment with dynamic revetments and other coastal-protection measures.

In response to these challenges and efforts, the visualization prototype developed in this study serves three primary communication objectives: 1) Reveal historical change: Provide side-by-side, time-stamped shoreline positions that make long-term trends visible; 2) Quantify process: Demonstrate key metrics, such as rates of erosion or sediment volume change, for audience to interrogate “how much” and “where”; and 3) Link data to action: Present information in a format that supports policy setting and land-use planning.

These objectives transform the visualization into a tool for both analytical reasoning and collaborative decision-making. Regionally, visualizing quantified shoreline dynamics exposes the threats to property and ecosystems, frames adaptation tradeoffs, and lays the groundwork for strategies such as environmental performance evaluation, shoreline restoration, and managed retreat. Locally, visualization resonates with their place attachment by telling a human-perspective story with scientific data. To effectively convey the notion behind the data, designers must understand how stakeholders’ values, interests, and needs influence their perspectives and understanding of these marine-terrestrial environments. This requires thinking of these environments as ‘coastal places’ when it is imbued with values and meanings, rather than simply ‘coastal spaces’, the physical dimensions of a locality (Newell and Canessa 2017). With place understanding, communicating information through stories is more evoking than graphs and numbers (Corner, Shaw, and Clarke 2018; Corner and Clarke 2016).

2.1.3. Data Collection

The data used in this thesis for developing the visualization prototype are drawn from an existing coastal science study, supplemented by contextual and policy-relevant information. These datasets are categorized into two types based on their origin and function: 1) primary data generated from scientific research, and 2) supporting data that provide background, interpretation, or spatial context. Data can be downloaded through the GitHub repository (https://github.com/little-x/visCRLC).

Table 4 Data Sources

Type	**Format**	**Description**	**Dimension**
Spatial-temporal Data			
Historical Shorelines	Shapefile (.shp)	Shoreline positions organized by blocks and groups	2D + Time
Shoreline Change Metrics	Microsoft Excel (.xlsx)	Recession/progradation/deepening/volume change rates across intervals	1D + Time
Contextual data			
Digital Elevation Model	.tiff	Topography of the surrounding terrain (2021)	3D (static)
Infrastructure Data	Shapefile (.shp)	Location of roads and public infrastructure	2D (static)
Property Parcel Boundaries	Shapefile (.shp)	Land ownership and zoning data	2D (static)
Place photos	.jpg	Photos of place of interest, infrastructure, and historic sites	/

Spatial-temporal Data

Data in the Kaminsky (2010)'s paper was maintained by an environmental specialist at Washington State Department of Ecology. The specialist shared a well-organized compilation of data products and offered a one-on-one consultation via video call to explain the data structure and processing methods. According to the documentation, spatial datasets were produced in ArcGIS, quantitative analyses were performed in MATLAB, and final tabular outputs were exported and visualized using Microsoft Excel.

These data encompass a range of spatial and temporal dimensions, reflecting the physical and geomorphological changes in the Grayland Plains area. Temporally, these data are organized chronologically over four intervals: 1700-1870s; 1870-1920s; 1920s-1950s; 1950s-2000. Data include:

1) Historical shorelines (2D) from 1870 to 2015, Grayland Plains shoreline is divided into blocks with an average alongshore length of 5 km. Blocks are further divided into groups representing 1-km alongshore sections of shoreline.
2) Shoreline change metrics (1D), including shoreline recession and progradation rates, deepening rates, and sediment volume change rates across time intervals and spatial units.

These research datasets are the basis for the main visual content in the web-based visualization.

Contextual Data

To contextualize the primary datasets and enrich the visualization narrative, supporting data were collected from public sources. These include both static and time-referenced spatial information relevant to topography, land use, and human development:

1) A digital elevation model representing surrounding topography as of 2021, used to generate an accurate 3D terrain for visualization.
2) Highway data representing the location of public infrastructure.
3) Property parcel data, offering insight into current land ownership patterns and potential vulnerabilities in coastal planning.

These supporting layers help situate scientific data within the broader landscape and socio-political context, enhancing the interpretability of the final visualization.

2.2. <u>Develop</u>: Align visualization design with Goals

Visualization should be governed by scientific principle and guided by design principle (Tufte 1997). This section demonstrated how forementioned visualization goals—Reveal historical change; Quantify process and Link data to action—are implemented through data processing, tools selection and the design rationale. These objectives shape the design choice including the 3-D viewport that supplies intuitive spatial context and the console controls that expose numerical detail on demand, ensures the visualization prototype bridge efficiently between coastal science and decision-making practices.

2.2.1. Data Processing

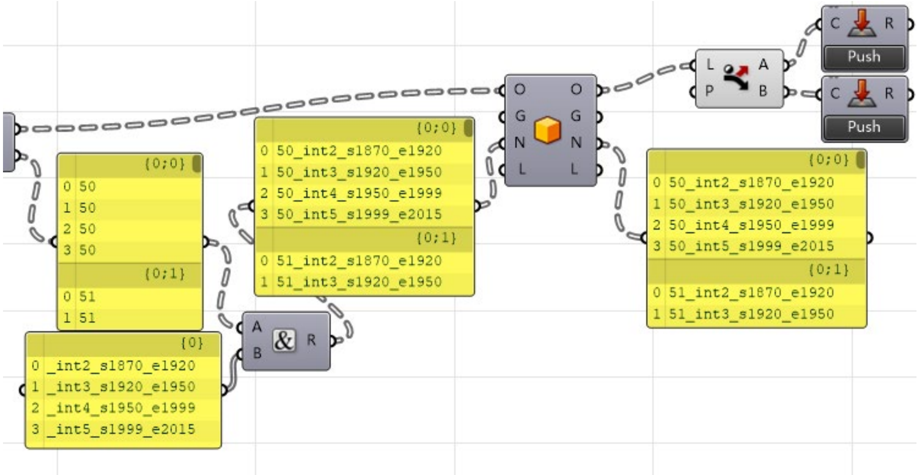
Data used in the visualization were processed using a combination of GIS, tabular data, and modeling tools. Spatial datasets, including historical shorelines, highway infrastructure and parcel data, were preprocessed in QGIS and exported as .dxf files to enable integration with 3D modeling workflows. Elevation data, including the digital elevation model (DEM) and bathymetry, were converted into raster format (.tif) for terrain generation. Change rate data, originally formatted in Microsoft Excel, were cleaned by time interval and group (shoreline segment), then exported as .csv files for binding with objects in 3D model and direct use in visualization scripts.

The preprocessing ensured all data layers were spatially aligned, temporally consistent, and optimized for real-time rendering in web-based environments. This step served as the bridge between environmental science data and design-driven modeling workflows.

2.2.2. Tools and Techniques

The visualization was developed using a combination of conventional landscape analysis and modeling software (for example, QGIS and Rhino 3D) and web-based visualization tools.

The initial 3D model, including base terrain, shore surfaces, and shoreline groups, was created in Rhino 3D, using the processed .dxf and .tif files. To enable selective visibility and data binding in the web environment, object names were systematically assigned to model elements using Grasshopper, Rhino's integrated visual programming interface. Each historical shoreline surface was named as their corresponding year, and each shoreline group were named in a structured format "{change rate}_Group{group id}_S{start year}_E{end year}". The finished 3D model with texture and naming metadata was then exported as .glb (glTF) files for integration into the web environment while preserving geometry, materials and object name.



```
{0;0}
0 50
1 50
2 50
3 50
{0;1}
0 51
1 51
```

```
{0}
0 _int2_s1870_e1920
1 _int3_s1920_e1950
2 _int4_s1950_e1999
3 _int5_s1999_e2015
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{0;0}
0 50_int2_s1870_e1920
1 50_int3_s1920_e1950
2 50_int4_s1950_e1999
3 50_int5_s1999_e2015
{0;1}
0 51_int2_s1870_e1920
1 51_int3_s1920_e1950
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2 50_int4_s1950_e1999
3 50_int5_s1999_e2015
{0;1}
0 51_int2_s1870_e1920
1 51_int3_s1920_e1950
```

Figure 7. Naming Convention in Grasshopper

The interactive visualization was implemented primarily using Three.js, a JavaScript library for real-time 3D rendering in the browser. This enabled immersive display of topography and shoreline change across historical intervals. Supporting 2D interface components such as a timeline toggle, legends, and tooltips were built using D3.js and Svelte, allowing for responsive interactivity and efficient data binding. These tools provided a flexible front-end framework for designing a user interface that supports both exploration and narrative communication.

The project was developed using a Vite build tool for fast local development and optimized production bundling. The complete website source code is version-controlled in a public GitHub repository (https://github.com/little-x/visCRLC), and the web-based visualization (https://little-x.github.io/visCRLC/) is deployed using GitHub Pages, which serves the static files directly from the repository's dist/ directory after each build. This approach enables reproducibility, transparency, and broad accessibility without requiring a backend server or cloud infrastructure.

The programming process is assisted by Visual Studio Code Copilot with ChatGPT o3 and Claude AI 3.7 for Svelte and JavaScript code generation. However, due to the data latency in the AI tools, some code syntaxes are from an outdated Svelte version, requiring manual rewrite for better performance and maintenance.

Table 5 Workflow and Tools

Phase	Tool / Software	File Format	Role in Workflow
Data Preprocessing	QGIS	.dxf, .tif	Export spatial vector and raster terrain surfaces
	Microsoft Excel	.csv	Clean and organize change rate data by group and time interval
3D Modeling	Rhino 3D	.3dm, .glb	Build 3D terrain, shorefaces, and grouped shoreline surfaces
	Grasshopper (Rhino plugin)	–	Automate object naming for visibility control and data binding
Web Visualization	Three.js	–	Render 3D scenes interactively in browser

D3.js	.csv	Bind data to 2D UI components (legend, tooltip, etc.)
Svelte	–	Manage component logic, interactivity, and UI layout
Github	–	Source code version control, website deployment

2.2.3.

2.2.4. Visualization Design Rationale

The visualization is published as a website for its portability, accessibility, and scalability. Websites embrace the opportunity of interaction feature, which is beneficial for engagement, communication of idea and. Interaction leads to Kinesthetic learning style, promoting insight through discovery (Dove and Jones 2012), supported by multimedia learning theory (Mayer, 2001). The inherent dynamism of interactive website provides a solid ground to the visualization of changes over time and space (Rodrigues, Figueiras, and Alexandre 2019), aligning with the dynamism of coastal science.

Based on regional and local scientific data, 3D scene is intuitive and meaningful to perceive, and responsive to audience’s information demand about potential costal threats, encouraging thorough exploration (Lieske et al. 2015). Compared to conventional scientific 2D map that emphasizes detailed analysis and precise reasoning, 3D view is beneficial for tasks requiring overviews and more holistic reasoning, (Saenz, 2017). Moreover, 3D visualization not only functions as information presentation, but also encourages participatory process with scientific data, stimulating public engagement at science-policy interface.

While combination of interaction and 3D potentially boost communication, challenges in sense-making with its dynamism should also be noted. Making sense of 3D dataset requires meticulously manipulating the data or the view, selecting place of interest, placing annotations and manipulating widgets (Besançon et al. 2021). In this study, visualization interface has three main components: a 3D viewport for immersive interaction, a control console for toggle changes, and annotations that present legend symbols, quantitative metrics and explanatory images. The interactivity matches the visual analysis convention “overview-first, zoom and filter, details-on-demand” (Shneiderman 1996). It facilitates user-directed data exploration while guiding attention to key phenomena—such as areas of rapid shoreline retreat or zones affected by anthropogenic infrastructure, highlighting the vulnerable area for decision consideration (Goudine, Newell, and Bone 2020).

Narrative is an account of a series of events and facts given in order with connection established between them (Segel and Heer 2010). In the science-policy interface, a clear narrative directs a viewer's attention and keeps viewer oriented, which helps solidify scientific data for political actions. In this project, a spatial-temporal narrative (Rodrigues, Figueiras, and Alexandre 2019) guides the visualization storyline. Through spatial objects' transformation and movement, audience perceive the passage of time (Peuquet 1994), and are helped to make predictions through this representation of change (Meirelles 2013). In this thesis, shoreline data spanning multiple historical intervals is displayed as a sequence of layers, allowing users to toggle through time to observe the changes. This narrative enables direct comparison between historical shoreline positions, while spatial overlays and color-coded symbols indicate associated variables such as shoreline change rates.

In this thesis, the interaction and the narrative follows the five-level taxonomy for engagement (Expose–Involve–Analyze–Synthesize–Decide) (Mahyar, Kim, and Kwon 2015). Users first see (Expose) the shoreline pattern, then toggle layers (Involve), analyze differences, synthesize implications for management, and ultimately decide on policy or design responses. Visualizing coastal changes encourage audience to provide thoughts, comments and ideas (Newell, Canessa, and Sharma 2017).

Finally, the visualization pipeline is deliberately modular. All geospatial inputs are integrated into the glTF file with corresponding object name for the following rendering stack (Three.js + Svelte + D3). This pipeline allows future data input new shoreline surveys, habitat layers, or policy scenarios without rewriting core code.

Together, the web medium, 3D scene, interactive interface, narrative timeline, and modular data design create a communication channel tailored to the spatial-temporal complexity of coastal change while remaining transparent and reproducible for the science-policy interface.

Figure 8. Visualization Prototype: Historical Evolution of the Grayland Plains Shoreline

2.3. Refine: Enhancing Visualization Heuristics

Where the Develop phase leaned on the designer’s intuitive judgments, the Refine phase subjects every decision to explicit and formative evaluation. This evaluation proceeds on two aspects: 1) internal heuristic walkthrough guiding systematic self-critique and quick iteration; and 2) external formative evaluation acquiring feedback from representative audiences revealing communication gaps.

2.3.1. Internal Heuristic Walkthrough

Internal heuristic walkthrough (Table 6) are organized around three interlocking design facets: 1) Visual encoding: the static visual grammar of color, shapes, scale, and typography; 2) Interaction: the dynamic behaviors that govern user experience including camera controls, layer toggles, tool-tips, and performance optimization; and 3) Narrative: the coherent story that emerges from the interplay between data and visual components. This classification foregrounds heuristic evaluation literatures in information visualization field (Errey et al. 2025; Zuk et al. 2006; Carpendale 2008), while adapted for the study’s characteristics in visualization design, interaction and communication purpose.

Visual encoding is the design choice presenting data in specific visual elements. For spatial data in this thesis, it is represented in 3D model of landscape reality. Unlike traditional 2D visualization, this visual form does not include complex visual encoding from data to abstract graphics, minimizing the comprehensive challenge to interpret. Visual encoding in 3D is mainly involved in the design decision of style, color, texture and annotation symbols.

While interaction facilitates visual analysis process “overview-first, zoom and filter, details-on-demand” (Shneiderman 1996), the heuristics examine the efficiency of each step, mostly navigation and selection, with reference from Heer and Shneiderman’s taxonomy of visualization interaction. Navigation is mainly used in orbiting and locating places in the 3D scene, while selection includes mouse hover and mouse click for toggling information.

To evaluate the effectiveness and cohesiveness of the visualization narrative, a set of heuristics for narrative visualization is adapted for this thesis, including three sub-facets—composition and layout for information distribution, reader experience, and credibility and trust related to data quality (Errey et al. 2025). Furthermore, visual narrative tactics and narrative structure tactics such as highlighting, transitional guidance and ordering (Segel and Heer 2010) are taken into account as refinement guidance.

Table 6. Internal Heuristic Walkthrough

Design facets	Sub-facets	Heuristic cues
Visual encoding	Color & Texture	· Are palettes semantically consistent and color-blind safe? · Do textures aid depth perception without visual clutter to the 3D model?
	Size & Shape	· Does the size of every element align with their priority?
	Typography	· Are fonts legible at default zoom? Are annotations explicit?
Interaction	Navigation	· Are orbit, pan and zoom discoverable? Is camera motion smooth? · Does navigation contribute to message conveying?
	Selection	· Can users toggle layers or hover for details without losing context? · Does selecting spatial-temporal data and numerical data mutually explaining?
Narrative	Layout & Composition	· Does the visualization flow logically? · Does viewports and visual components clearly convey message? · Is information density and visual complexity balanced?
	Reader experience	· Does the visualization personally relate to the reader's frame of reference?
	Credibility	· Does the narrative visualization identify a data source?

2.3.2. Formative Evaluation: Semi-structured Interviews

Even a carefully crafted heuristic review cannot fully anticipate the ways in which diverse audience will parse a visualization. Misinterpretation, inaccuracy, or inefficiency often emerge when visual encodings contradict cognitive expectations or data-to-design relationships are opaque. To complement the internal heuristic check, a brief formative evaluation was conducted with representatives of the intended audience.

Table 7 summarizes the interview framework, which foregrounds common communication breakdowns reported in the literature (Dasgupta et al. 2015). Although time constraints prevent formal user testing, two semi-structured interviews were carried out to elicit qualitative feedback on the prototype's communication strengths, limitations, and opportunities for improvement.

Prospective participants were contacted by e-mail roughly one week before the proposed meeting date. The e-mail message contained: 1) a brief study overview, 2) a hyperlink to the visualization prototype, and 3) the interview guide so that participants could review the questions (Table 7) in advance.

To capture distinct stakeholder viewpoints, the sample comprised an environmental specialist from a state coastal-management agency and a community-program manager from a local government office. Both participants possessed a thorough, working knowledge of shoreline-change issues in the study area, ensuring that their comments focused on the visualization's communicative utility rather than on basic content comprehension. Interviews were conducted via video call and lasted 30–90 minutes.

Table 7 Formative Evaluation Framework for Identifying Potential Communication Problems

Potential Communication problems	**Interview questions**
Misinterpretation	· What do you understand from the visualization at first glance? · Is it clear and informative?
Inaccuracy	· Does the visualization accurately represent the shoreline change data based on your knowledge? · Are there any critical details or data that you feel are missing or misrepresented?

Inefficiency	• Could you see this being used in your field informing policies? • Does this visualization engage you more than static maps or reports? • Is there anything confusing or visually overwhelming in the design? • Do the interactive elements enhance or hinder your understanding?
Suggestions for Improvements	• What changes would you suggest to improve clarity or effectiveness? • Is there additional data or context that would make this visualization more useful? • Would you prefer a different format (e.g., static infographic, animation, dashboard)?

3. Result: Visualization Design and Evaluation Interview

3.1. Visualization Design Outcome

Figure 8 shows the finished web-based visualization, Historical Evolution of the Grayland Plains Shoreline. When tested in Microsoft Edge browser on a mid-range laptop on a university Wi-Fi network (~200 Mbps download), the 3D scene loads in < 3 seconds, runs at > 60 FPS, and requires no plug-ins. This ensures fluid and responsive user experience on modern browsers.

Historical Evolution of the Grayland Plains Shoreline

Click and drag to rotate the scene
Left button: orbit
Right button: pan

About

This visualization explores coastal science communication, adapted from the study Historical evolution of the Columbia River littoral cell (Kaminsky et al., 2010).

Special thanks to Washington Department of Ecology for providing the data of historic shorelines and change rates.

Other Resources

North Willapa Bay Shoreline Erosion and Dune Restoration Graphics (Balderas Guzmán et al. 2025)

– Xiao, 2025

Figure 9. Visualization Outcome: Overview

3.1.1. Layout Components

Table 8 Visualization Layout Component

Component	Purpose	Key Content
3D viewport	Immersive geographic context	Historic shorelines, land-area change polygons, property parcels, and a textured topography/bathymetry surface
Control console	User-driven layer management	Year and rate toggles, additional data switches (transects, parcels)
Annotation panels	Additional information	Color legend, quantitative read-outs, photographs, and other resources

This three-panel layout exposes essential information first, while allowing users to reveal progressively richer detail as their questions evolve.

3.1.2. Interaction Features

The application adopts familiar, map-style camera controls. Users can orbit the 3-D scene by left-clicking and dragging, pan laterally by right-click-dragging, and zoom continuously with the mouse-wheel; a subtle on-screen hint in the upper-left corner reminds first-time visitors of this gesture vocabulary.

Temporal exploration is handled through two complementary toggles in the control console. The “Historic Shorelines” switch presents five buttons (1870, 1920, 1950, 2000, 2015) that instantly add or remove each shoreline polyline, allowing side-by-side or sequential comparison without camera reset. Directly beneath, the “Change in Land Area” toggle reveals a diverging-color raster that encodes net erosion (reds) and accretion (blues); an adjacent “Show/Hide Rate Values” button overlays the exact retreat or advance rates when quantitative detail is required, but otherwise keeps the view visually uncluttered.

To support site-specific discussion, additional toggle button let users overlay erosion-rate transects and property-parcel boundaries. These layers are hidden by default, preserving a clean first impression yet remaining instantly available for deeper information.

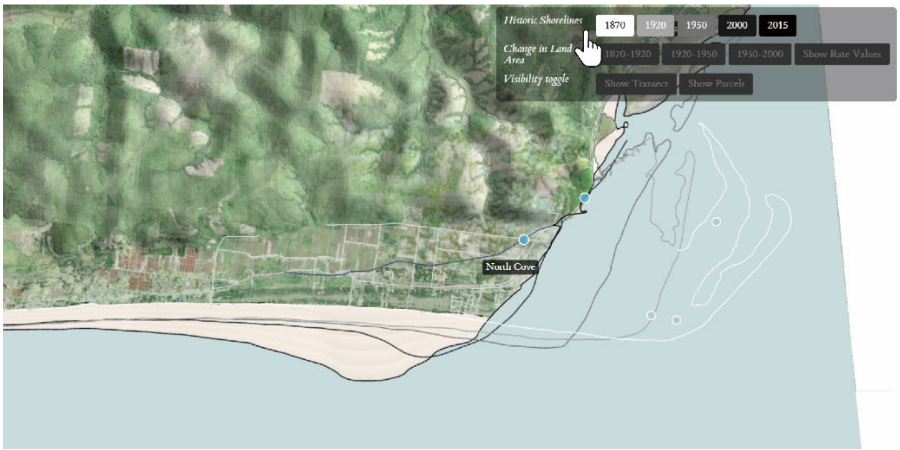
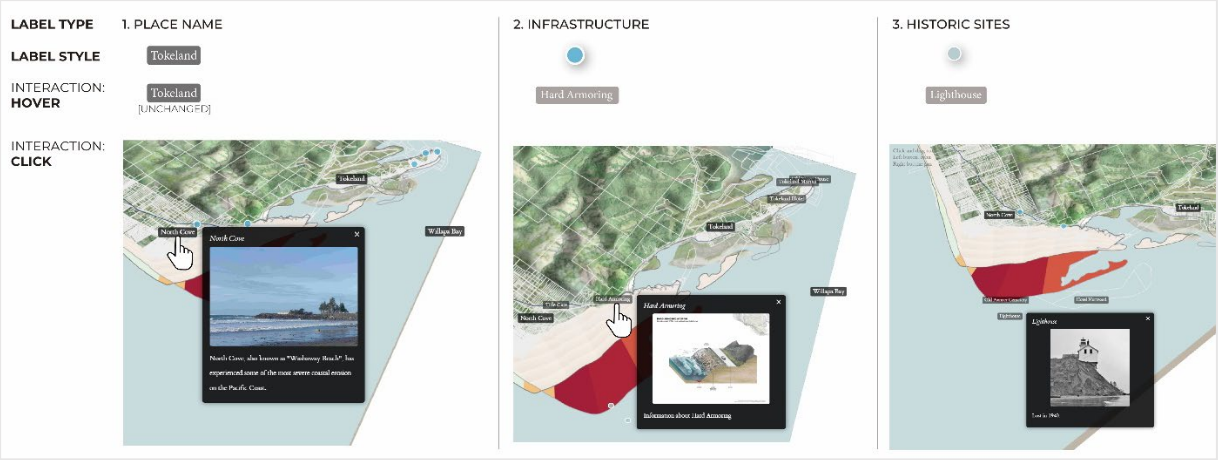


Figure 10. Historic Shorelines

Figure 11. Changes in Land Area

Figure 12. Parcels Visibility Toggle

Labels follow a three-tier hierarchy that balances context with legibility. Regional features such as Tokeland and Grays Harbor are permanently labelled with white text on black rectangles, anchoring the viewer throughout navigation. Existing infrastructure (for example, tide gate and hard armoring) appears as discrete light-blue points that reveal their names on hover and open concise information cards on click. Smaller historic landmarks, including the pioneer cemetery and lighthouse, are rendered as muted mini dots; they enlarge on hover and likewise expose photographs and brief introduction when selected. This progressive disclosure ensures that critical context is always visible while detail emerges only when the user requests it.



North Cove, also known as "Washaway Beach", has experienced some of the most severe coastal erosion on the Pacific Coast.

Information about Hard Armoring

Lost in 1940

Figure 13. Label Annotation

Immediately below the interactive viewport, a narrative panel provides the provenance, broader context, and supporting materials necessary for transparent interpretation. By collocating these materials with the visualization, the site maintains scientific rigor while remaining self-contained and readily shareable among policymakers, scientists, and the public.


About

This visualization explores coastal science communication, adapted from the study Historical evolution of the Columbia River littoral cell (Kaminsky et al., 2010).

Special thanks to Washington Department of Ecology for providing the data of historic shorelines and change rates.

Other Resources

North Willapa Bay Shoreline Erosion and Dune Restoration Graphics (Balderas Guzmán et al. 2025)

– Xiao, 2025

Figure 14. Narrative Panel

3.2. Interviews

Two qualitative interviews were conducted to gather feedback on the strengths, limitations, and suggestions for the prototype visualization, providing an empirical evaluation. The interviewees represented distinct stakeholder perspectives: an environmental specialist from a state agency, and a community program manager / engagement specialist from a local government office.

A shared point of positive feedback from both interviews was the interactive toggling between shoreline changes and spatial representations of change rates using color-coded polygons. This feature was widely recognized as intuitive and helpful in conveying spatial-temporal patterns. However, responses diverged on other aspects of the design, such as information density, labeling clarity, and preferred interface layout.

It is worth noting that the two interviewees viewed different versions of the prototype: the scientific audience was shown an earlier version of the visualization, while updates were made prior to the session with the community audience. These changes may have partially influenced the difference in reception and should be considered when interpreting their feedback.

Table 9 Critical Feedback from the Scientific Community

Problem type	**Cause of problem**	**Solution**
Chart appropriateness	3D scenes are hard for accurately reading data	Limit vertical rotation in 3D scene (polar angle < 60°), mostly showing the plan view.
Interactions	Navigating in 3D scene confuses	Limit orbit angle and zoom-in distance in 3D scene
Clutter	Z-fighting (surface overlap)	Hide unnecessary surface and avoid overlapping
	Color mixing of various visual variable	Choose different color hue for different elements
Distortion	Projection error	Align satellite texture with 3D surface
Communication gap	Lack of data explanation	Annotate jargon Explain data analysis process Show numerical data explicitly

Feedback from the scientific audience revealed skepticism toward the use of 3D scenes for data presentation. According to them, interpreting quantitative information in 3D is inherently difficult, a concern supported by previous findings (Saenz et al. 2017) This interpretive challenge can hinder audience engagement, as users struggle to extract precise meaning from spatial forms. The scientific perspective is shaped by disciplinary norms: although coastal science often collects data in three dimensions (e.g., shoreline profiles, bathymetry), it is typically visualized in 2D charts or maps to support accuracy and analytical clarity. This familiarity with 2D graphics may introduce bias against more immersive formats. Additionally, the complexity of 3D navigation involving multiple mouse interactions such as left-click orbiting and right-click panning, was reported as distracting, drawing attention away from the core message of the visualization.

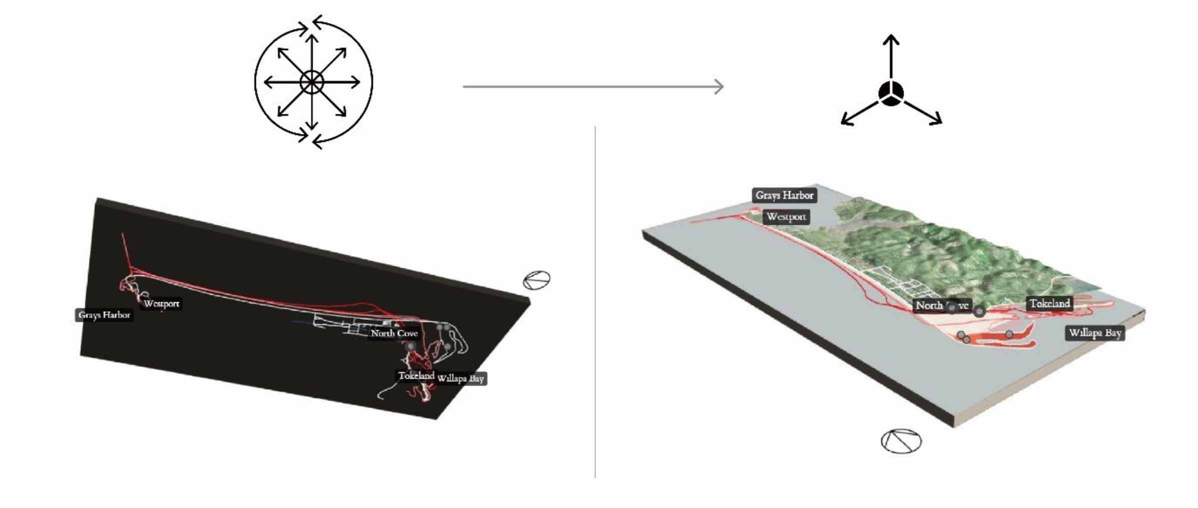


Figure 15. Refinement of 3D Navigation.

Left: Unrestricted navigation results in disorienting or ineffective perspective angles. Right: Controlled navigation improves user experience by limiting vertical rotation to 60°, constraining zoom range, and enabling cursor-centered zoom for more stable and intentional spatial exploration.

In contrast, the community audience responded more positively to the 3D scene, emphasizing its intuitive appeal. They noted that map reading is not a common skill among the public, and the 3D environment made it easier to identify places of interest. When zooming in, recognizable landmarks such as highways, drainage ditches, tide gates, and streams provided valuable orientation cues. This suggests that 3D visualizations may offer higher accessibility for non-technical audiences by supporting place-based interpretation.

To ensure a clear and usable 3D experience, common technical issues such as Z-fighting and pixelated textures had to be addressed during the modeling and rendering stages. Meanwhile, static 3D perspective illustrations (for example, Figure 3, right) were well-received by both interviewees. These curated perspectives offer the benefit of reduced interaction complexity while maintaining spatial expressiveness. The fixed viewpoint helps viewers focus on key spatial relationships without the distraction of navigation controls. As such, static 3D renderings may serve as a useful design reference for future development of more guided or semi-interactive visualization environments.

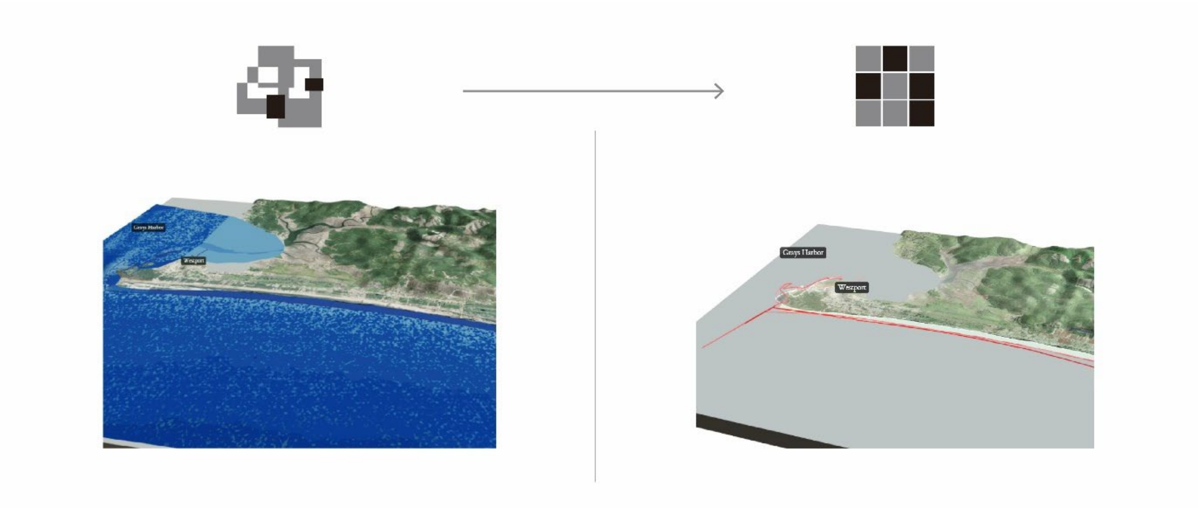


Figure 16. Refinement of Z-fighting.

Left: Visual flickering caused by Z-fighting, a rendering artifact that occurs when two surfaces are too close together relative to the overall model scale. Right: Improved visual clarity achieved by assigning explicit render order and removing overlapping or conflicting geometry.

Both interviewees responded positively to the basic interactive feature of toggling historical shoreline visibility. This feature was seen as intuitive and helpful for exploring coastal changes. However, they also offered targeted suggestions for improving the logic and structure of interaction. The scientific participant recommended allowing multiple historical shoreline layers to be displayed simultaneously for direct comparison (Figure 11), while change rate data should be restricted to display only one interval at a time (Figure 12). They also emphasized that change rate polygons should be viewed alongside the shoreline positions from the corresponding start and end years to preserve interpretability.

Building on this updated version, the community interviewee recommended the option to toggle off all historical data, leaving only the current shoreline visible to support place identification—particularly useful in public workshops or stakeholder meetings. Both interviewees emphasized the importance of keeping interaction mechanisms simple and ensuring that each step of the user’s experience leads to clear knowledge acquisition. They also highlighted the need to balance interactivity: encouraging user engagement without overwhelming them with too many options or controls.

Regarding annotations, the scientific interviewee stressed the importance of clarifying the calculation of change rates—particularly the definitions of "eras" and "intervals." They noted that eras refer to grouped historical shoreline datasets, while intervals represent the time spans between them. They also suggested that technical annotations such as transects used for rate calculations could be hidden from public-facing views to reduce cognitive load. In contrast, the community interviewee suggested using place-based annotations, including labels and popup photos, to help users recognize familiar areas. They further recommended integrating historic satellite imagery or reference photos from similar U.S. coastlines to show implementation outcomes, such as jetty construction or dune restoration projects.

Device accessibility was another key concern, particularly for community engagement. The community interviewee noted that mobile phones are far more commonly used than desktop computers among the public, making responsive mobile design essential. They also raised the issue of light/dark mode compatibility, noting that some display settings can cause color illegibility. These considerations highlight the need to test the visualization across different devices and display conditions during development.

Finally, the scientific interviewee proposed an alternative design layout (Figure 18) for managing multi-dimensional datasets, such as bathymetry. Rather than integrating all data into a single 3D scene, they recommended a dashboard-style interface with multiple synchronized 2D plan-view viewports. In this setup, each viewport could display a different dataset (e.g. shoreline positions, bathymetry, or sediment volume) in different eras, while allowing users to zoom to the same spatial scale for comparison. From the perspective of a scientific audience, this approach would better preserve data clarity while supporting more detailed scientific exploration. Reshaping the layout facilitate audiences’ analysis process (Lima 2009).

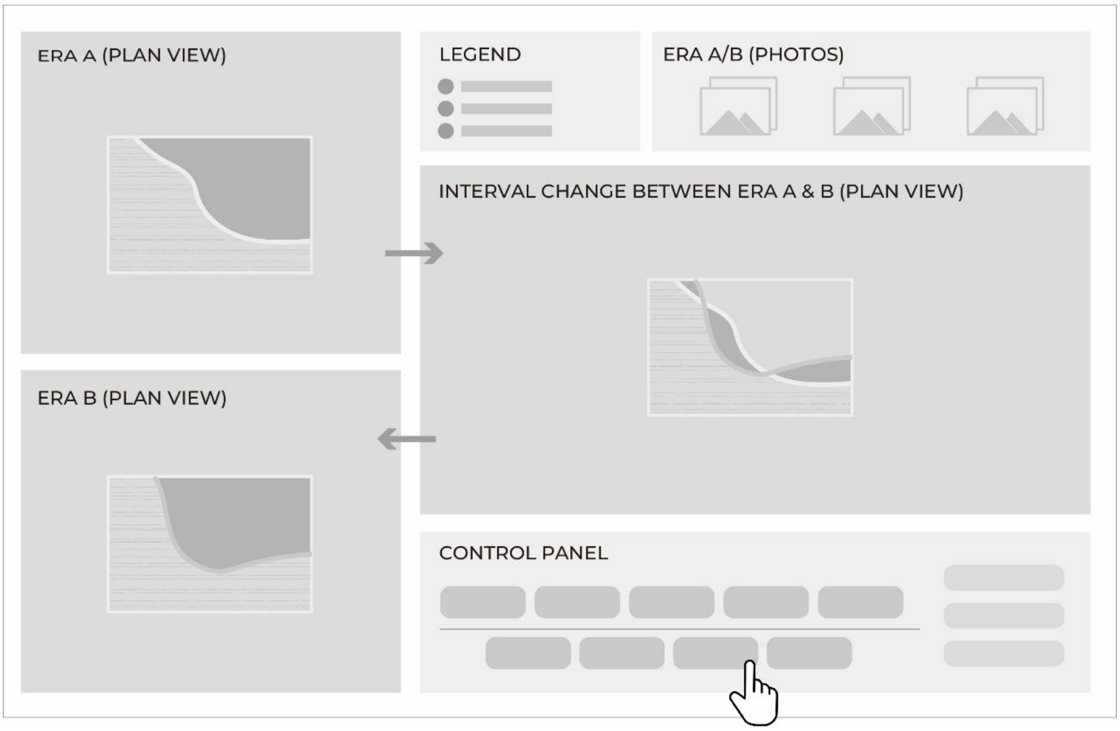


Figure 17. Alternative Dashboard-like Design Suggested by the Scientific Interviewee

4. Discussion

This study produced an interactive, web-based 3D visualization prototype to communicate shoreline-change research in the Grayland Plains. Pilot interviews with a scientific data specialist and a community program manager revealed both promise and limitations. The following sections synthesize key challenges that emerged and outline opportunities for future improvement.

4.1. Challenges

4.1.1. Data Gaps

Data shown in the visualization are limited due to unavailability, visual effect imperfection, loading performance optimization, and development time constraint. Insufficient data hampers the information density, thus constraining the audience's knowledge gained from the visualization.

To specify, some examples of data gaps and potential improvement are as follows. Inconsistencies in historical shoreline record prevent the development of a continuous shoreline evolution animation. Under this constraint, interpolation between historical shorelines can simulate the shoreline movement speed for a smooth animation. Another example can be seen in the incomplete jurisdiction data. Insufficient jurisdiction data obscures the relationship between eroding shoreline and property loss, which is an important reference for policy audience. A potential solution is to add a GIS layer of zoning data to the scene, while its visual and interaction effect needs to be embellished. Lastly, the separation between on-land topography and bathymetry produced a visual cliff at the shoreline. This thesis eventually filters out the bathymetry data, however in a more ideal situation, the bathymetry and upper-land topography are seamlessly blended.

4.1.2. Evaluation Framework

The formative communication evaluation framework (Table 7) was adapted from a set of descriptive taxonomy by Dasgupta (2015), originally devised for 2D static visualization in climate science. Although helpful for initial appraisal, it does not fully capture challenges unique to 3D, web-based, interactive environments—such as depth perception, camera constraints, and spatial navigation. A more comprehensive evaluation framework should address 3D-specific issues such as occlusion, z-order artefacts, and optimal camera zoning; and interaction-specific issues such as cognitive load of multiple controls, discoverability of hidden layers, and learnability of mouse/gesture paradigms.

Also, qualitative methodology introduced the subjective nature. Workflow and evaluation in this thesis provide a good starting point for science communication leveraging landscape architecture expertise, these experiences and findings need to be validated through broader tests. Mixed-method evaluation is expected in terms of combining qualitative interviews with quantitative usability metrics (e.g., task-completion time, error rate).

4.1.3. Audience Testing

Owing to time constraints, only two semi-structured interviews were conducted—one with a state data specialist, the other with a community program manager. While these sessions yielded valuable insights, a robust evaluation will require a larger, more diverse sample that includes engineers, municipal planners, elected officials, and local residents. Complementary methods such as online surveys, in-person workshops, or think-aloud usability tests, can capture a broader range of perspectives and quantify engagement levels.

4.1.4. Cross-scale Storytelling

The prototype visualizes processes that span an extensive littoral cell. Although pop-up photographs and place-name labels help ground the scene, the distant, bird's-eye perspective can dilute emotional resonance. Quantitative layers such as shoreline-change rates may appear abstract to non-specialists. Incorporating human-scale media, for example, street-level panoramas, historical photographs, or short narrative clips, could bridge the experiential gap and convey the lived consequences of coastal erosion more compellingly.

4.2. Opportunities for Future Study

Throughout the process of this thesis, several opportunities arise to pursue tangential topics in the overarching objectives, applying visualization to promote coastal science communication. Continued work on this subject is essential to enhance communication in a collaborative science-political interface and ultimately support inclusive and informed decision-making process for an environmentally friendly future.

4.2.1. Integration with Multi-variate Data

Coastal scientific data is multi-faceted. Besides spatial-temporal and multi-modal data explored in this thesis, there are multi-variate data consisting different attribute such as water temperature and salinity level, multi-run data from simulation with varied parameter setting, and multi-model data resulting from coupled simulation models (Kehrer and Hauser 2013).

Visualizing such heterogeneous information will require experimentation with alternative graphic forms (e.g., small-multiples, linked heatmaps, glyphs), optimization of pre-processing pipelines for web delivery, and further refinements in render-order management to maintain scene stability. Future work should also investigate narrative techniques that weave discrete variables into a coherent story without overwhelming users.

Regarding the issue of separation between on-land topography and bathymetry (as mentioned in 4.1.1 Data Gaps), a possible approach to seamlessly blend them is to explore both data alignment techniques and visual aesthetic strategies. From a data standpoint, more precise DEM merging techniques could be employed to interpolate across the shoreline transition, unifying resolution and coordination systems. This would reduce misalignment caused by datum mismatch or differing grid scales. On the visual side, aesthetic solutions such as gradient blending, shoreline contour buffers, or the use of semi-transparent transition zones could soften the seam, preserving legibility while avoiding abrupt visual breaks.

4.2.2. Evaluation Framework

While the current evaluation of 3D visualization are dominated by task-based studies (Amini et al. 2015; Herman and Stachoň 2016), a robust evaluation system for 3D interactive visualization is essential to target visual inefficiency with the novel features such as spatial depth and visual movement. Heer (2012)'s Taxonomy of interactive dynamics for visual analysis offers a good starting point to build a general evaluation framework on. Further work should combine qualitative visual analysis (e.g., cognitive walkthroughs, think-aloud protocols) with quantitative instruments (surveys, task-completion metrics, eye-tracking) to capture both subjective experience and objective efficiency.

4.2.3. Audience-Specific Visualization Strategies

Interview result indicates that domain experts and community stakeholders value different aspects of the visual representation with the same data. This interesting observation introduces a research opportunity to study how the audience attributes such as disciplinary background, spatial literacy and risk perception shape visual preference and comprehension. Such insights would: 1) Clarify problem definition in the Define phase by foregrounding audience-specific needs; 2) Guide design trade-offs in the Develop phase (e.g., 3D immersion versus 2D precision); and 3) Strengthen task selection in future evaluation instruments.

Targeted research on audience segmentation will therefore improve both the precision and the impact of coastal-visualization efforts.

4.3. Further Application

This visualization could be used as an effective tool for stakeholders in South Beach communities on Grayland Plains, for coastal hazard planning, infrastructure design, public education and policy development. For example, when used for coastal hazard planning and preparedness, planner and emergency managers can load projected storm surge or sea-level-rise scenarios atop the existing shoreline layers to assess flood extents in South Beach communities. By toggling between historical and projected shoreline positions, they can identify neighborhoods at highest risk and prioritize evacuation routes and shelter locations. For public engagement and education, local schools and visitor centers can incorporate the visualization into curricula or interpretive exhibits, using the model to show how South Beach has evolved since the early 20th century. Pop-up annotations—photographs of past jetty construction, archival maps, oral-history excerpts—help ground the data in lived experience.

Beyond its primary focus on science communication, the visualization tools and workflows explored in this thesis have broader applications within the landscape architecture field. Specifically, they offer potential benefits for enhancing site analysis, client communication, and design outcome presentation.

While GIS and 3D modeling are already widely used in landscape architecture—GIS for site inventory and analysis, and 3D modeling for form generation and visualization—these tools are often deployed in isolated phases of the internal design process. Traditionally, landscape design is communicated to clients and stakeholders through static deliverables such as site analysis diagrams, conceptual sketches, perspective renderings, and sectional drawings, typically compiled into comprehensive presentation boards or reports. With the advancement of visualization technologies, there is a growing trend toward incorporating multimedia content into design communication. Among these, video walkthroughs have become a popular method of conveying spatial experiences. However, such formats still rely on pre-defined perspectives chosen by the designer.

This thesis proposes a more dynamic alternative: integrating spatial-temporal data into web-based 3D environments. By migrating models from limited-access design software (e.g., Rhino 3D) to publicly accessible webpages using Three.js and open standards like glTF, the visualization becomes both portable and participatory. Interaction features, such as free navigation, visibility toggling, and real-time layer control, allow users to explore the virtual environment on their own terms.

This level of interactivity empowers clients and stakeholders to move beyond passive viewing and engage directly with the design. It enables comparison between design options, encourages exploration of areas of interest, and ultimately fosters more informed and collaborative feedback. In this way, interactive 3D visualization not only enriches the communication process but also supports more inclusive and consensus-driven design outcomes. Meanwhile, the urge to apply the latest technologies should be balanced with more comprehensive and critical evaluation of the application (Lovett et al. 2015).

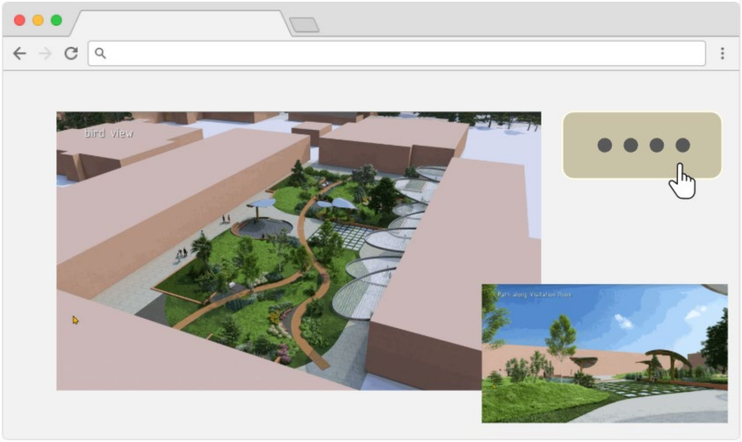


Figure 18. Potential Use in Landscape Design Presentation

5. Conclusion

This thesis has presented a study of 3D interactive web-based visualization design for coastal science communication. In this process, the author has explored visualization theories, tools, scientific data, potential audience and context, and structured the workflow by the define-develop-refine framework. Further, the thesis has demonstrated the strength and weakness of the visualization prototype by interviewing audience representatives from different backgrounds.

A three-phase *Define—Develop—Refine* framework was articulated and applied to the full pipeline. As exhibited in the thesis, 1) Define: establish communication goals, inventory available data, and sketch user scenarios for policymakers, agency scientists, and community advocates. 2) Develop: prototype rapidly from cleaning numerical and spatial-temporal data, generating and naming 3D model, to assembling an interactive scene and compressing assets for quick webpage loads. 3) Refine: iterate through heuristic walkthroughs and semi-structured interviews to examine visual encoding, interactive features and narrative.

For the visualization prototype, interviews demonstrate the split reception for 3D interactivity, depending on the viewer's background. The community manager praised the 3D scene for its intuitive, place-based orientation—confirming that immersive views can lower the cartographic literacy barrier for non-experts. The coastal-data specialist, by contrast, preferred 2D maps and requested side-by-side 2D dashboards for precise comparison. Both users valued the ability to toggle historical shorelines and change-rate layers, but both also cautioned against visual clutter and jargon. These observations indicate the need to meticulously examine audiences' potential actions to avoid confusion, and reinforce a core lesson from the literature review: effective visual communication is audience specific. Additionally, the science-policy interface involves interdisciplinary audiences, however, defining a prior focused audience group is essential to efficiently implement the specific visualization goal.

For landscape architects, fluency in data wrangling and web development can extend traditional strengths such as 3D modelling and storytelling, in order to amplify scientific data representation on to globally accessible platforms. The full pipeline in this thesis, from data acquisition and GIS pre-processing, through Rhino/Grasshopper modelling, to real-time rendering with Three.js, D3, and Svelte. Publishing the final scene on GitHub Pages (https://github.com/little-x/visCRLC) demonstrated that technically demanding 3D content can be served at scale without proprietary software or back-end infrastructure. The documented toolchain offers a reproducible template for both science communication and landscape design teams.

The thesis has implications for a number of areas: development of web-based 3D visualization for historical shoreline changes; use of these visualization participatory communication at science-policy interface; increase the accessibility of scientific data;

future study opportunities and further application for landscape design presentation.

In summary, the study exhibits 3D interactive web-based visualization can act as a powerful communication tool between coastal science and policy engagement, with design choices tuned for the cognitive habits and practical needs of each audience. By positioning landscape architecture as both the communicator and technologist, the thesis provides an insight that informative and inviting visualization could be a routine component in coastal resilience practice.

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