Measurements of wave runup and groundwater at Ostional beach in context of the TURTLE project

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Cover: Olive ridley turtle on Ostional beach (Luc Nederstigt, 2024)

Preface

This report presents the findings of an interdisciplinary study focused on advancing the protection of sea turtle nesting sites, specifically at Ostional Beach, through the integration of hydraulic engineering, collaborative strategies, and coastal management. The study is composed of three interconnected parts, each exploring different parts of the TURTLE project and contributing to the overarching goal of safeguarding these sensitive coastal environments.

The first part of the study examines wave runup and its interaction with the groundwater table, providing insights in these crucial dynamics for sea turtle nesting sites. The second part analyzes collaboration within the TURTLE project, investigating communication dynamics and cooperation among project partners with the goal of designing a framework aimed at improving future collaboration across the project. The third part focuses on coastal squeeze mitigation, discussing potential strategies to address this threatening phenomenon for sea turtle nesting sites. By linking together these three disciplines, this study provides a comprehensive overview of the challenges faced by the TURTLE project and provides valuable insights that can be applied to similar conservation efforts in other parts of the world.

This work would not have been possible without the guidance, support, and encouragement of many individuals and organizations. First and foremost, we extend our heartfelt gratitude to Dr. José Antolínez, our main supervisor, for his unwavering support in setting up this project, guiding us through potential research directions, and helping us overcome challenges along the way. Your guidance and encouragement made this remarkable experience possible. We also wish to thank our master track supervisors, Dr. Erik-Jan Houwing and Dr. Hayo Hendrikse, for their invaluable support in steering the specific components of this research. Additionally, we are grateful to Ir. Jakob Christiaanse and Ir. Meye van der Grinten for their valuable input during our meetings in Costa Rica, which greatly enriched this study. Our deepest thanks go to the staff at the Universidad de Costa Rica for welcoming us so warmly and making us feel at home from the moment we arrived. A special acknowledgment goes to Dr. Felipe Calleja Apéstegui, our supervisor in Costa Rica, for his tireless availability and willingness to assist, even when we were far from the university conducting fieldwork at the beach. We are also deeply appreciative of Ing. Diego Cornejo Corrales and Ing. Ronald Víquez Acosta for their expertise in helping us design and install the fieldwork setup during our first week at the beach. During our time at the beach, we were fortunate to have the assistance of Carlos Andrés Arrieta Rojas and Jesus Anchia Villegas from the university's research institute. Their readiness to answer our questions and them allowing us to store our equipment at the station was invaluable to the success of our fieldwork. Finally, we extend our sincere gratitude to all the interviewees of the collaboration study, who took time out of their busy schedules to participate in this study. Your enthusiasm and insights were critical to understanding the collaborative dynamics within the TURTLE project. Without your valuable contributions, this study would not have been possible.

¡Pura vida!

MDP 368
San José, Costa Rica, November 2024

Abstract

Sea turtle nesting beaches are under increasing pressure from climate change, rising sea levels, and human activity, making the protection of critical habitats like Ostional Beach, Costa Rica, an urgent priority. This study integrates the analysis of wave runup dynamics, groundwater behavior, stakeholder collaboration, and coastal squeeze mitigation to address the unique challenges at this vital olive ridley turtle nesting site.

Wave runup was examined using timestack imagery analysis. Two automated extraction models—entropy-only and entropy-saturation—were compared against manually digitized data. Results show that the entropy-only model is more reliable in capturing peak wave run-up values, a critical measure for understanding inundation risks. Challenges in accuracy, particularly for the entropy-saturation model, were linked to the site's unique environmental conditions, such as dark volcanic sand. The findings fill a gap in understanding how specific extraction methods perform under unique site conditions, with implications for improving future modeling efforts.

Groundwater dynamics were studied using pressure sensors installed in custom-built wells, revealing significant interactions with tidal forces. These measurements highlighted the role of tidal cycles in influencing groundwater levels, providing crucial insights into the potential for nest inundation. These findings extend existing knowledge by combining tidal and hydrodynamic factors specific to turtle nesting sites.

Collaboration within the TURTLE project was analyzed through semi-structured interviews and structural evaluation of partner interactions. A tailored framework was developed to enhance communication and coordination among stakeholders, addressing identified gaps and leveraging existing strengths. This framework contributes to more effective project management and the application of scientific insights in conservation strategies.

To mitigate coastal squeeze—a phenomenon where natural habitats are compressed by rising sea levels and human development—the study evaluated strategies such as foreland restoration and managed retreat. Findings suggest that integrating habitat restoration with community involvement is critical to preserving the ecological and social balance at Ostional Beach.

This study takes an interdisciplinary approach to explore how wave runup, groundwater behavior, and collaboration strategies can be effectively combined to support conservation efforts. The results stress the need for tailored, site-specific solutions that blend engineering, ecological, and social perspectives to protect endangered species and their habitats. By bridging knowledge gaps and offering practical recommendations, the research bolsters both local and global initiatives aimed at preserving vulnerable coastal ecosystems

Contents

1
Introduction

1.1. Introduction to the olive ridley and its mass-nesting

Ever since the interaction between sea turtles and humans began, sea turtle populations have degraded significantly worldwide (Lutz et al., 2002). At the moment of writing, two of the seven species of turtles are considered critically endangered, one as endangered, and two other species as vulnerable by IUCN-SSC Marine Turtle Specialist Group (n.d.).

Initially, the degradation of the sea turtle populations could be attributed to direct fishing of the sea turtles (Lutz et al., 2002). More recently, population declines have been driven by factors like by-catch, coastal development, poaching and egg harvest, light pollution, and climate change (Beber et al., 2024). We cannot fully know what roles sea turtles played centuries ago, but we know that today sea turtles play a vital role in ocean ecosystems by maintaining seagrass beds and coral reefs. Seagrass beds and coral reefs are important habitats for all kinds of marine life, which help balance food webs and facilitate nutrient cycling from land to sea (Oceana, 2010).

The most abundant turtle species is thought to be the olive ridley (*Lepidochelys olivacea*), this species of turtle is listed as vulnerable by Abreu-Grobois et al. (2008). The olive ridley is so abundant due to the mass synchronous nesting behavior that characterizes this species of turtle (Valverde et al., 2012). These turtle mass nesting events are also called *arribadas* (this word translates to arrivals in Spanish). During an arribada, thousands of female turtles migrate to the coast to lay their eggs simultaneously (Bézy et al., 2020). Arribadas occur in multiple places on different continents but are most frequent and largest in Mexico and Costa Rica. In Costa Rica, Playa del Ostional on the Nicoya peninsula has one of the largest and most frequent arribadas in the world (SWOT, 2021).

1.2. Turtle nesting beaches under pressure

The beaches where turtles nest are under pressure by a multitude of factors like egg harvesting, but also by sea level rise, which causes a significant loss of coastal habitats and increases the risk of nest inundation (Valverde et al., 2012). A small rise in sea level will cause a big loss in habitat area (Lutz et al., 2002, Fish et al., 2005, Fuentes et al., 2011). According to Lutz et al., 2002, increased sea levels can also contribute to altering the factors controlling the incubation of the turtles like moisture, salinity, and gas exchange.

Climate change also influences the frequency and intensity of storms. The combination of increased storm frequency, increased wave runup, and SLR increases the chance of nest inundation, which increases egg mortality and drastically decreases hatchling success (Beber et al., 2024). A study performed by Pike et al. (2015) found that inundation of green turtle eggs by 1 or 3 hours decreased egg viability by 10%, and submersion of the eggs for 6 hours decreased the viability by 30%, being even more vulnerable in the first two weeks after being laid and just before hatching.

Thus, gaining a better understanding of the hydrodynamics, and in particular wave runup and groundwater table dynamics of turtle nesting beaches is of importance for understanding how to better protect the species. With more understanding of the hydrodynamics on the turtle nesting beaches, we can make better predictions on the risks that are posed by the groundwater table on the turtle's nests. These predictions will inform better strategies for the protection or relocation of nests (Ware et al., 2019).

In direct response to these challenges, the TURTLE project was launched as a global research initiative. With sea turtles playing a critical role in coastal ecosystems, the project aims to develop nature-based solutions that not only enhance flood protection for coastal regions but also safeguard and restore turtle nesting sites. By integrating the technical expertise of hydrodynamic modeling, the practical application of coastal engineering, and the ecological insights from conservation efforts, TURTLE seeks to provide actionable strategies for mitigating the degradation of these vital habitats (TKI Deltatechnologie, 2024).

One of the central goals of the TURTLE Project is to bridge the gap between conservation needs and engineering solutions. The project conducts fieldwork to measure hydrodynamic processes, such as wave runup and groundwater dynamics, at key nesting sites like Galveston Bay, Texas. By integrating this data with global analyses of beach sediment characteristics and environmental conditions, TURTLE aims to develop tools that guide both short-term and long-term decision-making for coastal managers. This includes the creation of a metamodel for assessing seasonal flood risks to turtle nests, as well as engineering guidelines that enable sustainable flood protection measures without compromising the integrity of turtle nesting habitats (TKI Deltatechnologie, 2024).

To gain a more comprehensive understanding of how to ensure the long-term preservation of the Ostional nesting beach, it is crucial to thoroughly examine the current threats facing this unique ecosystem. Identifying these threats provides a foundation for developing effective strategies to mitigate them. Equally important is engaging with the local community to hear their perspectives on potential solutions. Local knowledge and opinions are invaluable, as they often reflect a deep connection to the area and practical insights into what might work in the context of Ostional's environment and culture.

1.3. Research objectives

This study is composed of three interconnected parts, each with its specific objective, all of which contribute to the overarching goal of protecting sea turtle nesting sites. These parts span multiple disciplines, linking together to provide actionable insights for the TURTLE project. In the following sections, each objective is discussed in detail, highlighting how they come together to emphasize the importance of an integrated, multidisciplinary approach.

1.3.1. Hydraulic fieldwork

The dynamics of wave runup and its interaction with the groundwater table are important in coastal engineering and have been studied thoroughly. This research aims to connect this knowledge about hydrodynamics with the measurements performed on the turtle nesting beach in Ostional which is essential to predict the impact of natural and anthropogenic factors on these sensitive coastal zones.

The challenge lies in accurately measuring and modeling wave runup and groundwater interactions in a complex, real-world environment. The dynamic coastal conditions at Ostional Beach, influenced by varying wave patterns, groundwater flow, and tidal changes, as well as the environmental conditions like heavy rainfall in raining season and low sun exposure, pose significant challenges to reliable data collection. The nesting success of sea turtles can be impacted by these factors, making precise measurements crucial. The goal of the fieldwork is to make measurements of two crucial coastal processes; wave runup and beach groundwater dynamics.

1.3.2. TURTLE project collaboration

The objective of the collaboration study is to analyze the roles and communication dynamics of the actors involved in the TURTLE project, with the goal of enhancing future collaboration. The study aims to identify current strengths and challenges in stakeholder interactions, map the existing communication structure, and understand the needs and expectations of the partners for future cooperation.

Ultimately, the objective is to develop a framework that fosters more effective collaboration, ensures that project outcomes are shared efficiently, and facilitates better alignment between partners. This framework will provide actionable insights for improving communication and overall project coordination, leading to a stronger and more cohesive research effort.

1.3.3. Coastal squeeze mitigation

The primary objective of the hydraulic structure study is to explore and highlight potential mitigation measures to address the issue of coastal squeeze affecting the Ostional sea turtle nesting beach. Coastal squeeze, a phenomenon where natural habitats are compressed between rising sea levels and human development, poses a significant threat to this critical nesting area. By identifying and evaluating possible solutions, the study aims to contribute to the preservation of the beach's ecological integrity.

Key topics to be addressed include a detailed analysis of various mitigation measures, as well as an assessment of their short-term and long-term impacts—both positive and negative. The discussion will encompass a range of factors critical to the beach's health and sustainability. Special attention will be given to the effects of these measures on wave run-up, which influences the beach's exposure to tidal forces, groundwater stability, which is crucial for maintaining the physical and chemical environment needed for successful nesting, and beach morphology, which affects the turtles' ability to access and utilize the area.

By focusing on these interconnected aspects, the study seeks to provide actionable insights and a balanced understanding of how possible mitigation measures can be leveraged to protect Ostional's nesting habitat while minimizing unintended consequences.

1.3.4. Integrated approach

This study adopts an integrated approach, combining hydraulic fieldwork, a collaboration analysis, and a coastal squeeze mitigation strategy to address the challenges faced by sea turtle nesting beaches. Each discipline provides unique insights while complementing the others, the hydraulic fieldwork examines dynamics that are critical to sea turtle nest survival, the collaboration analysis ensures that these results are applied and distributed among partners as effectively as possible while the coastal squeeze study evaluates mitigation measures for the loss of habitat occurring at the beach.

By combining these different perspectives, a comprehensive, holistic understanding of the challenges at Ostional Beach is provided by the study, bridging the gaps between the disciplines involved. The TURTLE project itself exemplifies the value of such integration, merging coastal engineering, conservation efforts, and biology to tackle the complex issues faced by sea turtle nesting sites. Similarly, this study demonstrates how multidisciplinary collaboration is essential for providing a full-scale description of the challenges faced by a sea turtle nesting site.

1.4. Research questions

From the integrated approach, the main research question of this study can be formulated as:

How can a multidisciplinary approach, integrating hydrodynamic analysis, collaborative strategies, and coastal engineering interventions, be applied to protect and sustain turtle nesting beaches?

Following these objectives and the main research question, the following field-specific research questions are formulated:

RQ1. How can wave run-up dynamics at Ostional Beach be accurately measured, considering the site-specific conditions and limitations of different measurement methods?

RQ2. How can the groundwater table dynamics at Ostional Beach be measured and what are its characteristics and impact on the turtle nesting site?

RQ3. How can collaboration in the TURTLE project be enhanced by addressing current challenges while leveraging existing strengths?

RQ4. What potential interventions can address coastal squeeze at Ostional Beach, and how do they compare in terms of wave run-up, groundwater stability, and beach morphology?

The field-specific research questions will be used to address the questions within each field of study and will collectively contribute to answering the main research question.

1.5. Report structure

This report is organized into seven chapters. Chapter 1 is the introduction and sets the context, highlighting the importance of Ostional Beach for olive ridley turtles and the challenges faced. Chapter 2 covers a literature review of wave run-up, groundwater dynamics, and coastal squeeze impacts, along with relevant methods and strategies.

Chapter 3 explains the site selection, data collection for wave run-up and groundwater, collaboration analysis, and evaluation of mitigation measures. Chapter 4, results, details findings on wave dynamics, groundwater behavior, collaboration, and coastal squeeze mitigation.

Chapter 5, discussion, interprets these results, focusing on conservation implications and challenges. In chapter 6, the conclusions summarize findings and propose recommendations. Finally, the references and appendices provide sources and supporting materials.

2

Literature review

2.1. Wave runup

2.1.1. Total water level

At the coast, the sea level is influenced by many factors. Tides, regional dynamics like storm surges and sea level anomalies coherent with el niño - southern oscillation, and changes in mean sea level like sea level rise combined produce spatially and temporally varying mean water levels. At the beach, water levels are further influenced by wave transformations in the surf zone through wave runup (Serafin et al., 2017).

The Total Water Level (TWL) at the beach is defined as the sum of wave runup (R) and still water levels (SWL). The total water level can be formulated as follows;

$$TWL = SWL + R \tag{2.1}$$

2.1.2. Wave runup

When waves approach the coast, a large part of the energy stored in the waves is dissipated through processes like wave breaking. The energy left that reaches the beach is converted into potential energy in the form of wave runup (Stockdon et al., 2006). Wave runup is a very important process in many coastal planning, nearshore oceanography, and coastal engineering applications.

The wave runup $R(y, t_i)$ is defined as the set of discrete maxima of the water elevation measured on the foreshore. Runup is a result of two different processes:

1. Maximum setup $< \eta >$ - Time-averaged water level elevation at the shore.
2. Swash $S(y, t_i)$ - Time-varying fluctuations of the water level around the mean.

The first process, setup, is the elevation of the mean water level driven by a cross-shore gradient in radiation stress. This results in a higher mean water level at the shoreline than further from the coast (Longuet-Higgins & Stewart, 1964).

The swash motion is generally defined as the time-varying intersection between the coast and sea (Stockdon et al., 2006). Swash represents the standing character of monochromatic waves which, according to Miche (1951) consist of two components; a progressive and a standing component. The progressive character of the waves has its energy dissipated during wave breaking when it nears the shore. The standing character arises from the reflection of waves from the coast, resulting in the swash motion.

Several studies have investigated the roles of infragravity waves and incident waves on the swash motion for different sites. For example, Guza and Thornton (1982) found that swash scales linearly with infragravity wave height but energy from the incident waves becomes saturated due to wave breaking in the surf zone. Other studies have confirmed this linear relation between the swash movement due to infragravity waves and offshore wave height H_0 (Holman & Bowen, 1984; Howd et al., 1991; Raubenheimer & Guza, 1996). A general expression for 2% exceedance wave runup ($R_{2\%}$) and swash (S) is proposed as follows (Stockdon et al., 2006):

$$R_{2\%} = <\eta> + \frac{S}{2}, \text{ where} \tag{2.2}$$

$$S = \sqrt{(S_{IG})^2 + (S_{inc})^2} \tag{2.3}$$

Here, S_{IG} is the swash movement due to infragravity waves and S_{inc} is the swash movement due to incident waves.

2.1.3. Empirical formulations

Wave runup predictions involve a lot of complexity due to the situation in the surf and swash zone with many variables and unknowns. Therefore, wave runup is usually not computed using numerical modeling but with parameterizations, simplifying the situation (Da Silva et al., 2020).

These empirical formulations for estimating wave runup usually contain simple parameters like the beach profile (β), offshore wave height (H_0), and offshore wave length (L_0). These three parameters are often used to describe a beach state and often expressed in a non-dimensional surf similarity parameter called the Iribarren number (Battjes, 1974):

$$\zeta = \frac{\beta}{\sqrt{H/L_0}} \tag{2.4}$$

Wave runup is usually expressed in a maximum runup (R_{max}) or the runup exceeded by the highest 2% of waves ($R_{2\%}$).

A widely used empirical formulation for predicting wave runup is the parameterization developed by Stockdon et al. (2006). $R_{2\%}$ can be determined using the significant wave height (H_s), offshore wave length (L_0), and beach slope (β). This parameterization is popular because it is very general, which makes it applicable to many (sandy) beaches and it uses only three variables which makes it easy to use. Caution should still be taken when using parameterizations like the one by Stockdon et al. (2006), because when there is little information on the underwater cross-shore beach profile available, parameterizations can introduce large errors in the estimation of wave runup (Da Silva et al., 2020).

Based on a large dataset, Stockdon et al. (2006) formulated parameterizations for all sandy beach types (dissipative, intermediate, and reflective). In his parameterization, a distinction is made between dissipative beaches ($\zeta_0 < 0.3$) and intermediate and reflective beaches. On dissipative beaches, the slope is not taken into account for the prediction of runup, which means it is only dependent on offshore wave height and wavelength. Stockdon et al. (2006) suggests the following formula for estimating wave runup on dissipative beaches:

$$R_{2\%} = 0.043\sqrt{H_0 L_0} \tag{2.5}$$

The general expression for all beaches (dissipative, intermediate, and reflective) is as follows (Stockdon et al., 2006):

$$R_{2\%} = 1.1 \left(0.35\beta\sqrt{H_s L_0} + \frac{\sqrt{H_s L_0 \left(0.536\beta^2 + 0.004\right)}}{2} \right) \quad (2.6)$$

2.1.4. Wave runup measurement techniques

Over time, wave runup measurement techniques have advanced significantly, moving from traditional manual methods to automated video analysis. These advancements have increased objectivity, efficiency, and temporal resolution in data collection.

Direct measurement techniques

The dual resistance wire technique uses two resistance wires placed across the beach. As the swash moves up and down, it alters the resistance of the wires, allowing water level measurements (Aarninkhof et al., 2005; Bailey & Shand, 1994). While objective and easily digitized, this method faces challenges in sensitivity, phase accuracy, and deployment in high-energy environments.

Another direct method, visual observation with stakes, involves positioning a graduated pole on the beach to record the highest point reached by each wave (Bailey & Shand, 1994). Although simple and inexpensive, it is subjective and labor-intensive, requiring continuous monitoring and manual recording.

Video analysis techniques

With the advent of video cameras, researchers began recording the swash zone, initially using hand-picking the swash edge from each frame (Aarninkhof et al., 2005). This approach improved temporal resolution and allowed more continuous data collection than direct measurement techniques; however, the early stages of video analysis remained subjective and labor-intensive.

To overcome these limitations, automated video analysis techniques were developed, using advanced image processing algorithms to detect and track the swash edge from video recordings automatically. These methods reduce operator subjectivity and the need for labor-intensive monitoring (Bailey & Shand, 1994).

2.1.5. Coastal imagery

Recording the shoreline with a camera and applying photogrammetry-based image processing techniques can effectively capture wave runup. The video footage must be processed and corrected for camera distortion before generating various types of images.

Pinhole camera model

Cameras can be described using various models that vary in complexity and application (Cattaneo et al., 2015). Among these, the pinhole camera model serves as a fundamental framework for understanding more intricate camera systems and is extensively used in computer vision and graphics to represent the relationship between a three-dimensional scene and a two-dimensional image (Ikeuchi, 2021). This model assumes an ideal pinhole through which light rays from the scene pass to project an inverted image onto the image plane (Cattaneo et al., 2015; Clarke & Fryer, 1998). The pinhole acts as the optical center, and the distance between the pinhole and the image plane is referred to as the focal length. The intersection of the optical axis and the image plane is known as the principal point, located at the midpoint of the image.

The pinhole camera model effectively describes how three-dimensional real-world coordinates (x, y, z) are translated into two-dimensional image coordinates (U, V). This transformation is governed by the projection matrix below, which encapsulates the camera projection process (Bruder & Brodie, 2020; Hartley & Zisserman, 2003).

$$\begin{bmatrix} U \\ V \\ 1 \end{bmatrix} = * \begin{bmatrix} f_x & 0 & U_0 \\ 0 & -f_y & V_0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} r_{11} & r_{12} & r_{13} \\ r_{21} & r_{22} & r_{23} \\ r_{31} & r_{32} & r_{33} \end{bmatrix} \begin{bmatrix} 1 & 0 & 0 & -C_{XW} \\ 0 & 1 & 0 & -C_{YW} \\ 0 & 0 & 1 & -C_{ZW} \end{bmatrix} \begin{bmatrix} X_W \\ Y_W \\ Z_W \\ 1 \end{bmatrix} \quad (2.7)$$

$$= \quad * \quad K \quad \cdot \quad R \quad \cdot \quad T \quad \cdot \quad \begin{bmatrix} X_W \\ Y_W \\ Z_W \\ 1 \end{bmatrix} \tag{2.8}$$

The projection matrix can be decomposed into three essential sub-matrices, each encoding a critical aspect of the camera's function (Bruder & Brodie, 2020; Hartley & Zisserman, 2003; Sturm & Maybank, 1999). The intrinsic matrix K describes the internal characteristics of the camera within the framework of the pinhole camera model, detailing parameters such as focal length and the location of the principal point. The rotation matrix R represents the camera's orientation in space through three rotation angles: azimuth, tilt, and swing. This matrix facilitates the transformation of world coordinates into the camera's own coordinate system. Finally, the translation matrix T defines the camera's positional coordinates, specifying the translation from the world origin to the camera center.

Distortion and calibration

Real cameras deviate from the ideal pinhole model due to the presence of lenses (Bruder & Brodie, 2020; Clarke & Fryer, 1998). The use of lenses introduces various distortions, namely radial distortion, which causes straight lines to appear curved in the captured image, and tangential distortion arises when the lens is not perfectly aligned with the image sensor (Hartley & Zisserman, 2003; Ikeuchi, 2021). Correcting these distortions, or *rectification*, is critical for obtaining accurate, geometrically correct scene representations (Cattaneo et al., 2015; Clarke & Fryer, 1998; Ikeuchi, 2021). Distortion correction is typically modeled using a polynomial function, with the coefficients determined during camera calibration (Cattaneo et al., 2015; Tsai, 1987).

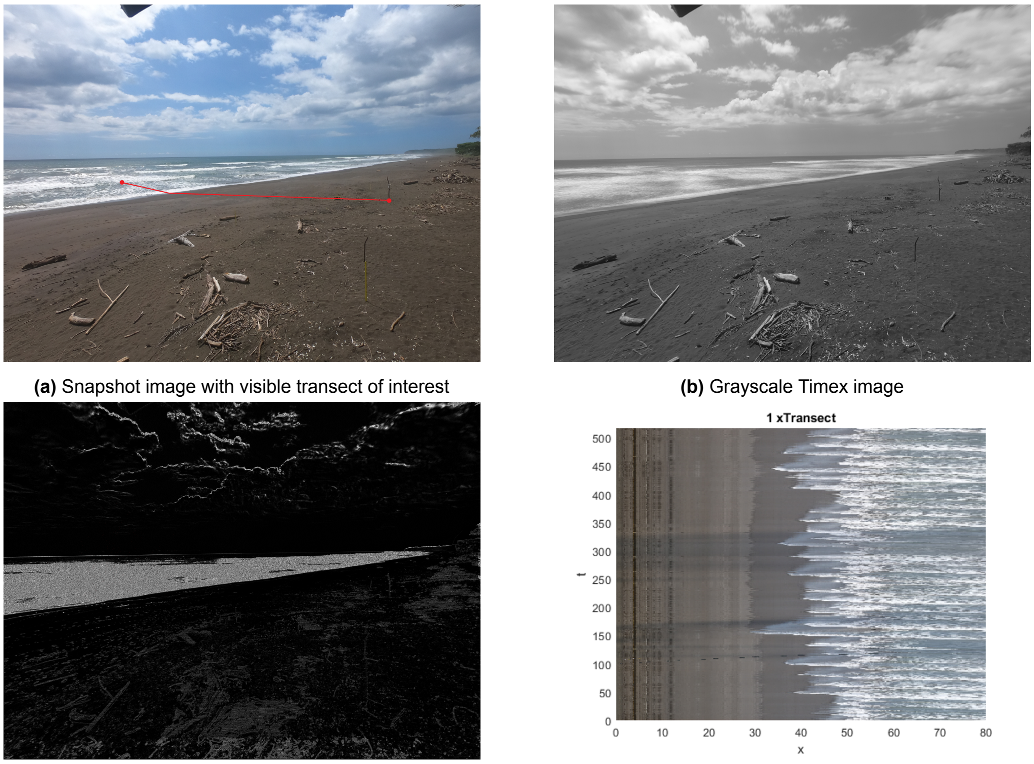
Camera calibration techniques estimate the parameters of the camera model, including distortion coefficients (Cattaneo et al., 2015). Among the various techniques, metric calibration methods are the most commonly employed. A widely used technique, known as Zhang's method, requires capturing images of a planar checkerboard pattern from multiple orientations to estimate both the intrinsic and distortion coefficients (Z. Zhang, 1999).

Types of images and their applications

Coastal images are essential for a wide range of applications in coastal management, research, and conservation. They offer a cost-effective, non-intrusive, and efficient means of collecting valuable data about coastal processes and dynamics. Various types of coastal images with different processing techniques and applications are listed below and visualized in Figure 2.1

1. **Snapshot images:** Snapshot images can be used for a variety of purposes in coastal management and research. For example, analyzing the local bathymetry, or as Simarro et al. (2015) states, the detection of beach cusps.
2. **Time-exposure (Timex) images:** These images are produced by averaging the pixel intensity over a substantial number of snapshots over a specific time interval, typically around 10 minutes. This averaging emphasizes areas of consistent wave breaking, which can be utilized to delineate preferred wave breaking zones in the surf zone and to estimate intertidal and subtidal bathymetry (Simarro et al., 2015).
3. **Time-variance images:** These images are generated by calculating the variance of pixel intensity values over time for each pixel location. High variance values usually correspond to areas exhibiting dynamic (water) movement, such as the swash zone. Variance images can be employed to detect the mean shoreline position and assess wave run-up (Simarro et al., 2015).
4. **Time-stack images:** A time-stack image is created by capturing RGB pixel values along a specific profile of interest at regular time intervals and subsequently stacking these values to form an image (Bailey & Shand, 1994). In this representation, the vertical axis corresponds to time, while the horizontal axis represents space along the chosen profile (Simarro et al., 2015). Time-stacks are particularly effective in visualizing temporal changes in the swash zone, allowing for analysis

of wave runup, shoreline oscillations, and sediment transport (Aarninkhof et al., 2005; Bailey & Shand, 1994; Simarro et al., 2015).



(a) Snapshot image with visible transect of interest

(b) Grayscale Timex image

(c) Grayscale variance image

(d) Timestack of transect of interest

Figure 2.1: Visualization techniques of coastal footage

2.1.6. Wave runup extraction from coastal imagery

While time-stack images provide a valuable visual representation of wave runup over time, they require data extraction methods to yield quantitative measurements. This section discusses the theoretical foundations of these data extraction techniques.

Manual selection

Manual selection of wave runup data from time-stack images is a traditional method that yields accurate runup measurements (Aarninkhof et al., 2005; Bailey & Shand, 1994). This approach involves tracing the shoreline in each frame of the time stack to create a time series of shoreline positions. While conceptually straightforward, this method is labor-intensive and time-consuming, particularly for extensive time-stack datasets. Furthermore, manual selection can introduce subjectivity, as different individuals may interpret the leading edge differently, potentially resulting in variability and bias in measurements.

Automated image processing techniques

Automated Image Processing (AIP) techniques offer a significant advantage by automating shoreline detection and extraction from timestacks, reducing manual effort and processing time. Several image processing methods can be employed, including:

- **Enhanced grayscale swash edge detection:** This method, proposed by Bailey and Shand (1994), employs a series of steps to effectively isolate and track the swash edge in grayscale timestacks. Key processes include removing horizontal features, enhancing vertical edge detection, applying upward smearing to maintain continuity, normalizing local contrast, and defining an edge region through least-cost path optimization. These steps facilitate the identification of areas with sharp transitions in pixel intensity, often corresponding to the wave runup's edges and boundaries.

- **Color channel differencing:** This technique involves calculating the difference between the red and blue color channels in a time-stack image to highlight the boundary between water and sand. This is based on the principle that sand pixels tend to have higher red values than blue values, while the opposite is true for water pixels (Huisman et al., 2011; Turner, 1998)
- **Intensity/saturation thresholding:** This method discussed by Huisman et al. (2011) involves setting a predefined saturation/ color-intensity threshold to distinguish between pixels representing water and sand from HSV-converted timestacks. Water pixels generally have lower saturation values compared to dry beach sand. Pixels with intensity values below the threshold are classified as water, while those above are categorized as sand. This approach is particularly relevant for dissipative beaches where the groundwater seepage line can be decoupled from the actual shoreline.
- **Local entropy analysis:** This texture-based method leverages the visual disparity in texture between the turbulent water motion in the swash zone and the smoother texture of the dry beach (S. Zhang & Zhang, 2009). The approach assesses the randomness or disorder of pixel intensities within a localized neighborhood surrounding each pixel. High local entropy values typically indicate regions of rough or textured appearance, whereas low values signify smoother regions. S. Zhang and Zhang (2009) notes that local entropy is highly effective in detecting dynamic swash zones, even in the presence of a seepage face.
- **Saturation-entropy model:** This hybrid approach combines elements of saturation and entropy analysis. As detailed by Bailey and Shand (1994) and van der Grinten (2024), this method applies Gaussian smoothing along the time axis of the saturation timestack image to delineate the effluent line, which serves as the boundary between saturated and unsaturated sand. This step minimizes noise above the effluent line, thereby reducing the influence of the seepage face on the final runup estimate. An entropy layer is then applied to the filtered timestack, with high-entropy pixels designated as water. The shoreline is subsequently derived from this binary mask.

2.2. Groundwater table dynamics

Beach groundwater is a system that can be seen as the interface between land and sea. It interacts with swash, but can also be considered a system by itself. The beach groundwater system is an unconfined aquifer, where the groundwater table is the upper boundary. Flows in the beach groundwater are driven by tides, waves, and swash. To a lesser extent, they are also driven by processes like evaporation and rainfall (Horn, 2006).

2.2.1. Definitions

Horn (2002) performed an extensive study on beach groundwater dynamics and the existing literature on this topic at the time. The following definitions are adapted from this study. The groundwater table can be defined as the equilibrium surface where the pore pressure is equal to the atmospheric pressure. This level is also called the phreatic surface. Groundwater pressure is higher than atmospheric pressure below the water table and lower than atmospheric pressure above the water table. Below the phreatic surface, the sand is permanently saturated with water. The zone between the phreatic surface and the sand surface is called the vadose zone. In the vadose zone, the pores are filled with a mixture of air and water. Due to capillary fringe, pores can be fully saturated, while the pore pressure on this location is negative. For this reason, it is better to define the groundwater table with pore pressure, not saturation.

2.2.2. Recent findings about the beach groundwater system

The behavior of the groundwater is dependent on the hydraulic conditions (tidal conditions, wave conditions, rainfall, and swash), but also on the sand characteristics (particle shape, size, and porosity) (Gourlay, 1992). The shape of the beach groundwater table is generally not flat. With a rising tide, the groundwater table generally tilts landward, and seaward with a falling tide. Also, it has been shown that the water table oscillations lag behind the tidal motion and that this lag increases landward (Horn, 2002). Water table elevations were observed to be asymmetrical since the water rises faster than it falls.

The tide and groundwater table can become uncoupled; this is the case when the groundwater exit point - this is the point where the groundwater table and the beach coincide - is no longer attached to the shoreline (Horn, 2002, 2006). This means that the tide falls more rapidly than the groundwater table. Between the exit face and the shoreline, a seepage face now exists (Horn, 2002). The size and shape of the seepage face depend on the tidal regime, hydraulic properties, sediment properties, and beach geometry.

Emery and Gale (1951) observed that the beach can act like a filter for the waves; only the waves with a lower frequency are visible in the groundwater. The amplitude and frequency of the wave spectrum both decrease landward. Small waves with a higher frequency are only visible close to the interface between sea and land, whilst lower-frequency waves can propagate much further landward (Horn, 2002).

2.2.3. Groundwater measurement techniques

The groundwater table can be measured using a PVC pipe which allows water to flow through but does not allow sediment to flow into the pipe (Baird & Horn, 1996). The surface of the water inside the pipes is at atmospheric pressure, which means that this gives the location of the groundwater table.

It is possible to measure the groundwater table manually using electronic dipmeters, although these were found to not be very accurate (Baird & Horn, 1996; Horn, 2002), or by using a tube and lowering it in the well while blowing through it to find the water level (Horn, 2002). Manual observations are generally suitable for a sampling period of 15-20 minutes because they can quickly become very labor-intensive.

If a time series with a higher sampling frequency is needed, it is possible to measure the groundwater table with pressure transducers. When a sampling frequency of less than 1 minute is required, Turner (1998) recommends using buried pressure transducers, with a screen to prevent sediment from entering the sensor (Horn, 2002). The buried sensor will however not necessarily measure the groundwater table because changes in hydraulic potential might not be linear in hydrodynamic conditions (Horn, 2006).

An important factor in the measurement of the groundwater table using both wells and buried sensors is the response time of the system. A certain time is needed before the measurement device registers the actual change because water takes time to flow in or out. This response time is dependent on the instrument that is used and the hydraulic conductivity of the beach (Baird & Horn, 1996; Horn, 2002, 2006).

2.3. Hydraulic structures literature review

In this section, the phenomenon of coastal squeeze and its specific occurrence at Ostional Beach will be explored in detail. The aim is to provide context for understanding the challenges posed by coastal squeeze and how these challenges impact the nesting habitat of sea turtles in Ostional. Coastal squeeze is the main possible threat observed at the Ostional nesting beach.

2.3.1. Coastal squeeze in Ostional

Coastal squeeze is a process in which coastal habitats, such as beaches, wetlands, and dunes, become increasingly confined due to the dual pressures of rising sea levels and human development. Climate change significantly exacerbates this issue by causing sea levels to rise and altering coastal dynamics. As a result, the available nesting areas for sea turtles are shrinking, directly threatening their reproductive success and population stability (Mazaris et al., 2009).

At Ostional Beach, coastal squeeze arises due to the unique proximity of the village to the shoreline. The village, which has been situated adjacent to the beach for many decades (local source), historically encroached upon the beach itself. Until 1982, construction on/near the beach was common (Wikipedia, 2024). However, since 1982, the beach and surrounding waters have been designated as a protected area, halting further development. Despite this protection, the absence of a buffer zone between the village and the beach has resulted in a narrow margin of space for the natural dynamics of the shoreline.

While coastal squeeze has not yet posed direct risks to the residents of Ostional, it is already affecting the nesting habitat of sea turtles. This impact manifests in several ways:

- Loss of nesting habitat: Coastal squeeze directly reduces the available beach area for sea turtles to nest. This results in fewer suitable nesting sites, compromising the reproductive success of the species.
- Increased nest density: With less space for nesting, the density of nests increases. High nest density can lead to density-dependent issues, including competition for space, increased rates of nest destruction, and heightened vulnerability to predators and environmental pressures. These factors collectively reduce hatchling survival rates.
- Altered nesting success: The location and conditions of nests play a critical role in hatching success. Coastal squeeze forces turtles to nest in less optimal locations, increasing the likelihood of nest inundation, predation, and exposure to environmental stressors. Such conditions can negatively affect embryonic development, leading to lower fitness in hatchlings.
- Heightened vulnerability to climate change: Coastal squeeze compounds the risks posed by climate change. Rising sea levels intensified storms, and changes in sediment transport further threaten nesting beaches, amplifying the challenges faced by sea turtles in sustaining viable populations.

The specific challenges at Ostional Beach are twofold: the immense number of turtles that arrive to nest during mass nesting events (arribadas) and the steadily diminishing size of the beach. Together, these factors create a scenario where favorable nesting sites are becoming increasingly scarce, leading to issues such as inundation, overcrowding, and possible reduced hatchling success rates.

2.3.2. Possible mitigation measures

Three primary mitigation strategies are commonly proposed to address coastal squeeze, according to (Dronkers, 2022):

- Foreland creation: Constructing new landforms, such as artificial dunes or barriers, to expand or protect coastal habitats.
- Foreland restoration: Restoring degraded coastal habitats to their natural state to enhance resilience and ecological function.
- Preparing for retreat: Facilitating the inland migration of coastal habitats by removing barriers and allowing natural processes to occur unimpeded.

Ostional beach presents unique challenges for the implementation of these measures due to its environmental and social context. As a sandy beach with a reef located offshore, and as part of a legally protected area, options like foreland creation and foreland restoration face significant opposition. Discussions about artificial structures, such as artificial reefs or constructed barriers, were deemed unacceptable by both the residents of Ostional and experts at the University of Costa Rica (UCR). The primary reason for this opposition lies in the area's protected status, where construction activities are viewed as inconsistent with the principles of conservation and the values of the local population.

Given these constraints, this study will not include further exploration of artificial reef construction or similar interventions. Instead, the results section will focus on evaluating the feasibility and implications of other potential mitigation measures, comparing their effectiveness in addressing the challenges posed by coastal squeeze at Ostional Beach.

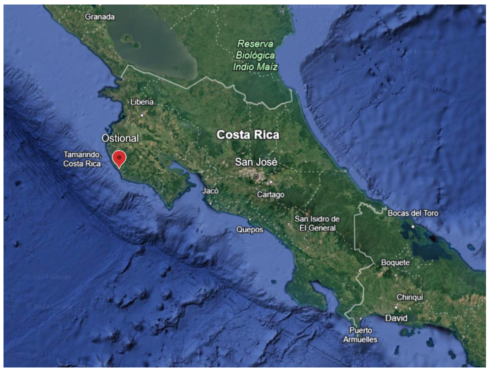
3
Methodology

This chapter discusses the methodology of the research. First, the research site is shown and discussed. Afterward, the method of wave runup and groundwater table measurement are explained. Then, the method for the stakeholder analysis within the TURTLE project is provided. Lastly, the methodology for a coastal squeeze mitigation strategy is discussed.

3.1. Research site

The research site is located in Ostional, a small town in Guanacaste province in Costa Rica. Ostional lies on the west coast of Costa Rica, neighboring the Pacific Ocean. Figure 3.1a shows an image of the beach, and Figure 3.1b shows the location of Ostional in Costa Rica.

(a) Photograph of Ostional beach



(b) Location of Ostional in Costa Rica (Google, 2023)

Figure 3.1: Research site location

The beach of Ostional stretches for approximately 7.5 km and three different sections can be distinguished on this stretch. The most northern part - in front of Ostional town - is called Playa del Ostional. Just south of Ostional is a small river estuary. South of this area is a stretch of beach called Main Nesting Beach. On the southern boundary of the main nesting beach lies another estuary, south of this estuary is located Playa Nosara. These three stretches of beach were potential research sites. Figure 3.2a shows the different beaches on a satellite image of the area.

Upon physical inspection of the beaches, Playa del Ostional was selected as being the best location for the research site. This stretch of beach was selected mainly for ease of access; to reach the more southern beaches, the equipment would have to be transported through the river every day. Additionally, Playa del Ostional was relevant to the study since this beach is also a turtle-nesting beach. Figure 3.2b shows the location of the research site on Playa del Ostional.

(a) Different beaches in Ostional area (Google, 2023) **(b)** Research site on Playa del Ostional (Google, 2023)

Figure 3.2: Overview of the research site and its surroundings

In the first week in Ostional, on the 25th of September, a GPS rover was available for use. The GPS that was used is a Sokkia GRX1 GNSS Receiver (SOKKIA Europe, n.d.) with an accuracy of 10 mm horizontally and 15 mm vertically. It was used to measure the topography of the research site on four transects at the research site. In post-processing, bicubic interpolation was used to make a visualization of the topography of the research site in the form of a contour plot. This contour plot is shown in Figure 3.3. The reference elevation is MSL.

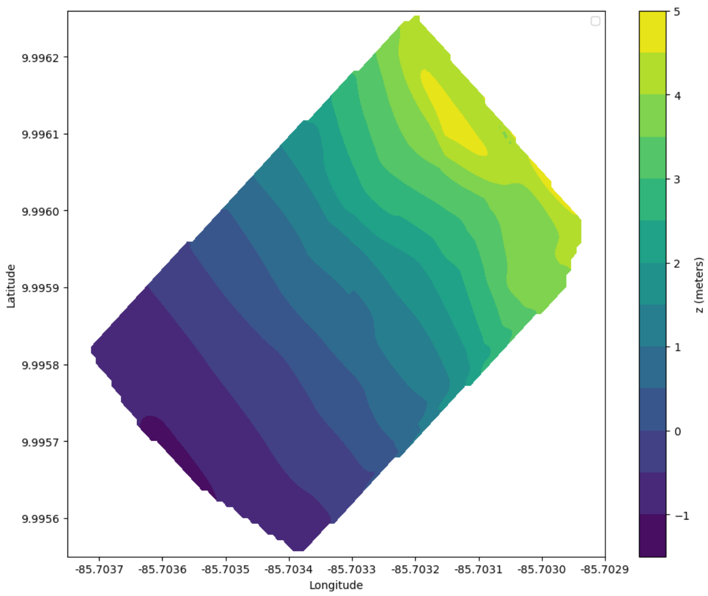


Figure 3.3: Topography of the research site on 25/09/2024

An important consideration when choosing the placement of the wells and the camera is the tidal conditions during the measurement period. Not a lot of tidal data is available for Costa Rica's coast. UHSLC (2024) makes predictions and measurements in Quepos, a city that lies approximately 180 km south of Ostional. This dataset can be used to approximate what tidal conditions should be expected during the measurement period. Figure 3.4 shows the prediction of the tide in the measuring period in Quepos. In the beginning, there will be a spring tide transitioning to a neap tide. The tides will stay relatively constant until the last week. From the 15th of October, there will be a strong spring tide on its way with the highest and lowest tides so far. In this prediction, we can also see that the tide has a diurnal character, with small daily inequalities.

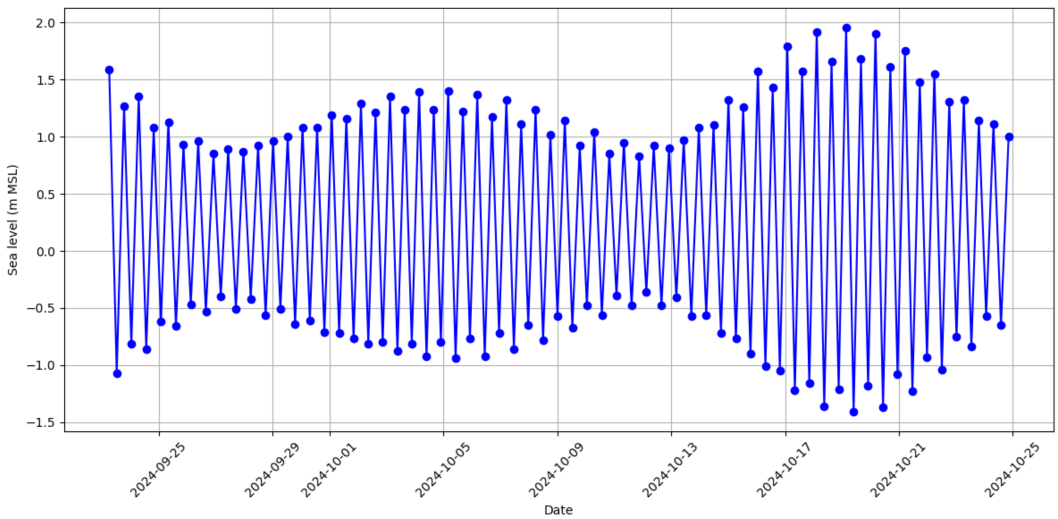


Figure 3.4: Prediction of the tide in Quepos from 23rd of September to 25th of October

3.2. Wave runup

Accurate measurement of wave run-up is crucial for understanding the hydrodynamic processes at the beach and tracking shoreline movement patterns. This section outlines the methodology used to capture, process, and extract wave run-up data, incorporating multiple extraction techniques and a comparative analysis of extraction-model performance.

3.2.1. Field setup

The field setup was optimized to capture time-lapse images and record daily topographic changes, forming the basis for accurate wave runup measurements. This subsection covers camera selection, configuration, positioning, and the daily reference measurements needed to ensure consistent and reliable image data.

Camera selection, configuration, and positioning

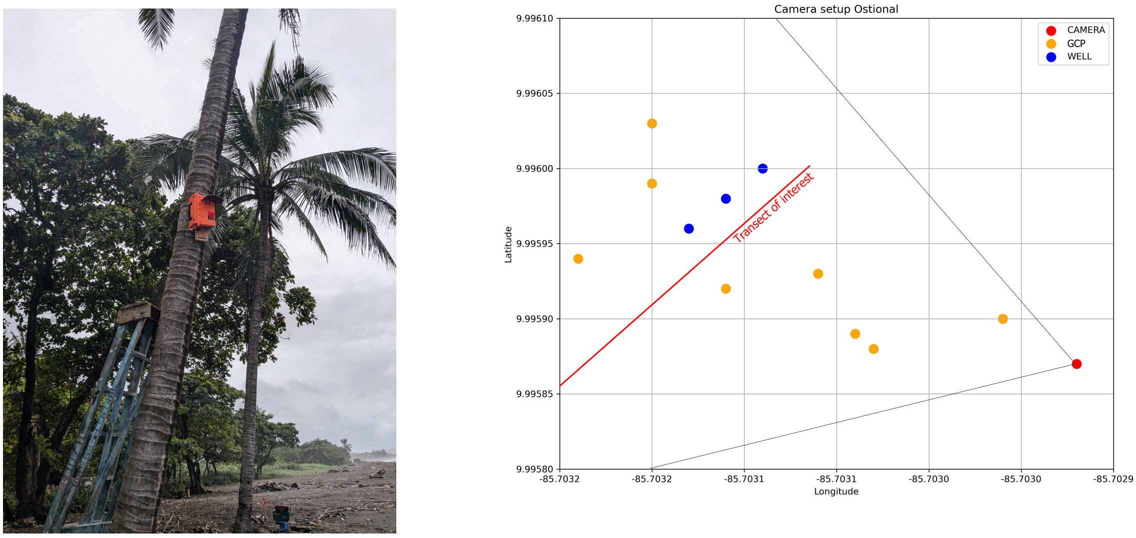
The GoPro Hero 7 Black was selected due to its availability, compact size, and durability. Given the camera's limited battery life, an external battery is used to extend operational time during monitoring sessions. The camera is configured in *timelapse photo* mode, capturing at a rate of 1 frame per second (fps) with the highest available resolution (12 MP) and using the linear view setting. This setup generates one high-resolution image per second. The linear view corrects for the GoPro's wide-angle lens distortion, creating an output that closely resembles a standard linear lens.

The camera was securely positioned in a protective box attached to a tree with zip ties, ensuring consistent placement and environmental protection. The field of view (FOV) was aligned with the transect of interest from a side angle, with the camera elevated to capture the entire target area unobstructed.

Manual daily topography measurements

Accurate positioning of Ground Control Points (GCPs) was crucial for translating the camera's viewpoint to real-world coordinates. Eight GCPs were established along the transect of interest. Sticks were driven into the ground to serve as reference points, with their coordinates determined using a rover, which was available for only one day. GCPs were positioned parallel to the shoreline, and daily elevation differences were recorded directly on each stick.

For the daily transect measurements, the following method was employed: a laser tool and a measurement stick were used in conjunction with two known locations within the transects. The procedure involved placing the laser at the first known location (Well 2) and aligning it precisely with the second known point within the transect (Well 3) to ensure consistent directionality each day. Elevation was then measured at intervals of every 3 meters along this line.



(a) Camera box on tree

(b) Field setup

Figure 3.5: Visualization of measurement site

3.2.2. Image processing

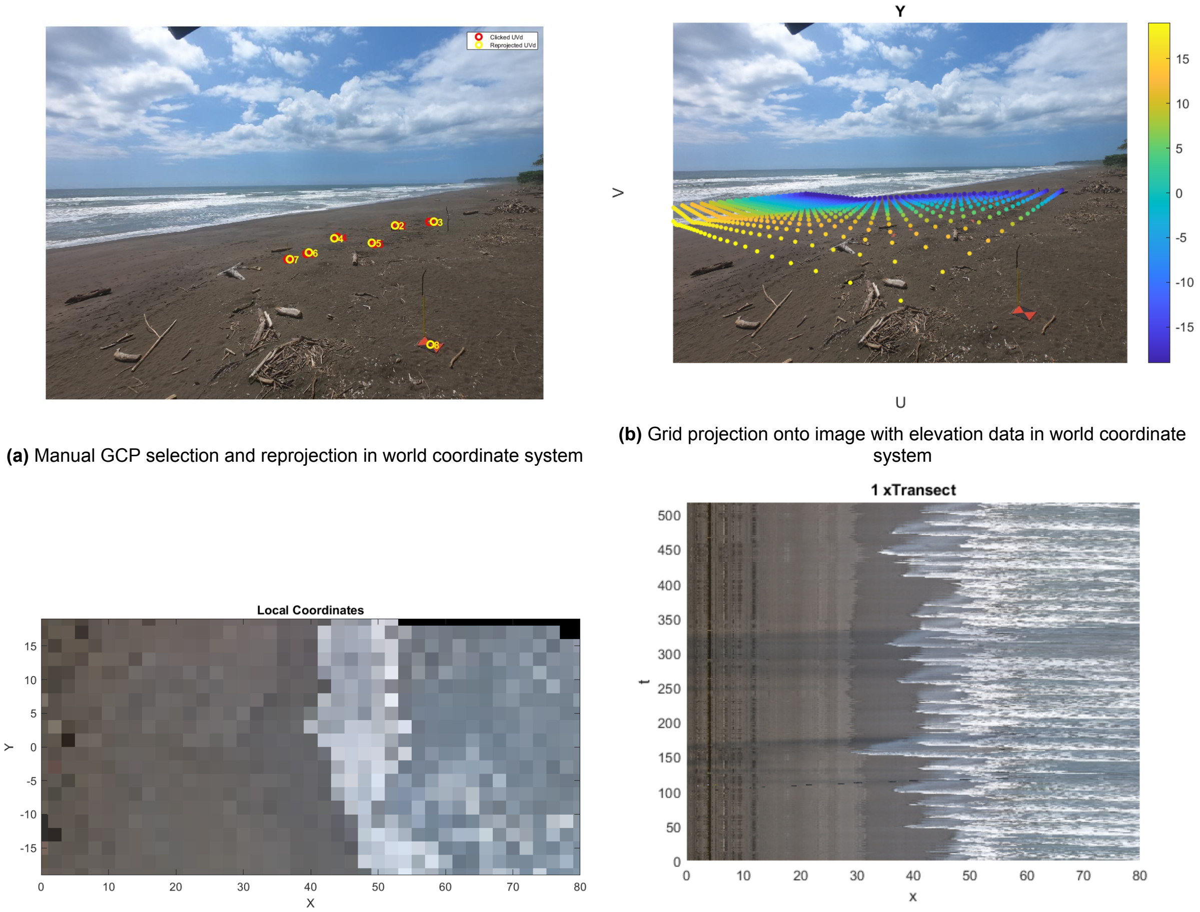
Following field capture, images were processed to generate time stacks. Key steps included camera calibration, geo-rectification, and time-stack generation, transforming image data into spatiotemporal measurements representing the beach environment.

Camera calibration

Intrinsic calibration is performed in a lab environment to determine parameters specific to the GoPro Hero 7 Black, allowing metric information extraction from 2D images. A checkerboard with known dimensions is used with Bouguet (2004)'s MATLAB camera calibration toolbox executes a two-step process based on the extended pinhole camera model: Initial parameter estimates were obtained via Direct Linear Transformation (DLT), approximating 3D-to-2D coordinate relationships. Nonlinear optimization followed, refining parameters through iterative adjustments with the Levenberg-Marquardt algorithm to minimize reprojection error.

Time-stack generation

To generate time-stacks, the *CIRN Quantitative Coastal Imaging Toolbox* developed by Bruder and Brodie (2020) is employed, following a systematic, multi-script procedure. This toolbox uses a pinhole camera model with distortion correction to accurately georeference the images. It requires intrinsic camera parameters along with an initial estimate of the extrinsic parameters to calculate the projection matrix based on daily Ground Control Point (GCP) data. The process begins by manually selecting the pixel coordinates of each GCP, facilitating the transformation of real-world coordinates (x, y, z) into image coordinates (U, V). Figure 3.6a displays both the manually identified GCP pixel positions and their reprojection, based on the computed extrinsic parameters.



(a) Manual GCP selection and reprojection in world coordinate system

(b) Grid projection onto image with elevation data in world coordinate system

(c) Image re-projected with local coordinates-system

(d) Timestack of selected transect

Figure 3.6: Timestack generation

Terrain elevation of the area of interest was integrated for accurate geo-rectification, allowing transformation of image coordinates (U, V) into local coordinates $(x_{\text{local}}, y_{\text{local}}, z)$, this has been done by manually altering the internal code of Bruder and Brodie (2020)'s CoastalCam Toolbox. During time-stack generation, a grid is projected onto the image, see Figure 3.6b, with each grid point assigned an elevation value based on interpolation of the manually performed daily transect measurements. This step facilitates the conversion of the cross-shore transect in world coordinates to a local coordinate system, yielding a rectified image, see Figure 3.6c). In this reprojected image, the vertical axis corresponds to the cross-shore dimension, while the horizontal axis represents the alongshore dimension.

Finally, From the reprojected geo-rectified image the cross-shore transect of interest is chosen, for which an RGB pixel-based time stack is generated by compiling the transects spatially over time, producing a spatio-temporal representation of wave activity along the shoreline, see figure 3.6d.

3.2.3. Wave runup extraction

Wave runup extraction from time-stacks involves both manual and automated methods. This section outlines the processes and models used to track shoreline movements over time, including custom adaptations for the distinct sand color and beach characteristics at Ostional.

Manual digitisation

For this study, wave run-up was manually digitized from timestack images using a custom MATLAB script provided by van der Grinten (2024). This process involved selecting distinct points along each wave's uprush and backwash to trace the shoreline movement over time. Each timestack was loaded into MATLAB, split into sections, and displayed for manual digitization. Wave uprush was identifiable as a bright white-to-gray contrast, while the backwash was represented by darker areas, and thus more difficult to identify.

The MATLAB script allowed us to select points on the displayed timestack sections by clicking, and pixel coordinates were saved for each clicked point. The selected points were then saved as arrays for further analysis. This methodology, as applied to the timestack image dated October 4, is presented in full in Appendix A.

Automated wave runup extraction model

The wave run-up data at Ostional Beach were automatically extracted from the timestacks using an adapted model based on the work by van der Grinten (2024), originally developed for analyzing wave run-up on a dissipative beach in Galveston, Texas. This model is grounded in a layered Entropy-Saturation framework, which leverages the optical properties of the beach environment to estimate shoreline positions over specified time windows and detect the effluent, as detailed in Section 2.1.6.

Two different methods were conducted by some alterations of the model:

- **Model 1: Entropy-saturation** This approach uses the full original Entropy-saturation model, employing both entropy and saturation layers. The saturation component is critical here for filtering out foamy areas, thus refining the delineation between wet and dry regions and enhancing overall contrast in the extracted boundaries.
- **Model 2: Entropy-only** In this approach, the saturation component is deactivated, simplifying the model to focus exclusively on entropy as the distinguishing feature. This method provides a more streamlined analysis that relies solely on the entropy layer to detect the wet/dry boundary.

The model, originally designed to operate at a frame rate of 2 frames per second (fps), was adapted for the 1 fps rate used in the processed timestacks for this study. Consequently, several parameters were adjusted. These modifications include reducing the recommended window size from 500 to 250, decreasing the neighborhood size from 5 to 3 pixels for entropy calculation, and lowering the Gaussian blur from 201 to 101 for the saturation calculation.

Model assessment

The performance of the two automated runup extraction methods is evaluated through both qualitative and quantitative measures. First, a visual inspection of the runup results plotted over the timestack provides an initial assessment. Quantitative evaluation is then conducted by comparing the automated runup data to manually extracted values, employing two primary statistical metrics: bias and the Pearson correlation coefficient.

The Bias metric quantifies the average error between the automated and manual runup data, indicating whether the model tends to over- or underestimate runup values systematically. Bias B is calculated using the formula below with N: the total number of data points, A_i: the model data at point i, and M_i, the manual data at point i:

$$B = \frac{1}{N}\sum_{i=1}^{N}(A_i - M_i) \tag{3.1}$$

The Pearson correlation coefficient r measures the strength and direction of the linear relationship between the automated and manual runup datasets. The Pearson coefficient r ranges from -1 to 1, where values closer to 1 indicate a strong positive correlation, values closer to -1 indicate a strong negative correlation, and values near 0 imply weak or no correlation. It is calculated as:

$$r = \frac{\sum_{i=1}^{N}(A_i - \bar{A})(M_i - \bar{M})}{\sqrt{\sum_{i=1}^{N}(A_i - \bar{A})^2} \cdot \sqrt{\sum_{i=1}^{N}(M_i - \bar{M})^2}} \tag{3.2}$$

To provide a more detailed evaluation of each model's performance over time, the bias and Pearson coefficient are computed over three specific time windows:

- **Entire dataset:** Calculations of both bias and Pearson coefficient are performed over the entire dataset to provide an overall evaluation of the model's accuracy.
- **Sliding 1-minute window :** This approach involves calculating the metrics over a rolling 1-minute window, which moves along the dataset. This sliding window allows for an assessment of the model's performance in capturing wave runup dynamics within shorter time frames, effectively highlighting any temporal variations in accuracy.
- **Fixed model window:** The metrics are also computed within fixed windows matching the size of the window used by the automated model. This approach ensures direct comparability by aligning the metric calculation intervals with the model's temporal structure, thus reflecting its operational framework.

This methodological framework provides an assessment of each automated model by evaluating both overall performance and temporal variability. The use of bias and Pearson coefficient across multiple windows allows for nuanced insights into the model's accuracy and reliability for wave runup extraction.

3.3. Groundwater table measurements

To measure the beach groundwater table, it was decided to use wells since measuring in the well gives the groundwater table - not the pore pressure. Also, the wells are relatively easy and cheap to construct with simple materials. Additionally, the sensors were required to be removed during the night. It is easy to remove and replace the sensors in the wells.

It was chosen to make three wells. These wells were constructed by hand with materials from local hardware stores. The goal was to make a well that was easy and cheap to construct. In appendix C a guide for the construction and installment of the wells is provided. An image of the final design of the well we used can be found in Figure 3.7.

3.3.1. Fieldwork setup

The three wells were placed at regular intervals of 3.11 m. They are numbered from one to three, with well 1 being the closest to the shoreline and well 3 being the most landward. After placement, the wells were located using the Rover GPS. The coordinates of the wells on the 25th of September 2024 can be found in Table 3.1.

Well number	**Latitude (**°N**)**	**Longitude (**°W**)**	**Elevation (**m MSL**)**
1	9.99596	85.70313	2.981
2	9.99598	85.70311	3.301
3	9.99600	85.70309	3.600

Table 3.1: Well locations

At the moment that the wells were placed there was no knowledge about the depth of the groundwater table in the beach, which made it difficult to decide the cross-shore location of the wells. The wells shouldn't flood from the top, but also they shouldn't be placed so high that they don't measure anything. They were placed in a location where the high tide would just reach most days of the measuring period, around the Mean Higher High Water (MHHW). Placing the wells in this location made sure that there was a high chance of measuring groundwater - at least during high tide - but minimized the chance of the wells becoming flooded by wells or tide.

3.3.2. Pressure transducers

The logger used for measuring the groundwater table is the Global Water WL16 Water Level Logger (Global Water, n.d.). This is a submersible pressure logger which can measure water level, pressure

Figure 3.7: Final design of the well

data, and temperature. It can record 18759 values, with a maximum sampling frequency of 10 Hz. It automatically compensates for temperature (between −1.1 °C and 21.1 °C) and it is vented for barometric pressure compensation. It requires two 9V batteries to work. The accuracy when the temperature is stable is ± 0.1 %. When the temperature is unstable, the accuracy of the sensor is ± 0.2 %

The loggers were set to record at a frequency of 1 Hz. This is a high enough frequency to be able to capture groundwater table fluctuations due to swash. Calibration of the loggers was done before each deployment with the Global Logger software. For calibration of each logger, the following steps were taken: the sensor was placed inside a bucket of seawater, and the water level at the sensor was measured and entered into the Global Logger software. Now the software measures the current through the sensor and displays it in the program. Once the value stabilizes, this is entered into the software and the sensor is removed. After removing the sensor, the water level is set to 0 and the sensor measures again. Wait once again until the value stabilizes, and enter this in the program. The logger is now calibrated. The logger is synchronized with the NIST.gov time server (NIST, n.d.). After calibration, the loggers are ready for deployment. The sensors were attached to a metal rod as shown in Appendix C, mounted at a distance of 190 cm below the cap. The distance from the top of the well to the beach was measured every day to know how deep the water table was below the surface of the beach. After measurements, the sensors were removed from the wells, and data was retrieved from the loggers using the Global Logger software.

At the same time as measuring the water pressure within the wells, the atmospheric pressure was recorded. When the atmospheric pressure changes, the reading by the sensor is not completely accurate anymore, since it was calibrated for a different atmospheric pressure. This means that during measurement, the water elevation that is measured needs to be compensated for atmospheric pressure. The loggers that were used have built-in atmospheric pressure compensation (Global Water, n.d.), so this was not necessary for this research. The atmospheric pressure during the measuring period was recorded anyway with the *Sensor Logger* application, which utilizes the barometric sensor within the smartphone to record atmospheric pressure (Madison, 2020).

Precipitation data during the measurement period is interesting as well, to see its effect on the groundwater table. The Instituto Meteorológico Nacional de Costa Rica (IMN) is Costa Rica's National Meteorological Institute, serving as the country's official authority for weather, climate, and atmospheric monitoring. Established as a public agency, the IMN provides essential services for tracking weather patterns, issuing weather forecasts, and monitoring climate trends (Instituto Meteorológico Nacional de Costa Rica, 2024a). IMN has an automatic station in Garza (Instituto Meteorológico Nacional de Costa Rica, 2024b), a town close to Ostional. The data for the measurement period will be provided, but only after the report submission date. On IMN's website, it is possible to see the rain data for each station in the last 24 hours. This data was recorded, but very inconsistently which makes it difficult to use.

3.3.3. Data analysis

To verify if the data recorded by the *Sensor Logger* app was accurate, the recordings were compared to data from IMN. The IMN automatic station on the Universidad de Costa Rica campus measures barometric pressure and shows the measured values of the last 24 hours on its website (Instituto Meteorológico Nacional de Costa Rica, 2024c). In Figure 3.8 below, the data from the *Sensor Logger* app and the data from the station are compared. It can be seen that the measurements are close and that the barometric pressure measurements of the phone are accurate.

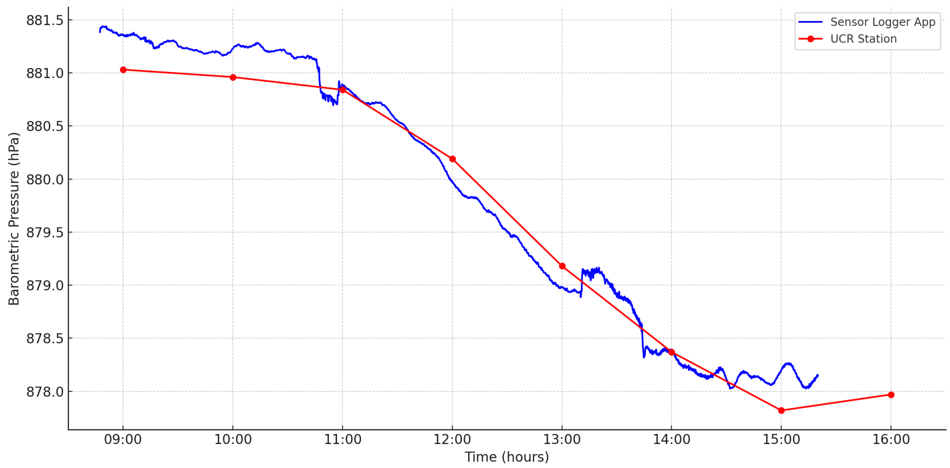


Figure 3.8: Pressure comparison: Sensor Logger app vs UCR station (30/10/2024)

3.4. Collaboration analysis

To gain insight into the current collaboration and communication practices among the various actors involved in the TURTLE project as well as their views on future collaboration, semi-structured interviews were conducted with representatives from each organization listed in Table 3.2. These interviews gathered detailed information about their roles, communication methods, objectives, the challenges they encountered, and their views on future collaboration. A list of the interview questions can be found in Appendix D.

3.4.1. Semi-structured interviews

Interviews were conducted using a semi-structured format that allowed flexibility to explore various topics and insights unique to each actor's involvement. Follow-up questions were used to clarify and expand on each actor's responses, providing depth to understand each organization's motives, challenges, and experiences. Interviews were conducted through Microsoft Teams or in person, depending on participant location and availability.

Institution	Country of origin	Type
Delft University of Technology	Netherlands	University
Universidad de Costa Rica	Costa Rica	University
Exeter University	United Kingdom	University
Texas A&M University	United States	University
Federal University of Rio Grande do Sul	Brazil	University
Deltares	Netherlands	Research institute
Topconsortium voor Kennis en Innovatie (TKI) Deltatechnologie	Netherlands	Consortium
Sea Turtle Conservancy	Costa Rica	Conservation agency
World Wide Fund for Nature (WWF)	International	Conservation Agency
Boskalis	Netherlands	Dredging company

Table 3.2: Actors involved in the TURTLE project

All interviews were transcribed using Rev.com, an AI-powered transcription service that ensures accuracy. Data from interviews were securely stored and used in this report with explicit consent from interviewees.

3.4.2. Data analysis

Interview data were analyzed to evaluate the project's current structure and communication practices. Key themes from the interviews were identified, focusing on collaborative strengths, existing challenges, and potential improvement areas.

3.4.3. Framework development

Insights gained from the data analysis informed the creation of a strategic framework aimed at addressing the challenges and enhancing collaboration within the TURTLE project. This framework was designed to support more effective communication, foster greater engagement among project partners, and improve the sharing of research findings. It builds on the key themes identified in the analysis, including collaborative strengths, existing disconnections, and opportunities for improvement. By grounding the framework in empirical data from the interviews, it provides a practical and targeted approach for improving collaboration within the TURTLE project.

The framework incorporates actionable strategies that reflect the specific needs and dynamics of the TURTLE network. These strategies include promoting engagement through the introduction of weak links, strengthening cross-partner communication to facilitate the exchange of insights, and ensuring the effective dissemination of findings to maximize project impact. To ensure continued relevance, the framework is designed to be adaptable, evolving in response to partner feedback and project developments.

3.5. AI usage

This report was developed with the assistance of AI tools to enhance its clarity and structure. AI was also employed for the transcription of interviews, ensuring accuracy and efficiency in capturing the insights shared by participants. These tools were used as support, with all content reviewed, analyzed, and interpreted by the authors to ensure alignment with the study's objectives and context.

4

Results

4.1. Wave runup results

This section presents the performance assessment results of the two automated wave runup extraction methods. The wave runup extraction and timestack production were applied to data collected on October 4, 2024, covering a measurement period of approximately four hours.

4.1.1. Visual performance assessment

A visual inspection of the model outputs overlaid on timestacks from October 4 reveals notable performance differences between the two models. As shown in Figure 4.1, which displays a sample timestack from that day, the entropy-only model (blue) demonstrates an ability to approximate maximum wave runup reasonably well. In contrast, the saturation-entropy model (red) shows more erratic behavior, with predictions frequently deviating from the observed runup peaks. This pattern remains consistent throughout the dataset, as illustrated in Appendix A, where additional plots from the October 4 measurements display similar model performance characteristics.

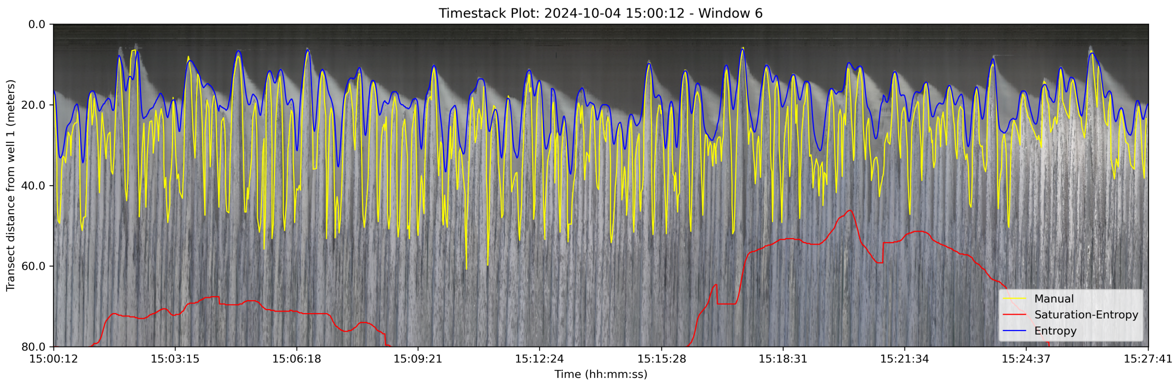
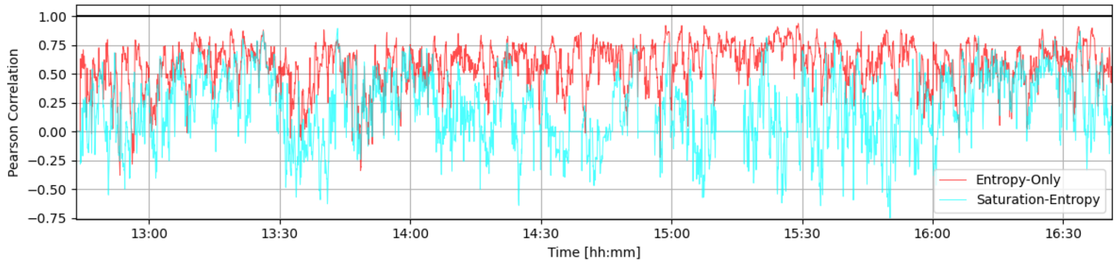


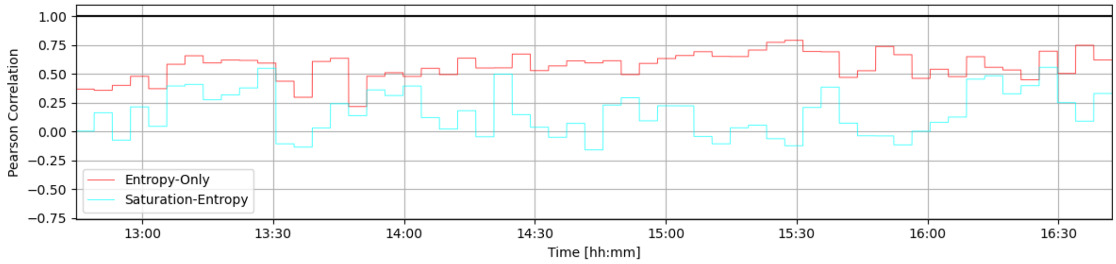
Figure 4.1: Timestack 6 (Appendix A)

4.1.2. Statistical performance assessment

In the following, a comparative analysis of automated wave runup extraction models, namely the saturation-entropy and entropy-only models, is conducted against manually selected wave runup data. Figure 4.2a and Figure 4.2b display the Pearson correlation coefficient for each model, computed over a 1-minute sliding window and a 250-second fixed window (the same window sizes used for calculating the wave runup data within the models), respectively. These figures highlight the consistency of each model over time.



(a) Coefficicient for sliding 1-minute window



(b) Coefficient for fixed 250-second-window

Figure 4.2: Pearson correlation coefficient compared to manually extracted wave runup data for 4 October 2024

Table 4.1 summarizes the Pearson correlation performance for each model. The entropy-only model consistently yields higher Pearson correlations in both window configurations. The overall Pearson correlation for the entropy-only model across the entire dataset is 0.69. Also, both window types suggest a moderate to strong alignment with the manually extracted data, with a mean coefficient of 0.57. In contrast, the saturation-entropy model exhibits a total Pearson correlation of -0.11, with notably lower maxima and a negative total correlation for both window calculations, indicating very weak alignment overall.

	Saturation-entropy		**Entropy-only**	
Window [s]	Sliding-60	Fixed-250	Sliding-60	Fixed-250
Mean	0.19	0.16	0.57	0.57
Max	0.90	0.56	0.94	0.79
Min	-0.75	-0.16	-0.38	0.22
STD	0.29	0.19	0.19	0.12
Overall	**-0.11**		**0.69**	

Table 4.1: Summary of Pearson-correlation comparison for automated runup extraction methods for a sliding window of 1 minute, and a fixed 250-second window

Table 4.2 provides a comparison of bias values. The entropy-only method shows a total bias of -11.3 meters, indicating a large but closer approximation to the manual measurements than the saturation-entropy model, which has a much larger total bias of 32.4 meters. The bias variability, indicated by the standard deviation, is considerably lower for the entropy-only model, with values of 2.8 and 2.3 meters for the two window types, compared to 14.6 and 13.9 meters for the saturation-entropy model. This suggests somewhat better consistency in the entropy-only model across time.

Overall, these results suggest that the entropy-only model outperforms the saturation-entropy model in terms of both correlation with manual observations and bias stability.

	Saturation-entropy		Entropy-only	
Window [s]	Sliding-60	Fixed-250	Sliding-60	Fixed-250
Mean	32.5	32.4	-11.3	-11.3
Max	62.7	55.7	-3.5	-6.1
Min	4.3	8.0	-21.4	-17.2
STD	14.6	13.9	2.8	2.3
Overall	**32.4**		**-11.3**	

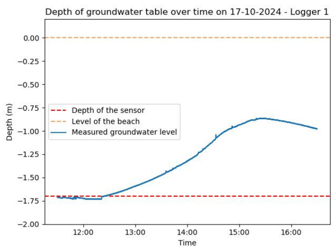
Table 4.2: Summary of bias comparison for automated runup extraction methods for a sliding window of 1 minute, and a fixed 250-second window

4.2. Groundwater table measurements results

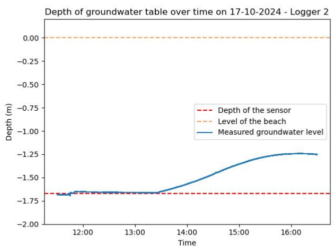
In this section, the results of the beach groundwater table measurements are shown, discussed, and analyzed.

4.2.1. Towards spring tide - 17 October 2024

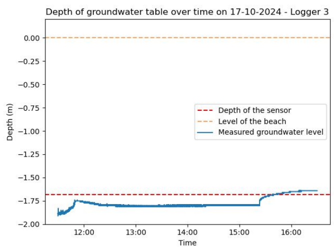
All of the results have been processed in Python and visualized in plots. The plots for all days and all loggers can be found in appendix B. Figure 4.3 shows the results of the measurements that were made on October 17, 2024. The measurement period on this day is from approximately 12:30 to 17:00. The results are very clear on this day because this was during the spring tide period (see section 3.1). The results of the measurements in wells 1, 2, and 3 can be seen here next to each other. In Figure 4.3d, the measurements of the three loggers are placed in the same figure. Be aware that the y-axis on this graph is not the elevation of the water table compared to a common reference level, but the depth of the water table measured from the level of the sand, and the elevation of this level is different for the wells. On this graph, the peaks of the measured groundwater table are also marked and annotated.



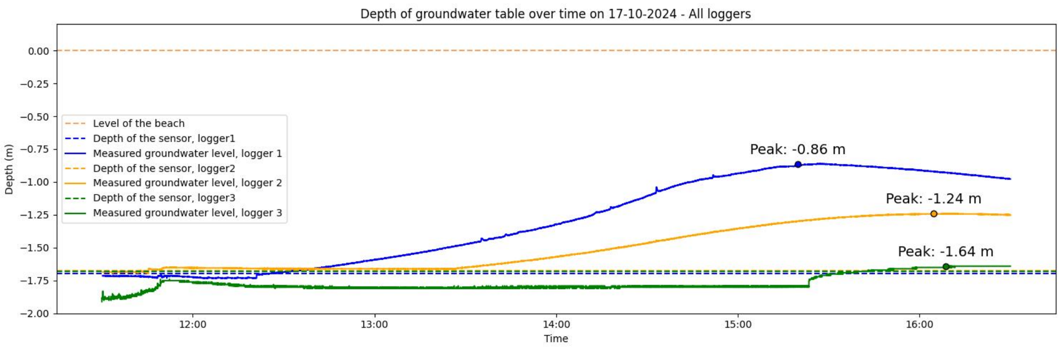
(a) Logger 1 - Well 1



(b) Logger 2 - Well 2



(c) Logger 3 - Well 3



(d) All measurements of the day in one plot

Figure 4.3: Groundwater table measurements on the 17th of October 2024

Logger 1
Well 1, which is the well closest to the shoreline, shows a sinusoidal shape with a period similar to that of the M2 tide. There is unfortunately no tidal gauge available near the measurement site. The closest one is in Quepos, almost 200 km from Ostional. Although this station is great for predicting when the neap and spring tide will be, it can not easily be used to determine the exact tide at a stretch of coast so far away. A computational model might be able to predict the tide here to a certain accuracy. An even better option would be placing a measuring buoy near the coast of Ostional. Unfortunately, it is now difficult to say anything about the delay between the tide and the measurements of the groundwater table.

There are some small and short peaks, or fluctuations, visible at some places in the measurements. This will be discussed further in the discussion.

Logger 2
In the measurements made by logger 2, a very similar sinusoidal shape is visible, signifying a tidal dependency. This sinusoidal shape in logger 2 has a lower amplitude compared to logger 1. This would signify that the amplitude of the tidal effect on the groundwater table decreases landward. Another interesting thing is that the peak of this sinusoidal shape is about 1.5 hours later than the peak measured in logger 1. This peak is after a rising tide, so this signifies that there is a delay in this tidal dependence the further landward one measures.

The curve for this logger is very smooth and no peaks are visible, in contrast to what was observed in the measurements of logger 1.

Logger 3
Logger 3 has not measured the groundwater table at all during the day. There is a large fluctuation in the measurements, even when it does not measure. Also, straight after calibration, measurements are off by 20 cm already, because at this time the logger is still outside the well and it should measure zero. This logger will not be taken into account in the analysis here.

Groundwater table change in time; beach cross-section
In Figure 4.4, the groundwater table is plotted at six different moments in time, distributed from the beginning to the end of the measurements, again on 17 October. In the plot, we have a local coordinate system on the horizontal axis, a cross-section of through the wells, where well 3 is placed at $x = 0$. On the vertical axis, we have the elevation from MSL. The measured level of the sand is assumed constant for each day in the plots. The level of the wells is what was measured on the first day with the rover. The groundwater table elevation is here also given from MSL. Note that the measurements from logger three are not included here, because its measurements were not considered reliable. Also note that in the first two time steps, logger 2 was measuring its maximum depth, which means that the actual groundwater depth could have been deeper than displayed.

In this plot, similar observations can be made compared to what we observed in Figure 4.3. We see that the effect of the tide is very large, and is most visible at well one, closest to the shore. The amplitude of the groundwater table movement is here much larger than the amplitude at well 2. In this plot, we can also see very nicely how there is a delay in response to the tide landward. This is best visible in the last two graphs, 15:30 and 16:15. Here we see that the groundwater table has already started to lower at well 1, but is still increasing at well 2.

Also, this graph shows clearly that the groundwater table at the location of well 2 can be higher than at well 1. This was not very clearly visible in 4.3, because there, the groundwater table depth is plotted compared to the sand level, and in 4.4 it is plotted against MSL.

4.2.2. Neap tide - 9 October 2024

In Figure 4.5 the measurements of 9 October are shown. This day was during a neap tide, and that is well visible in the graphs. It is visible that the amplitude of the groundwater movement is much smaller than what was seen on 17 October, during spring tide. Now, logger 1 measures a peak in groundwater table elevation of −1.38 m, where on 17 October a peak of −0.86 m was measured. According to this

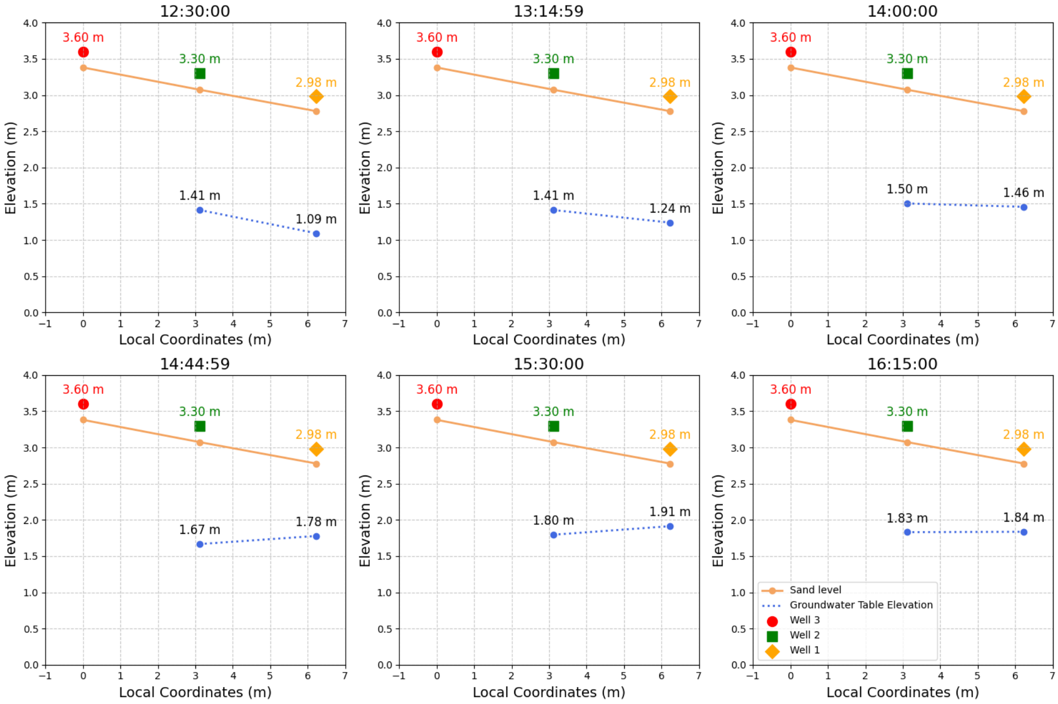
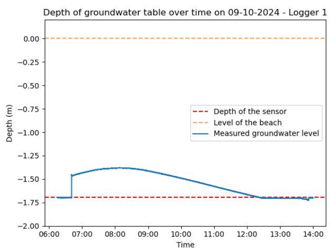
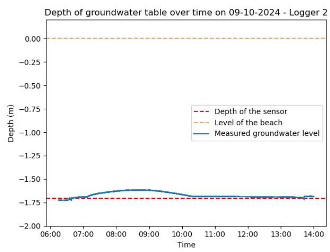


Figure 4.4: Change in cross-section of the beach in time on 17-10-2024

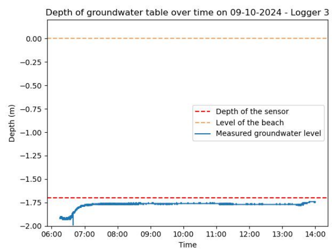
observation, it can be assumed that the peak in the groundwater table on the beach is highest during spring tide periods.



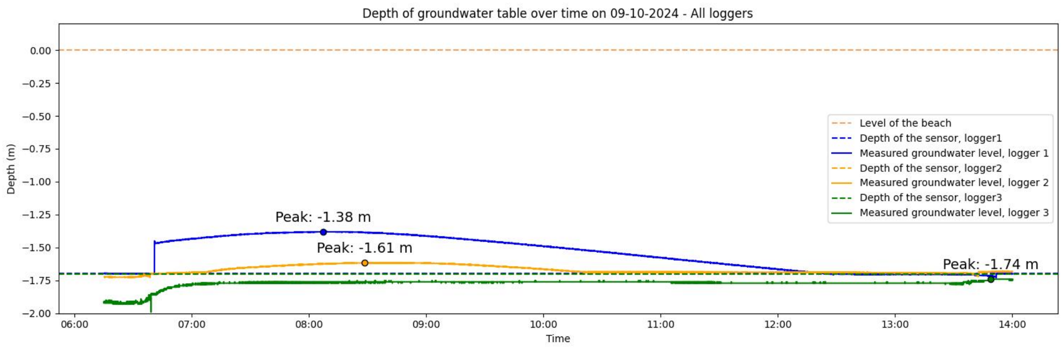
(a) Logger 1 - Well 1



(b) Logger 2 - Well 2



(c) Logger 3 - Well 3



(d) All measurements of the day in one plot

Figure 4.5: Groundwater table measurements on 9 October

Groundwater table change in time; beach cross-section

Additionally, the groundwater table is plotted in the cross-section through the wells in Figure 4.6. The same plot was made for 17 October in Figure 4.4. Here the elevations are given from MSL in different time steps in the measuring period. Note that in the last two time steps, well 2 measured the maximum depth, so the actual groundwater table could be lower than what is shown. We see again similar results compared to what we saw on 17 October. We see a higher amplitude in the movement of the groundwater table in well 1 compared to well 2, and we see a slight delay in this movement landward, although less pronounced than was seen in the graph for 17 October. Something interesting here, which was not visible in the graph for 17 October is that during the whole measurement period, the water table in well 2, further landward, is higher than the groundwater table in well 1. This means that the groundwater table is tilting seaward for the whole day; during both rising and falling tide.

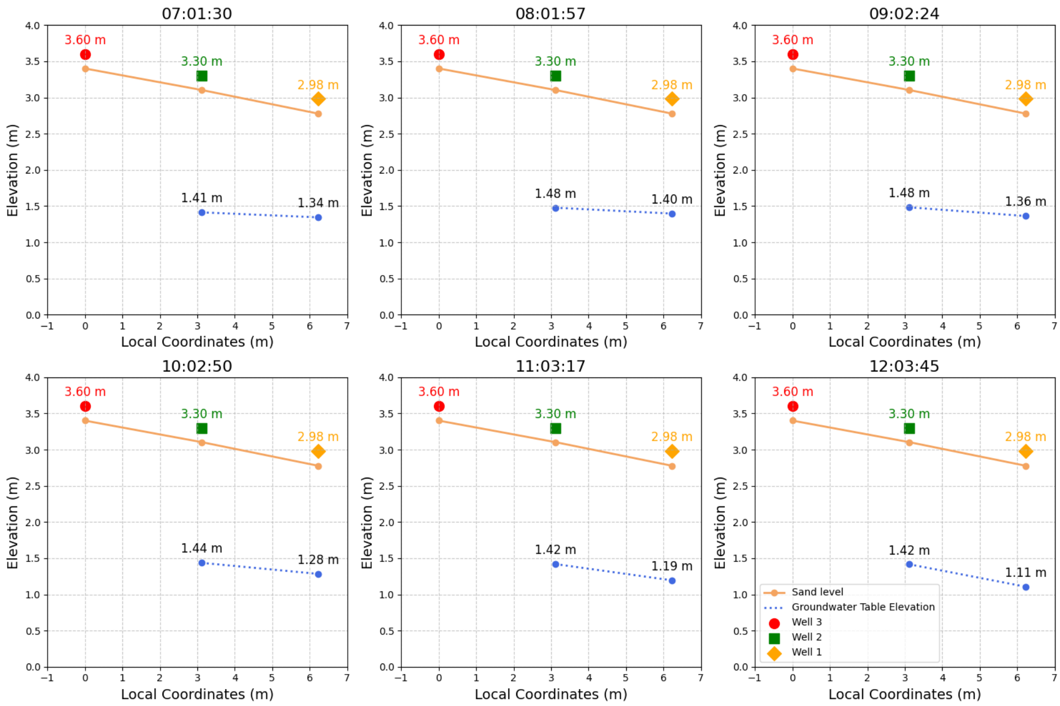


Figure 4.6: Change in cross-section of the beach in time on 09-10-2024

4.3. Collaboration analysis results

In the following section, the results and analysis of the interviews are presented.

4.3.1. Partner background and involvement

Based on the conducted interviews, an overview of the key partners involved in the TURTLE project is presented, highlighting their organizational background, motivations, and roles. By examining each partner's expertise and contributions, insights are gained into how partners from different disciplines collaborate to achieve the shared goal of protecting sea turtle nesting habitats. Understanding the specific reasons for their involvement and the roles they play is essential to understanding the project structure and how it brings together engineering, conservation, and research to develop sustainable solutions.

Delft University of Technology

The Delft University of Technology serves as the lead institution in the TURTLE project, with its role initiated by José Álvarez Antolínez, whose work in coastal engineering inspired a multidisciplinary approach to addressing challenges at sea turtle nesting sites. Recognizing the vulnerability of these coastal habitats to erosion, sea-level rise, and climate-driven disturbances, Professor Antolínez saw an opportunity to integrate coastal engineering expertise with conservation biology. His goal was to bridge the gap between ecological preservation and engineering solutions, creating sustainable, nature-based interventions that would not only protect vulnerable turtle nesting areas but also contribute to broader coastal resilience efforts. Following Antolínez his establishment of a PhD position within the project, Jakob Christiaanse joined, and together, they have played instrumental roles in coordinating the TURTLE project.

As the primary coordinating institution, the Delft University of Technology collaborates with the other partners to design and execute the project its fieldwork and analytical phases, including research campaigns in Galveston, Texas, and Costa Rica. These campaigns focused on measuring wave run-up, groundwater dynamics, and beach morphology to assess how these factors influence turtle nesting success. In addition to conducting this fieldwork, the Delft University of Technology also serves as the main bridging institution between the different disciplines involved in the project such as conservation agencies, biologist institutions, and engineering universities. These collaborations are essential for integrating datasets and information from different disciplines, contributing to the overarching goal of providing actionable, science-based strategies that benefit both biodiversity and coastal communities.

Universidad de Costa Rica

The Universidad de Costa Rica has a specific research institute named IMARES. This unit focuses on understanding and managing the dynamic processes of rivers, estuaries, and coastal areas, particularly addressing issues like sediment transport, erosion, and hydrodynamic modeling. IMARES works on practical applications in these environments, providing insights for infrastructure development, flood risk management, and sustainable coastal development.

Felipe Calleja Apéstegui from IMARES was contacted by José Álvarez Antolínez through a mutual colleague concerning the possibility of setting up fieldwork expeditions to Playa del Ostional. Playa del Ostional is a sea turtle nesting site located in Guanacaste, Costa Rica. Over the next years, IMARES and the Universidad de Costa Rica have played a significant role in facilitating and coordinating field trips by students from the Delft University of Technology in Costa Rica. Multiple excursions have been undertaken to Playa del Ostional. During these field trips, beach morphology, wave runup, and groundwater table levels have been studied, as well as sand characteristics and seasonal changes. During these field trips, the UCR provided access to their facilities, and logistical support and advised on research methodologies.

For IMARES and the Universidad de Costa Rica, there are multiple reasons to be involved in the TURTLE project. Firstly, the collaborative effort with the Delft University of Technology offers the opportunity to do research at the beach in Ostional without investing too many valuable resources. It also strengthens the ties between the two universities.

Exeter University

The University of Exeter is a research institution in the United Kingdom, with departments in environmental science, marine biology, and conservation studies. Within the university, the Center for Ecology and Conservation has conducted numerous studies aimed at preserving marine ecosystems, among which sea turtle nesting sites.

Exeter University's involvement with the TURTLE project started through a collaboration with the Delft University of Technology. The university was contacted by a representative from the coastal engineering department within the Delft University of Technology with the goal of further integrating the biology side of turtle research into the project. A dataset containing sand samples, previously collected on sea turtle nesting sites by Exeter University, was also shared with the Delft University of Technology. Originally, the dataset was collected to study microplastics at sea turtle nesting sites but was made available to researchers from the Delft University of Technology for further tests.

Texas A&M University

The Texas A&M University is a renowned university out of College Station, Texas. They also have a branch campus in Galveston, Texas. Because Galveston is home to a turtle nesting site, turtles are seen as very emblematic for this campus. At the Galveston campus, research is conducted in various departments relating to sea turtles. The marine biology department of the university does work on the biological aspects of the species for example. There is also an active group within the marine science and oceanography department as well as coastal engineering doing research related to the turtles.

Texas A&M University became involved in the TURTLE project through its established connections with the Delft University of Technology and a long history of collaboration focused on flood risk and resilience. A faculty member at the Delft University of Technology linked the departments of both universities in the context of the TURTLE project to explore the possibility of a field case in Galveston. This led to a joint fieldwork expedition measuring groundwater, hydrodynamics, and sand characteristics at the sea turtle nesting site in Galveston.

Within the project, Texas A&M University contributes insights into coastal hydrodynamics. As a university contributing to research, their main reason for involvement is knowledge dissemination. The TURTLE project also offers the opportunity for both universities to strengthen ties and work together, something that is valued by both partners.

Federal University of Rio Grande do Sul

Inaiê Miranda is an oceanographer with a PhD focused on marine geology, specifically in the areas of morphodynamics and coastal processes. Based in Brazil at the Federal University of Rio Grande do Sul, her current research focuses on nature-based solutions for coastal management, specifically examining how natural processes can be leveraged to mitigate erosion and adapt to climate impacts without relying solely on traditional hard-engineering structures.

Inaiê Miranda her current role in the project is limited, she is working with José Álvarez Antolínez from Delft University of Technology on a paper incentivizing the use of nature-based solutions over hard structures but is not involved in any of the fieldwork or other activities within the project. Her participation in this study is mainly based on possibilities for future collaboration in the TURTLE project. One of these possibilities includes expanding the fieldwork conducted in Galveston, Texas, and Costa Rica to encompass beaches in Brazil, where Miranda's expertise, connections, and research focus could be valuable.

Sea Turtle Conservancy

The Sea Turtle Conservancy (STC) is the world's oldest organization dedicated to sea turtle research and conservation, having been established in 1959 and headquartered in Gainesville, Florida. Through research, education, campaigning, and the preservation of their natural habitats, STC seeks to assure the survival of sea turtles throughout the Caribbean, Atlantic, and Pacific. Their pioneering efforts, especially in Costa Rica, helped create Tortuguero National Park, which now safeguards the world's second-largest population of green sea turtles. The group has expanded its activities throughout the world over the years, tackling important problems including habitat loss, poaching, and the effects of climate change.

The STC's involvement in the TURTLE project originates from its long history of sea turtle conservation and research. One of their representatives got involved with the TURTLE project after being approached by the Delft University of Technology to provide insights into how physical oceanography could be linked to the biological aspects of sea turtle conservation, particularly for the Olive Ridley arribadas (mass nesting events) at Playa Ostional in Costa Rica.

His involvement in the TURTLE project has largely been as an external expert, providing guidance on the biological aspects of the turtles and their interactions with the environment. His interest in the project mainly lies in the triggers behind the mass nesting events of the Olive Ridley turtles. Another aspect of his role within the project is enabling collaboration between different disciplines, connecting the people within the project with biologists to integrate information and data from different fields.

World Wide Fund for Nature

The World Wide Fund for Nature (WWF) is a leading, global conservation organization. They aim to halt the degradation of the planet's natural environment and help communities around the world conserve the natural resources that they depend on. Promoting sustainability is another one of their goals, along with protecting and restoring species and their habitats.

This is also how they became involved with the TURTLE project. An important sea turtle nesting site in Suriname was under pressure from erosion, endangering the various turtle species laying their eggs there. They contacted the Delft University of Technology and Deltares to investigate possible solutions for this problem. In the TURTLE project, WWF plays a key role in bridging the gap between conservationists and engineers. Some of the challenges they face in their conservation work require technical solutions, for which they rely on the expertise of parties like the Delft University of Technology and Deltares, like the case in Suriname.

Their role also includes advocating for the preservation of these nesting sites and ensuring that technical solutions are produced that fulfill the right conservation goals, prioritizing what is most urgent. Additionally, they also serve as a facilitator, ensuring that local conservation groups and international partners collaborate effectively. They also help with the communication of project findings to a broader audience, raising awareness about the importance of protecting sea turtles and their habitats.

Deltares

Deltares is an independent institute for applied research in the field of water and subsurface, based in the Netherlands. Deltares focuses on innovative solutions for complex water-related challenges, offering research and consultancy services globally. As a nonprofit organization, its mission is to develop sustainable solutions for delta regions, coastal areas, rivers, and other water systems. Deltares has different areas of expertise such as floods, sea-level rise, and subsidence, from which they provide decision-makers with practical solutions for water management, coastal protection, and flood risk mitigation (Deltares, n.d.).

Deltares became involved in the TURTLE project via a joint effort with WWF and the Delft University of Technology. In this project, Deltares was consulted on possible causes for beach erosion in Suriname and potential solutions to mitigate this, in order to protect a sea turtle nesting site. For this project, Deltares made analyses based on satellite images and worked with the WWF and Delft University of Technology as well as a local Suriname coastal expert.

Their motivation to get involved in the TURTLE project stems from multiple factors. Firstly, their expertise in coastal dynamics, particularly in sea turtle nesting areas in Suriname, adds significant value to the project. Additionally, Deltares' interest in nature-based solutions aligns well with the goals of the TURTLE project.

Topconsortium voor Kennis en Innovatie (TKI) Deltatechnologie

TKI Deltatechnologie is part of the Dutch Topsector Water initiative, focusing on promoting public-private partnerships that drive innovation in water-related fields, including coastal protection, delta management, and sustainable water technologies. The organization's role is to allocate research funding and foster collaboration between knowledge institutions, private companies, and governmental bodies. Through these efforts, TKI Deltatechnologie aims to enhance the global competitiveness of the Dutch water sector, contributing to the development of cutting-edge solutions for water management challenges (TKI Deltatechnologie, n.d.).

TKI Deltatechnologie became involved in the TURTLE project by providing critical funding to support the research initiatives. Their engagement is mainly to facilitate and ensure a successful collaboration between the research institutions and private partners. By enabling public-private partnerships, TKI ensures that the project aligns with broader innovation goals and meets the necessary funding criteria. The main motivation for their involvement lies in advancing nature-based solutions for flood protection, aligning with the project's goals to create sustainable coastal interventions that also protect sea turtle nesting habitats.

Boskalis

Boskalis, headquartered in the Netherlands, is an international leader in dredging, maritime infrastructure, and environmental solutions. The company provides services for sustainable and innovative solutions across coastal, river, and delta areas, which include beach nourishment, port development, and flood protection. Boskalis is committed to advancing nature-based solutions, integrating environmental expertise with engineering to create projects that balance infrastructure needs with ecological preservation, particularly in sensitive marine and coastal areas.

Boskalis became involved in the TURTLE project after recognizing the alignment between their goals for sustainable coastal development and the project's objectives of supporting sea turtle habitats through nature-based solutions. They then decided to join the TKI project. Boskalis's interest in the TURTLE project lies in gaining insights into how they can design their dredging and coastal nourishment activities in a way that is favorable for sea turtles and their nesting behavior. Last year, for example, they carried out a beach replenishment project in Togo and Benin where turtle nesting played a role.

Their involvement in the project as well as communication with the other partners is limited so far. Until now, they have contributed with laboratory resources and in-kind support for sediment analysis.

4.3.2. Project structure

The structure of the TURTLE project can be understood from the interviews conducted. TURTLE operates with a network structure. Network governance involves "a select, persistent, and structured set of autonomous firms (as well as nonprofit agencies) engaged in creating products or services based on implicit and open-ended contracts to adapt to environmental contingencies and to coordinate and safeguard exchanges. These contracts are socially-not legally-binding"(Jones et al., 1997, p. 914).

In this network Delft University of Technology plays a central role and has a substantial responsibility as the primary link connecting all partners. This structure is described as a *lead organization governed network* by Provan and Kenis (2007). This form of governance is characterized by a highly brokered network with few direct organization-to-organization interactions, instead, the network is governed by a leading organization, facilitating collaboration between the partners. In the TURTLE project, Delft University of Technology fulfills this role, acting as the central coordinating entity that facilitates collaboration among partners. Figure 4.7 shows this current structure, with Delft University of Technology as the lead organization connecting all partners.

Figure 4.7: Current structure of the TURTLE project, with Delft University of Technology as the central hub coordinating with all partners.

The TURTLE project uses a project-based approach, where collaboration shifts depending on the needs of each specific project. When data collection or fieldwork is required, the right partners come together to form an effective working team. This setup allows connections to be either loosely or tightly coordinated, depending on the project's needs. Once a specific project wraps up, the level of interaction with those partners typically reduces. Orton and Weick, 1990 explains that the uni-dimensional interpretation of loose and tight coupling represents a spectrum. At one end, tightly coupled systems consist of responsive components that do not act independently. At the other end, loosely coupled systems have independent components that do not respond to each other.

The tightening of connections for specific projects can for example be observed in the projects in Suriname and Galveston where specific field work was conducted. TURTLE's structure becomes more focused, with a smaller group working directly together. Partners collaborated based on the project's specific requirements, as shown in Figure 4.8. This setup allows for close collaboration with only the necessary partners during the project, and interaction is scaled back after the project concludes. It must be noted that in the current structure, there is limited to no connection between the actors involved outside the project.

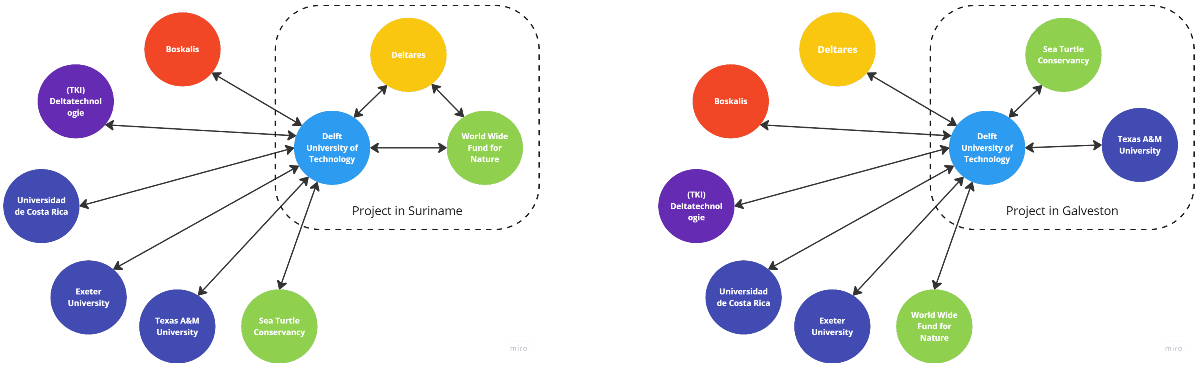


Figure 4.8: Structure of the TURTLE project in Suriname and Galveston, showing Delft University of Technology as the central hub with connections to various partners.

Overall, this structure demonstrates TURTLE's flexibility in moving between broad, consortium-wide collaboration and more focused, project-based teamwork.

4.3.3. Key themes from interviews

This section discusses the primary themes identified from interviews with the TURTLE project partners, revealing core aspects of their involvement and perspectives on collaboration.

Involvement

Partners had various comments on their involvement in the project and how certain factors promote or limit their ability or willingness to be involved. One frequently mentioned positive aspect was the interdisciplinary nature of the project, which combines conservation, biology, and engineering. Partners expressed enthusiasm about collaborating with individuals from different backgrounds, as it broadened their perspectives and enhanced the project's overall impact. This interdisciplinary nature not only motivated participation but also fostered a sense of value in contributing unique expertise. Another factor positively influencing partners' involvement, as mentioned by multiple stakeholders, was having shared goals among actors. Partners emphasized that a shared mission was one of the main drivers of collaboration. Closely linked to this is the mutual benefit of relationships within the project, which was also highlighted as a key reason for involvement.

Conversely, a frequently mentioned factor limiting further involvement was a lack of funding or difficulty securing funding. The inability to secure the necessary resources restricts deeper engagement for various stakeholders. Many expressed that limited budgets often required a narrow focus on immediate, small-scale deliverables, which reduced the potential for long-term research or expansion. Additionally, most partners noted a sense of disconnection from the broader TURTLE project due to the project-oriented, "on-demand" engagement model. This approach meant that collaborators were often involved only in specific sub-projects or fieldwork, without a clear understanding of how their contributions fit into the larger initiative. In some cases, collaborators were even unaware that their work was part of the TURTLE framework. Many partners expressed a desire to be more involved but felt uncertain about how to engage beyond their assigned tasks.

Communication

The on-demand communication model was perceived as practical for most partners, allowing them to focus on core responsibilities without a constant expectation of involvement. This flexible approach was especially appreciated by partners balancing multiple commitments. However, the demand-driven nature of communication also contributed to a sense of isolation for some collaborators, as previously mentioned in the *Involvement* section.

Many partners expressed a desire for structured periodic updates, such as summaries or symposia, to keep them informed of overall progress without overwhelming them with frequent emails or meetings. For instance, the suggestion of periodic virtual symposia was raised to provide high-level updates, helping partners remain connected to the TURTLE project even if they were not actively involved at that time. This would enhance engagement and allow partners to feel informed without extensive or disruptive communication.

Virtual communication through meetings was the most employed form of communication throughout the project. Generally, this was considered effective and convenient, especially given the international nature of the project. Occasional in-person meetings were mentioned as valuable for stronger relationship building and connections between the partners.

Interdisciplinary collaboration and data sharing

The interdisciplinary nature of the project was highly valued, with participants noting that integrating expertise from conservation, biology, engineering, and social sciences was essential to advancing project goals. Partners observed that the alignment of shared objectives and recognition of each collaborator's contributions fostered a sense of collective responsibility and engagement within the project. They also observed that working with colleagues from other disciplines broadened their views and provided new insights, benefiting not only the project but also their personal development.

In addition to interdisciplinary collaboration, data sharing emerged as another central theme, with participants emphasizing the need for accessible, long-term datasets. Effective collaboration depends on systems that allow partners to contribute and access data in real time, facilitating cross-disciplinary insights and supporting cohesive research efforts. Such systems would also reduce the need for constant updates, as partners could directly access results from other disciplines as needed. This accessibility would empower partners to proactively contribute to different parts of the project whenever they identify opportunities for input.

Outcomes with impact

The final key theme that emerged from the interviews focused on ensuring the project's outcomes have a tangible impact. Many partners emphasized the importance of linking research with practical applications. By collaborating with conservation groups, government agencies, and community leaders, the project's insights can influence strategies to protect coastal ecosystems rather than remaining solely in scientific publications.

Non-profit organizations like WWF and STC were identified as key players in disseminating knowledge beyond the scientific community. These organizations are strategically positioned to drive actionable change through public outreach, which not only extends the project's impact but also boosts public recognition.

Participants also frequently highlighted the value of social media and visual content in engaging the public. In an age of digital connectivity, concise, visually appealing summaries—such as videos or infographics—can be more effective than traditional academic reports for reaching wider audiences. By leveraging social media, the project can raise awareness and foster a deeper connection between people and the conservation goals of the TURTLE project. This kind of engagement is vital for generating public support and mobilizing community action toward conservation. Increased visibility could open doors for additional funding opportunities as well.

4.3.4. Relating key themes to structure

In this section, the relation between the key themes identified in the interviews and the TURTLE project's current governance structure is explored, with many of the challenges partners face possibly stemming from the network's organizational setup. As outlined in Section 4.3.2, the TURTLE project follows a network structure led by Delft University of Technology, which acts as the central coordinating body.

This arrangement, while facilitating efficient coordination, also shapes partners' experiences in ways that reveal both the strengths and limitations of the existing structure.

The interviews highlight the importance partners place on aligning project goals, which aligns with existing literature on network structure. However, while the focus in literature is on the importance of goal similarity, it distinguishes this from strict goal consensus. Research indicates that when there is a shared consensus on broad, network-level goals, participants tend to be more engaged and collaborative, especially in non-hierarchical, voluntary networks (Van De Ven, 1976). Exact alignment on purposes, by contrast, may lead to challenges when collaborating within a network (Park, 1996). With a consensus on overarching goals, rather than identical objectives, partners can pursue their own aims while contributing to the network's broader mission (Provan & Kenis, 2007). This perspective reflects partners' comments in interviews, where a shared mission and mutual benefit emerged as key motivations for their involvement. The diverse specific objectives originating from the different disciplines, such as advancing academic knowledge or supporting sea turtle nesting site conservation, resonate with Park's (1996) findings on avoiding conflicts in collaborative networks.

The sense of disconnect that many partners feel from the TURTLE project can be tied to its current lead organization-governed network structure. In this structure, collaboration is highly project-based; partners work intensively with specific other partners for certain periods, depending on the project's needs. Once a particular sub-project concludes, however, interaction between those partners significantly decreases. In the absence of new initiatives requiring their expertise, communication often fades or even ends entirely. During sub-projects, relations can be described as functional and strong, where partners contribute essential expertise or resources, as described by De Bruijn and Heuvelhof (2018). Such relationships are intensively engaged only when they serve clear, immediate project goals.

While this project-based approach effectively mobilizes specialized resources, research by Granovetter (1973) indicates that weak or incidental relationships—those outside core, task-specific needs—are also critical for partner engagement within a network. Even though these relationships are used less frequently and may not serve immediate project needs, they help keep partners connected to the broader project and its goals, especially when their expertise isn't currently needed. Provan and Kenis, 2007 also suggests that weak ties support continuous involvement and reduce the disconnect felt during inactive periods. Regular interactions among a diverse set of partners foster trust and shared commitment, which ultimately strengthens each partner's connection to the project as a whole (Emerson et al., 2011). In the TURTLE project, the absence of these broader, weaker ties likely contributes to the sense of disconnection expressed by the interviewees.

Granovetter's (1973) weak ties theory and Emerson et al.'s (2011) research on increasing connection to projects by having regular interactions among partners directly applies to the partners' expressed desire for periodic updates or symposia in the interviews. Their preference for these occasional interactions aligns with network theory's emphasis on weak, incidental connections as critical components for sustained engagement. These weak ties—formed through periodic, broad-reaching updates—can keep partners connected to the project's overarching mission, even during periods of inactivity.

The mention of data sharing in the interviews aligns with these theories as well, as it could contribute to an increased number of weak ties within the project. Making results and datasets accessible within the network would allow partners to proactively contribute to various aspects of the project, even in areas where they are not directly involved. This approach could increase the number of weak ties among partners, potentially enhancing overall engagement and interdisciplinary collaboration.

Lastly, the emphasis interviewees placed on effectively communicating results, especially beyond the scientific community, connects to the current lead organization structure. While this centralized setup effectively coordinates partners for specific sub-projects, it may limit sustained connections with end-users, such as community organizations, NGOs, and local governments, who are essential for putting scientific insights into practice. Because partners are not directly connected to all projects, the responsibility to communicate results across the network largely falls on Delft University of Technology, which may limit the dissemination of findings and reduce opportunities for partners to engage with outcomes from projects they were not directly involved in. Collaboration with community-focused partners like WWF and STC often remains tied to individual projects or fieldwork, which could lead to missed opportunities for sharing results from other projects through their networks, potentially reaching new audiences or strengthening relationships. Increasing weak links to these organizations could help extend the project's influence beyond academia.

To summarize, the key themes highlight both strengths and challenges within the TURTLE project's current collaboration model. While the lead organization network structure allows Delft University of Technology to efficiently coordinate sub-projects and leverage specialized expertise, it also limits sustained engagement and continuity among partners. This centralized structure, combined with the demand-driven communication model, fosters an "on-demand" collaboration that can lead to reduced involvement and a sense of disconnection from the broader project vision. Partners' expressed needs for periodic updates, interdisciplinary data sharing, and stronger ties with end-user organizations emphasize the importance of more integrated, inclusive communication strategies. These findings underscore the need for a refined collaboration approach that balances centralized coordination with mechanisms to build weak ties and ensure continuous engagement.

4.3.5. Strategic framework for enhanced collaboration

This section presents a strategic framework designed to enhance collaboration within the TURTLE project, creating a more interconnected and resilient network. Practical implementation measures are provided, along with key success factors to ensure the framework's effectiveness.

Framework objectives

The main objective of this strategic framework is to enhance the TURTLE project's collaborative structure by addressing identified challenges in partner engagement and communication while retaining the current structure's strengths. To achieve this, the framework seeks to:

- **Enhance partner engagement:** Create a collaborative environment where partners remain actively connected to the project's overarching vision, even when not directly involved in specific sub-projects. This objective aims to encourage a sense of continuity and shared purpose across all participants, regardless of their level of active participation.
- **Facilitate interdisciplinary data sharing:** Enable partners from diverse fields to easily access and contribute data, enhancing synergies across conservation, biology, and engineering. This objective aims to promote collaborative opportunities and cross-disciplinary insights, ultimately strengthening research output and impact.
- **Improve communication with end-users and external stakeholders:** Develop effective channels for disseminating project outcomes to external stakeholders, including conservation groups and the public, ensuring that findings support actionable conservation strategies and gain public support.

Together, these objectives aim to build a more integrated network that supports both short-term project needs and the long-term goals of conservation and sustainability.

Retaining current structure strengths

While this framework introduces strategies to address identified challenges in collaboration, it is equally important to retain the strengths of the TURTLE project's existing structure. The lead organization model, with Delft University of Technology at the center, has proven effective in coordinating sub-projects and leveraging specialized expertise from diverse partners.

One key strength of this structure is its ability to use project-specific collaboration, where partners contribute expertise as needed while avoiding unnecessary resource strain. This demand-driven engagement model has supported a flexible operational approach, which partners find beneficial when combining the project with other responsibilities. This flexibility is essential to maintain when designing new strategies that aim to increase communication or partner inclusion. Efforts to broaden involvement should be carefully balanced to avoid including partners in sub-projects where their time and resources may not be used effectively.

Additionally, the emphasis on interdisciplinary collaboration has proven to be a critical asset. The structure facilitates integration across conservation, biology, and engineering fields, creating an environment where diverse perspectives contribute to a holistic approach. By retaining this focus on interdisciplinary work, the TURTLE project can continue benefiting from innovative solutions that emerge when multiple fields interact, strengthening the project's research impact and aligning well with partners' enthusiasm for interdisciplinary cooperation.

Overall, the framework aims to preserve these core strengths: efficient coordination, flexible engagement, and interdisciplinary collaboration. Any new strategies introduced will be designed to enhance, rather than disrupt, the operational effectiveness of the current model. By building on this solid foundation, the framework can support improvements in engagement and communication while maintaining the efficiency and adaptability that have contributed to the TURTLE project's success.

Promoting engagement: Building weak links

Creating a more cohesive and interconnected network within the TURTLE project requires the development of weak links among project partners. Defined by Granovetter (1973) as non-task-specific, occasionally used connections, weak links allow partners to stay engaged with the project's overarching goals even when not directly involved in specific sub-projects. Such connections bridge communication gaps, mitigate feelings of isolation reported by some partners, and maintain a unified vision across the network.

One primary challenge identified in partner interviews was a feeling of disconnect for those not directly engaged in particular sub-projects or phases. Due to the TURTLE project's structure, partner engagement is often project-specific, leading to intermittent involvement and a diminished sense of continuity. Cultivating weak links addresses this issue by fostering a sense of community across the network, enabling partners to feel more consistently connected to the project's progress and long-term objectives. For instance, brief but regular updates or informal discussions on recent fieldwork findings or new methodologies could sustain partner interest and encourage interdisciplinary insights without demanding full-scale commitment to every sub-project. Figure 4.9 illustrates a possible structure incorporating weak links, represented by the dotted lines. It is important to note that this is a conceptual visualization, intended to show how these weak links might function within the network. These links could form between any of the partners in various configurations.

Establishing weak links offers a balanced approach that complements the TURTLE project's existing structure while enhancing partner engagement. This strategy respects the practical limitations on partner time and resources, creating an environment where collaborators remain connected to the project's mission. The following sections on communication and results dissemination will detail how weak links can further contribute to building a cohesive and resilient network.

Strengthening communication: Improving ambient awareness

To enhance engagement and cohesion within the TURTLE project without requiring intensive participation, a targeted communication strategy focused on ambient awareness is essential. Ambient awareness can help partners stay connected with ongoing progress and developments in a low-effort way, aligning well with the TURTLE project's flexible, project-based collaboration model. Defined by Leonardi (2015), ambient awareness is an awareness of communications occurring among others in the organization, which provides a sense of connection even in the absence of frequent direct interaction.

Ambient awareness allows partners to sense the presence of others within the network and stay updated on their progress, even when working on separate projects or during low-interaction periods. This form of low-maintenance communication suits TURTLE's flexible, project-based structure, which values partners and their other responsibilities. Regular but brief updates such as fieldwork summaries, milestone achievements, or information on upcoming goals can establish a steady, low-barrier flow of information creating this ambient awareness. These updates enable partners to check in on each other's work at their own convenience, making it easier for them to stay engaged.

Moreover, ambient awareness encourages proactive collaboration and engagement. When partners are aware of each other's progress and findings, they can choose to engage when they feel they can

Figure 4.9: The TURTLE project structure including weak links

add value. For instance, by having access to updates or summaries shared within the network, partners can identify when their expertise might benefit a project themselves, instead of only contributing when they are asked to do so. This supports the interdisciplinary nature of the TURTLE project, as partners from different fields may bring valuable perspectives to sub-projects they aren't directly involved in, potentially sparking new insights that may not have been anticipated by the core team.

This approach also aligns well with the concept of weak links, promoting engagement across the network. As partners become more aware of each other's activities, they feel more connected to the larger network (Morrison-Smith et al., 2021), fostering a sense of motivational presence. This is the feeling of being part of a community of contributors, as described by Olson and Olson (2014). Additionally, allowing partners to choose when to engage, rather than limiting interactions to the sub-projects they are asked to be a part of, facilitates the formation of weak links. Increased opportunities for proactive engagement strengthen the network's collaborative workings, creating a more resilient and cohesive project environment.

Ensuring impact: Increasing result transmissibility

To maximize the impact of the TURTLE project and ensure that the results find their way into actionable conservation strategies a clear understanding of how to effectively share results is essential. An important part of effectively disseminating results is how these can be framed in a way to increase transmissibility among the general public. Given the TURTLE project its conservationist nature, gaining public interest presents a big opportunity to increase the project its impact. Effectively sharing findings in a way that resonates with the public not only raises awareness but could also inspire public support. This support could in turn provide the project with pathways to new funding opportunities (Milkman & Berger, 2014).

To enhance the public transmissibility of TURTLE project findings, focusing on strategic framing methods is essential. Research suggests that scientific discoveries are more likely to spread widely when they are presented in ways that evoke emotional engagement, highlight practical relevance, or are simply interesting to the audience (Milkman & Berger, 2014). In this context, TURTLE's findings can be communicated to inspire a connection to turtle conservation, leveraging emotional language and visuals to resonate with the public's inherent care for wildlife preservation. Additionally, presenting the project's discoveries as practically useful to broader environmental goals can enhance public support. This might include linking TURTLE's insights to broader discussions on climate change, coastal health, or biodiversity, framing findings as contributions to solving pressing global issues. Framing the results in a manner that underlines both the urgency and the feasibility of action can inspire greater public interest and a willingness to support the project's initiatives, potentially leading to new funding pathways that can sustain and expand the project's impact.

Partners like WWF and the Sea Turtle Conservancy (STC) could play a pivotal role in enhancing the public reach and impact of TURTLE project findings. These organizations bring valuable experience in effectively communicating conservation research results to wide audiences. Leveraging their established channels and expertise in crafting emotionally resonant and actionable messages can help TURTLE findings connect more with the public. Their involvement could amplify public understanding and support, as their communication strategies are already trusted sources for conveying critical conservation needs, ultimately aiding the TURTLE project in building a strong foundation for public engagement and potential funding.

Implementation

To provide a better understanding of how this framework could be applied to the current structure of the TURTLE project, an implementation of tangible strategies is presented.

The current structure lacks a dedicated space for supporting overall collaboration. This can be addressed by creating a Microsoft Teams environment or a similar platform, where results can be stored, and posts can be created for partners to interact with. This approach also helps to establish weak links by providing involved actors the option to engage at their own convenience. The Microsoft Teams environment aligns with the data-sharing aspect of interdisciplinary collaboration, as stakeholders can access data on demand. Posts in the Microsoft Teams environment are a great way to have brief updates such as fieldwork summaries, milestone achievements, or information on upcoming goals contributing to improving ambient awareness.

A weekly or monthly update would inform partners about current developments and upcoming events, these updates function as reminders because not all partners will systematically engage through the Microsoft Teams environment. For example, if the projects in Suriname or Galveston had provided recurring updates, other partners would have been aware of these initiatives. Stimulating their engagement and allowing other partners to potentially contribute to the projects. During interviews, some completed projects were found to be barely known to stakeholders not directly involved. These weak links help bridge the closed project sphere, as illustrated in Figure 4.10. Again, this is a conceptual visualization of how these weak links might form within the network. These links could form between different partners in different configurations.

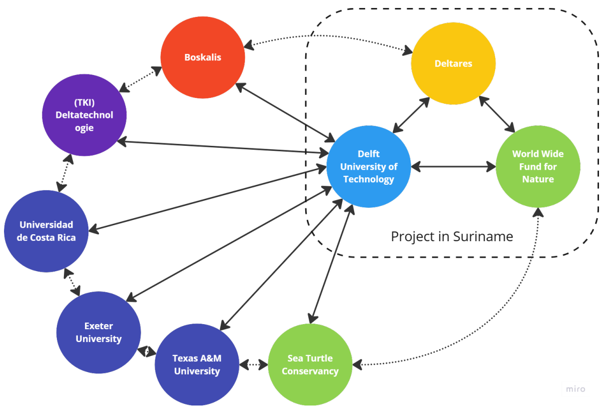


Figure 4.10: The creation of weak links breaching the project sphere

To determine the timing and method for sharing updates, a communication plan could be implemented. This tool would collect stakeholder preferences regarding update frequency and format, as shown in the blank communication plan in Figure 4.11. By gathering information on the communication preferences of all stakeholders, they can be updated in a manner that suits their needs. It is also important to balance actor involvement, as not every partner may wish to be informed about every detail.

Another means of communication that fosters engagement, as mentioned by multiple stakeholders, is

F2F Face to face | E Email | O Online meeting | R Report | PM Progress meeting

	Delft University of Technology	Universidad de Costa Rica	Texas A&M University	Exeter University	Deltares	Boskalis	World Wide Fund for Nature	Sea Turtle Conservancy	(TKI) Deltatechnologie
Weekly									
2-weekly									
Quaterly									
Ad-hoc									miro

Figure 4.11: Blank communication plan for the TURTLE project.

a symposium. This could be held online or in person and would provide a space for all stakeholders—and potentially even the public—to come together. A symposium is an excellent way to build a sense of community, enhancing engagement and connection to the project.

To communicate with the public, tools other than a shared environment for partners should be used, but they could be similar in concept. As mentioned in "Increasing Result Transmissibility," sharing findings in a way that resonates with the public is essential for progress. Currently, a Google search for the project yields only the TKI Delta webpage, the TU Delft webpage, and one article. However, this article cannot be accessed directly from the main project pages. Additionally, the project has a limited presence on social media with; a post found from the TU Delft Civil Engineering and Geosciences faculty, highlighting the nomination of the paper, "Distribution of Global Sea Turtle Nesting Explained from Regional-Scale Coastal Characteristics," for the Best Climate Action and Energy Paper (TU Delft, 2024).

It would be beneficial to create a centralized page where all project information is stored. The TKI consortium's webpage is an ideal location, as it already partially serves this purpose. Adding a section labeled "Results" on this webpage would allow for easy access to project outcomes. When new results are available for public viewing, promotion channels should be utilized to increase visibility. Social media posts with links to this page—and therefore the results—are excellent promotional tools, as all partners can share the same webpage where the project and its findings are available. Using partners as communication channels is a powerful way to create exposure, as most partners have an established presence on social media. Partners like the WWF are already skilled at conveying impactful messages. Collective sharing of results also enhances engagement with the project, as partners promote the overarching consortium's outcomes and engage with them in the process. Over time, it would be ideal to create short, comprehensible summaries of results specifically for social media. These summaries can be used to promote full reports and engage a broader audience.

In conclusion, three ways to stimulate engagement with project partners have been outlined: regular updates at a frequency that partners can choose, an online environment for convenient interaction, and a symposium for more intensive engagement. For public interaction, a centralized page for easy access to results is proposed, alongside engagement through partners' social media.

Monitoring and evaluation

Effective monitoring and evaluation is essential for assessing the success of the TURTLE project's collaborative framework and identifying areas for improvement. This step is crucial to ensure that implemented strategies such as weak link development, improved communication practices, and increased public engagement are achieving their intended outcomes. By continuously tracking the framework's effectiveness, the TURTLE project can adapt to evolving partner needs and external pressures.

- **Partner engagement:** By keeping track of interactions in the Teams environment and responses to updates sent, partner engagement can be traced continuously. Regular analysis of these metrics will indicate engagement levels and potentially highlight areas that require additional attention.

- **Data accessibility and interdisciplinary collaboration:** Monitor data exchange frequency and cross-disciplinary access rates within the shared data platform. Increased cross-partner access, interactions, and collaboration requests will serve as indicators of effective interdisciplinary synergy.
- **Public engagement impact:** Measure reach, engagement, and user interactions with public-facing content with analytics tools such as Google Analytics. By tracking which content resonates most, adjustments can be made to maximize visibility and impact.

Feedback loops can be utilized to ensure that the results from the monitoring directly inform adjustments to the collaboration strategy. Regularly aggregated findings can be discussed with partners, and any necessary changes to engagement or data-sharing procedures will be considered cooperatively. This iterative process ensures an effective use of the strategy by keeping it responsive to partner needs.

Conclusion
The presented collaborative framework offers a dynamic, adaptable approach to reinforcing partner relationships, fostering interdisciplinary collaboration, and enhancing public engagement. By aligning objectives with practical tools, this framework provides actionable strategies that respond directly to challenges frequently identified by partners. It also preserves the strengths of the existing structure, creating a balanced approach that promotes engagement while maintaining stability. Through its flexibility, the framework is well-equipped to support ongoing project goals, address evolving needs, and sustain an effective collaborative environment.

4.4. Hydraulic Structures Results

Several mitigation measures are possible at Ostional Beach to address the challenges of coastal squeeze. In this section, these measures will be outlined, and their positive/negative as well as short-term/long-term effects will be discussed. The measures under consideration include:

- Foreland creation
- Foreland restoration
- Preparing for retreat

4.4.1. Foreland creation

Foreland creation refers to the process of establishing new landforms, such as marshes or mangroves, which act as natural buffers against flooding and coastal erosion. This approach is particularly significant in low-lying coastal areas and river deltas that are vulnerable to rising sea levels. By absorbing wave energy, these natural features help mitigate the impact of storm surges and reduce the risk of flooding.

The importance of foreland creation is twofold. Firstly, it enhances flood protection. Natural forelands, such as salt marshes and mangroves, absorb wave energy and reduce the force of storm surges on coastal infrastructure, providing a cost-effective defense against flooding (McIvor et al., 2013). Secondly, forelands provide ecosystem services, including habitats for biodiversity, carbon sequestration, and water filtration (Kim et al., 2016). Foreland creation can involve either restoring degraded areas or creating entirely new forelands by stimulating sediment deposition or depositing dredged material.

Despite its benefits, foreland creation is not without challenges. While it is often viewed as a cost-effective alternative to hard engineering solutions, there are concerns about ecosystem disruption, social and economic impacts, and the long-term viability of newly created habitats (Verheem & Laeven, 2009).

At Ostional Beach, foreland creation poses significant challenges. The absence of existing forelands in the area means that any new creation would likely disrupt the current ecosystem. Additionally, the unique ecological dynamics of Ostional, particularly its role as a major nesting site for sea turtles, could be profoundly affected. The impact on wave run-up, groundwater stability, and beach morphology would be unpredictable and potentially detrimental. Given these considerations, foreland creation is not a viable mitigation measure for Ostional Beach.

4.4.2. Foreland restoration

Foreland restoration focuses on rehabilitating coastal habitats, such as intertidal marshes and wetlands, that have been degraded or lost due to human activity. The aim is to restore the natural functions of these ecosystems, which provide critical flood protection, habitat for wildlife, and overall coastal resilience.

Effective foreland restoration relies on promoting natural sedimentation processes to rebuild habitats. In temperate regions, salt marshes are the primary focus, whereas tropical and subtropical regions prioritize mangroves due to their critical roles in coastal protection and biodiversity (DeCelles & Giles, 1996). A common method is managed realignment, which involves removing or breaching embankments to restore tidal influences and allow wetlands to re-establish naturally (Esteves & Esteves, 2014). This may also include vegetative measures or targeted sediment deposition.

Foreland restoration offers several benefits, including enhanced flood protection, improved water quality, new habitats for biodiversity, and increased carbon sequestration. However, these efforts must be tailored to the historical, social, and ecological contexts of the area. Engaging local communities and stakeholders is essential to ensure the success and sustainability of restoration projects.

At Ostional Beach, the feasibility of foreland restoration is highly limited. The absence of natural forelands, aside from the offshore reef, makes this measure largely incompatible with the existing environment. Attempting to introduce restored forelands would likely disrupt the delicate ecological balance, with potentially catastrophic effects on wave run-up, groundwater stability, and beach morphology. Furthermore, the area's protected status prohibits interventions that could harm the natural ecosystem. Consequently, foreland restoration is not a viable option for this location.

4.4.3. Preparing for retreat

Preparing for retreat, also known as managed retreat, involves the strategic relocation of communities, infrastructure, and ecosystems to adapt to coastal changes. At Ostional Beach, this approach would mean allowing the coastline to naturally migrate inland while ensuring that the community and its infrastructure adapt to these changes (Bongarts Lebbe et al., 2021).

Managed retreat requires long-term planning, considering future climate scenarios to anticipate and mitigate risks. Key steps include:

1. Comprehensive planning: Developing detailed strategies that outline when and how to relocate communities and infrastructure while ensuring minimal disruption.
2. Community engagement: Involving residents in the planning process is crucial, addressing their concerns and preferences to ensure equitable and just outcomes.
3. Legal and policy frameworks: Implementing zoning regulations to restrict development in high-risk areas and establishing policies to support relocation efforts.
4. Incremental adaptation: Gradual relocation efforts, starting with "no-regret" strategies that provide immediate benefits and flexibility for future adjustments.

From the perspective of wave run-up, groundwater stability, and beach morphology, preparing for retreat appears to be the most suitable option. By allowing natural processes to take place gradually, the coastline can adapt without the need for disruptive engineering interventions. However, the success of this measure depends on clear agreements with the local community, ensuring that their needs and cultural values are respected.

4.4.4. Future plan

Considering the potential impacts of various mitigation measures on the protected environment, it is evident that the solution space for Ostional Beach is limited. Hard engineering solutions are largely unsuitable due to the area's ecological sensitivity and protected status. Instead, the focus must shift toward collaboration between the government, local communities, and nature. A planned retreat strategy could provide a long-term solution by relocating the community further inland, thereby creating space for the beach to expand naturally and sustain turtle nesting habitats.

Such a plan should include comprehensive monitoring and documentation to serve as a model for future managed retreat efforts. While the worst-case scenario would involve no changes to current practices, a proactive retreat strategy offers a pathway to balance ecological preservation with community needs, ensuring the long-term viability of Ostional Beach as a critical nesting site for sea turtles.

5

Discussion

5.1. Wave runup

This section discusses the spatial accuracy of the timestacks, the environmental influences and impacts on the timestacks and data extraction, the manual runup selection process, the model performances, and future research for wave runup in Ostional.

5.1.1. Spatial accuracy of timestacks

The accuracy of photogrammetrically derived products, such as our timestacks, is inherently linked to the precision of various underlying processes, including the calibration of intrinsic camera parameters and the accuracy of ground control points (GCPs).

Symbol	Description	Unit	Value	Uncertainty
u_0	U component of principal point	pixels	2038.26	12.46
v_0	V component of principal point	pixels	1472.31	16.46
f_x	U component of focal length	pixels	1998.85	7.45
f_y	V component of focal length	pixels	1993.85	7.26
k_1	Radial Distortion Coefficient	-	-0.0047	0.0074
k_2	Radial Distortion Coefficient	-	0.00267	0.0079
k_3	Radial Distortion Coefficient	-	-0.0056	0.00257
p_1	Tangential Distortion Coefficient	-	0.0055	0.00205
p_2	Tangential Distortion Coefficient	-	0	0

Table 5.1: Camera calibration parameters and their uncertainties.

Table 5.1 presents the intrinsic camera parameters, where sub-pixel accuracy was achieved for focal length and principal point. However, radial and tangential distortion coefficients exhibited higher uncertainties. As outlined in Section 3.2.2, we employed Bouguet (2004)'s MATLAB toolbox, which estimates intrinsic camera parameters based on an extended pinhole camera model. The higher uncertainties in distortion coefficients likely stem from the limitations of Bouguet's method when dealing with highly distorted images, such as those captured by fisheye lenses (Bruder & Brodie, 2020). While the GoPro 7 Black camera was set to 'linear' mode to reduce fisheye effects, internal corrections may introduce systematic errors. Additionally, the simultaneous estimation of lens distortion and camera parameters can lead to coupled errors, affecting overall accuracy (Ricolfe-Viala & Sánchez-Salmerón, 2011). To mitigate these issues, separate calibration of lens distortion and pinhole parameters can be considered.

To address these issues, Hartley and Zisserman (2003) and Ricolfe-Viala and Sánchez-Salmerón (2011) recommend separate calibration for lens distortion and pinhole parameters to reduce coupling and improve calibration stability. User-driven factors can also affect calibration precision. Inaccuracies may result if corner detection is rushed, or if the calibration checkerboard is not perfectly planar.

Symbol	Description	Unit	Value	Uncertainty
x	X-coordinate of camera position	m	642167.3569	0.39702
y	Y-coordinate of camera position	m	1105235.5777	0.16795
z	Z-coordinate of camera position	m	6.9371	0.20449
Azimuth	Camera azimuth angle	$^\circ$	275.7747	0.3916
Tilt	Camera tilt angle	$^\circ$	85.444	0.70302
Swing	Camera swing angle	$^\circ$	-0.95163	1.3805

Table 5.2: Solved camera extrinsics and NLinfit error for camera parameters in a UTM world coordinate system.

The extrinsic camera parameters, presented in Table 5.2, which define the camera's pose in 3D space, also exhibit larger uncertainties, particularly in the azimuth and tilt angles. Higher uncertainties in azimuth and tilt angles are observed, possibly influenced by the intrinsic parameter uncertainties. In particular, as Ricolfe-Viala and Sánchez-Salmerón (2011) notes, inaccuracies in intrinsic parameters can propagate to extrinsics. Additional factors may include the with software corrected wide-angle imagery of the GoPro, while Bruder and Brodie's (2020) MATLAB model for extrinsics presumes a standard distortion model rather than a fisheye. Another potential source of error is a sub-optimal GCP network, with insufficiently spread or linearly aligned GCPs, which may degrade the accuracy of the 3D to 2D transformations. Tsai (1987) describes that iterative calibration methods are highly dependent on good initial parameter estimates, and suboptimal starting values may lead to convergence issues and increased extrinsic uncertainty, ultimately impacting point clouds and timestacks.

GCP network accuracy significantly impacts the photogrammetric process overall. Reprojection error quantifies the accuracy with which the projection matrix can predict pixel coordinates from GCP world coordinates. Table 5.3 and Figure 5.1 display the reprojection errors for the GCPs, which or not insignificant. The larger errors could be attributed to errors in the extrinsics or factors such as poor image quality, inaccurate GCP coordinates, inaccurate GCP pixel selection, or limitations in the optimization algorithm.

GCP	Unit	X Error	Y Error
2	m	0.08	-0.26
3	m	-0.08	0.56
4	m	0.46	-0.39
5	m	-0.30	-0.04
6	m	-0.25	0.17
7	m	-0.01	0.12
8	m	0.01	-0.00
RMSE	**m**	**0.23**	**0.29**

Table 5.3: Horizontal reprojection errors for each ground control point (GCP)

Figure 5.1: Visual representation of GCP reprojection

The total spatial error of the timestacks is influenced by a combination of factors, including intrinsic camera calibration errors, georeferencing uncertainty, image resolution and quality, and atmospheric conditions, where atmospheric distortions can affect the accuracy of the measurements. A significant concern is the potential for a structural error in the timestacks. Due to the aforementioned limitations and uncertainties, the absolute spatial accuracy of the timestacks may be compromised. This structural error, which for our data based on the GCP reprojection error, could go up to 0.5 meters, could introduce bias in the reference level to the 3D-world, for example, our results could structurally estimate the true wave runup 0.5 higher in z level then is true. This bias could potentially affect the interpretation of long-term trends and comparisons between different datasets.

It is crucial to acknowledge and quantify the potential impact of these uncertainties on the derived results. By understanding the limitations of the methodology, researchers can interpret the findings appropriately and draw meaningful conclusions.

5.1.2. Environmental impacts

Environmental conditions play a critical role in determining the quality and readability of timestack images, directly influencing both manual and automated wave run-up extraction methods.

Lighting conditions are particularly influential. Variations in sunlight, cloud cover, and shadow can affect image contrast, complicating the delineation of the waterline from the surrounding beach (Bailey & Shand, 1994; Simarro et al., 2015). At Ostional, the black volcanic sand intensifies this challenge, as the high reflection from the sand surface can exaggerate glare, particularly under direct sunlight. During periods of low-angle sun exposure (e.g., early morning or late afternoon), reflection at the seepage face can create bright spots that interfere with waterline detection (see Figure 5.2). Low contrast and glare can hinder both manual and automated extraction methods, such as our entropy and saturation-based analyses, which depend on consistent pixel intensity gradients to identify wet/dry boundaries. Aarninkhof et al. (2005) recommends setting an intensity threshold to screen out images with poor lighting to improve data reliability.

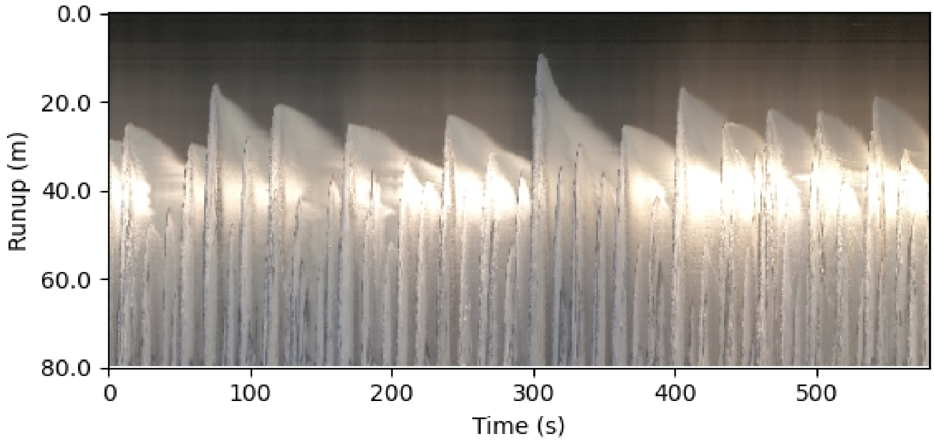


Figure 5.2: Example low sun effect on timestack image

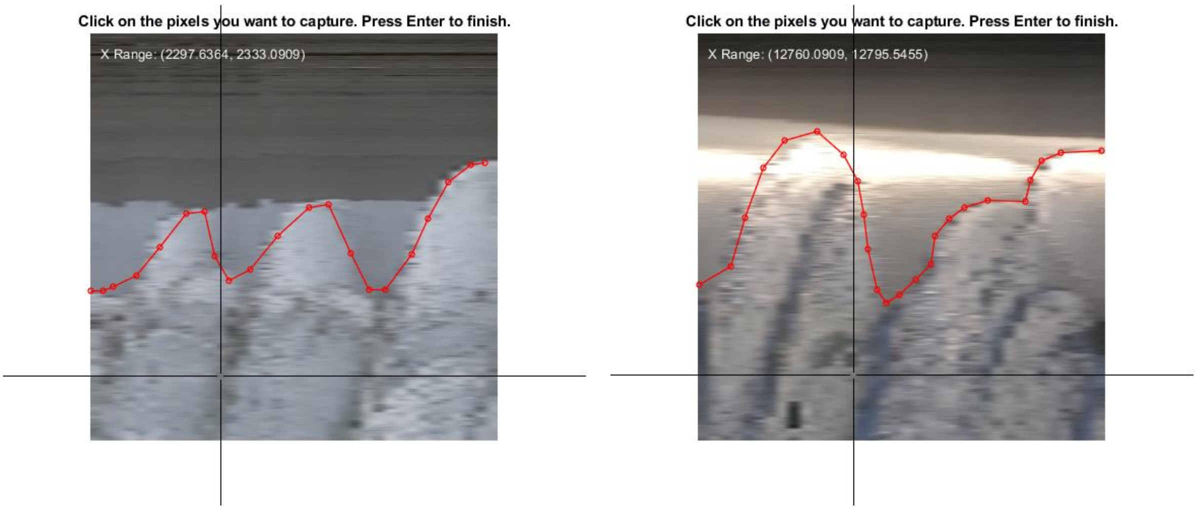
Weather conditions such as rain and fog can further reduce visibility and image quality (Huisman et al., 2011; Uunk et al., 2010). Heavy rain, which is not uncommon in the rainy season of Costa Rica, in particular, can lead to very low contrast conditions, making it impossible to reliably detect the water line in any way (Bailey & Shand, 1994). On top of that windy conditions can induce camera vibrations, resulting in blurry images and wobbly timelapse imagery, leading to increased spatial inaccuracy of the timestacks and extracted wave runup data.

Presence of objects or people: Moving objects, beachgoers, or vehicles within the camera's field of view can introduce spurious features in the timestack, affecting the accuracy of runup extraction (Simarro et al., 2015).

In conclusion, environmental factors can introduce significant challenges to wave runup extraction from timestack images. Careful consideration of these factors and the implementation of robust image processing techniques are essential to ensure accurate and reliable results.

5.1.3. Manual selection of wave runup

Here the process and accuracy of the manual wave runup selection are critically evaluated. As shown in Figure 5.3, the selection process was subject to considerable interpretative judgment and felt choice-based; the precise boundaries between swash and backwash were often unclear, necessitating arbitrary distinctions. As noted in the previous section, numerous environmental factors varied throughout the timestacks, adding to the complexity and increasing the reliance on subjective judgment in identifying the wave runup. In retrospect, the manual selections used in this study may have been overly restrictive, frequently excluding portions of the backwash, potentially introducing error and bias. By focusing predominantly on the swash boundary, the full extent of wave retreat may have been underestimated, leading to a more constrained representation of the runup dynamics.



(a) Example 1 **(b)** Example 2

Figure 5.3: Manual selection process of wave runup from timestack

Subjectivity is a recognized limitation of manual selection methods (Aarninkhof et al., 2005; Bailey & Shand, 1994). Studies indicate that reliance on human interpretation can introduce inconsistencies in data, both between different operators and within the same user's assessments over time. For instance, Bailey and Shand (1994) reports standard deviations of up to 10% in runup measurements, underscoring the potential for error even with carefully conducted manual selections. Moreover, manual selection is time-intensive; digitizing longer time series can take hours, thus limiting the number of timestack images and transects that can feasibly be analyzed within a study's timeframe.

The implications of these inaccuracies are particularly significant, as manual selection is used as the baseline for evaluating our automated wave runup extraction models. Both systematic and random errors introduced by manual selection can affect model comparisons, with user subjectivity potentially skewing results with consistent operator bias.

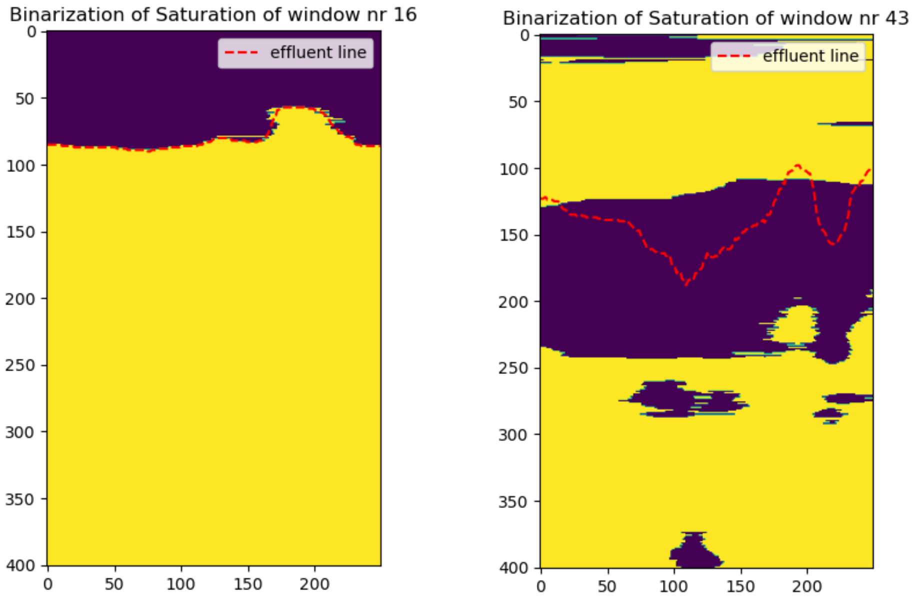
5.1.4. Model performance

The comparative results in section 4.1 demonstrate a clear performance advantage of the entropy-only model over the saturation-entropy model in automated wave runup extraction. While both models were applied under identical configurations, the superior performance of the entropy-only model indicates that entropy-based features alone may be more effective in capturing the characteristics of wave runup events in this dataset.

Entropy-saturation model performance

Visual and statistical assessments reveal significant error and erratic behavior in the saturation-entropy model, indicating it may inadequately capture wave runup dynamics. This discrepancy likely stems from the model's assumptions, which appear misaligned with the patterns observed in manual data. Notably, the model's negative overall correlation suggests an inverse relationship with the observed data.

Given that the entropy-only model demonstrates significantly better performance, the issue likely stems from the saturation component of the saturation-entropy model. As discussed in Section 2.1.6, this saturation layer relies on color intensity for detection. The saturation-entropy model performed well under the conditions in Galveston, Texas, as shown by van der Grinten (2024). However, the volcanic grey-black sand at Ostional Beach, which might have lower color intensity and saturation than Galveston's yellowish sand, may hinder the model's ability to detect the effluent line (i.e., the boundary between wet and dry sand).



(a) Correct example

(b) Inorrect example

Figure 5.4: Effluent line calculation through saturation binarisation across two window types

Rather than filtering out noise above the effluent line, the saturation layer may introduce further inconsistencies, as displayed by most saturation-visualization windows like in Figure 5.4b. The model likely misclassifies parts of actual wave data as noise, disrupting the binarisation process in the entropy layer. As a result, the output contains systematically lower values, as shown in Figure 5.5, thereby underrepresenting the true runup dynamics. This is corroborated by statistical analysis, with a bias of 32.4 m, which supports the hypothesis that the saturation-entropy model does not accurately capture wave runup under the conditions at Ostional.

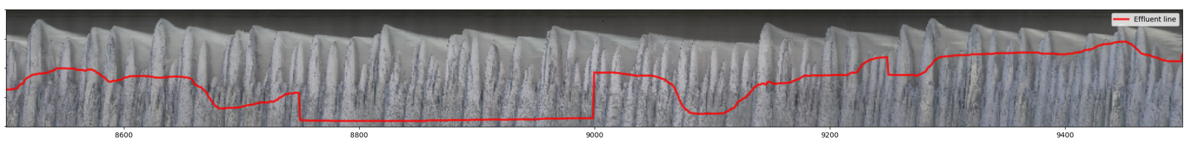


Figure 5.5: Effluent line over timestack

Entropy-only performance

The entropy-only model demonstrates reasonably positive results, as evidenced by both visual performance analysis and statistical metrics. While the model shows a reasonably high Pearson correlation of 0.69, it also presents a substantial bias of -11.3 meters. This bias suggests that the model excels at estimating the peak values of wave runup but is less effective in capturing the lower extents, particularly the wave backwash.

The model's capacity to reliably capture maximum wave runup makes it particularly useful for assessing peak wave behavior, which is a crucial factor in understanding coastal dynamics and evaluating the risk of turtle nest flooding. This is particularly important for the context of the Ostional Beach study, where extreme runup values play a central role in assessing the impacts on turtle nesting sites.

An alternative explanation for the high bias may lie in the manual selection process, which, as previously discussed, could have been too conservative in defining the extent of the wave backwash. If this is the case, the entropy-only model may actually be better at capturing the backwash than the statistical analysis suggests. Likely, both factors, the model's tendency to prioritize maximum runup values and the conservative nature of the manual selection, are interacting to produce the observed bias, highlighting the complexity of the wave dynamics in this study.

5.1.5. Future research for wave runup in Ostional

Currently, only one of the nine days of collected wave runup camera footage has been analyzed due to time limitations. Future research should prioritize a comprehensive analysis of the entire dataset, as it could reveal valuable insights into temporal variations and model robustness.

Investigating extraction models that consider Ostional's dark sand and high contrast conditions, particularly for enhancing the color contrast in time-stacks, could be instrumental in improving wave runup accuracy. Leveraging the full dataset and investigating alternative models could allow for a more comprehensive understanding of wave interactions at Ostional. For example, implementing a machine learning model like that of van der Grinten (2024) could be beneficial. A custom neural network trained specifically on Ostional's dataset could incorporate input channels that account for the unique conditions in Ostional.

Georeferencing accuracy should be improved for long-term research at Ostional Beach to ensure data can be accurately compared and referenced to real-world 3D coordinates. Future studies could explore advanced calibration techniques that account for lens distortion and camera orientation. Additionally, using a normal-lens camera, increasing the number of well-distributed GCPs, and applying robust optimization algorithms can enhance photogrammetric accuracy. As Hartley and Zisserman (2003) suggests, incorporating soft constraints in parameter estimation can guide the model toward optimal values, improving stability and accuracy.

5.2. Groundwater table

5.2.1. Key findings

Measurements were made near the high tide shoreline, and higher up the beach. The measurements were made in both neap tide and spring tide. During the spring tide, measurements were made on 17 October, when the maximum water level was higher than MHWS in Quepos UHSLC, 2024. Even at the shoreline, the highest groundwater level that was measured was −0.86 m (see Figure 4.3). Higher up the beach, at the location of well 2, the highest measured groundwater level is −1.24 m.

The measurements showed that the beach groundwater table shows a largely sinusoidal movement, with minimal variation from this movement. In the measurements of logger 1, small fluctuations are visible. These fluctuations are not visible in the measurements from logger 2.

The amplitude of the groundwater table's motion decreases landward, and the groundwater table's movement is delayed (phase-shifted) moving landward. The amplitude in the groundwater table movement is larger during spring tide than during neap tide. This is in accordance with what Horn (2002) has found. Furthermore, in the measurements during the neap tide period, it can be observed that the groundwater table at well 2, further landward than well 1, is at all times higher compared to the groundwater table in well 1. This is not seen in the measurements during the spring tide period. Horn (2002) found that the groundwater table at rising tide generally tilts landward, and seaward at falling tide. In the measurements of this study at neap tide, the groundwater table tilts seaward at both falling and rising tides.

5.2.2. Interpretation

The sinusoidal movement that is observed in the measurements has a period that is similar to the tide. In section 3.1, the tidal conditions during the measurement period were discussed. Fitting a sinusoidal function to the data, to find out if the period of the groundwater table's motion is close to that of the tide gives very varying results for the different days and loggers. This is because the measuring periods were shorter than a full cycle. This means that not enough time for each cycle is captured every day and the fit is a bit different for every day. Thus, it is not possible to give a number on the period of the oscillation of the groundwater table. However, it is visible that the motion has a period in the same order of magnitude as the tide, is present every day, and shows variations in amplitude coinciding with the neap and spring tides. Based on this, it is possible to say that the motion in the groundwater table is mainly induced by the tide.

The fluctuations we see in the measurements of logger 1 can be attributed to several things. These could for example be moments where wave runup flooded water into the wells from the top, causing a short peak in the groundwater table, but stabilizing again quickly. Although the caps which were screwed on the top of the wells were not watertight, there was only a small space where water could enter the well from the top. It is unlikely that the logger would capture this flooding to such an extent. They could also be currents in the groundwater due to long waves, but they are not visible to the other loggers, and they are very infrequent and inconsistent, making this explanation unlikely. Another explanation is that these peaks could simply be inaccuracies in the sensor. This is the most likely explanation, since during calibration, the logger was already fluctuating (very slightly). It is very well possible that it has made larger misreadings in later measurements.

Since the groundwater table in the beach was measured to be quite deep, it would not have posed a threat to the nests, at least in the conditions in which was measured. According to Trullas and Paladino (2007) and Whiting et al. (2007), the average depth of the nest of an olive ridley turtle is approximately 40 cm. The groundwater table that was measured reached only a maximum of 86 cm below the level of the sand. The water level at high tide on this day was comparable to MHWS. However, more research should be performed to be able to give a more pronounced conclusion on the risk to the nests. For example, the influence of rain, the locations of the nests, and the effect of storms have not been investigated.

5.2.3. Strengths and limitations

The strength of this research is that the measurements were performed with a high frequency, making sure to capture small variations in the groundwater table accurately. According to Global Water, n.d., the logger has a high accuracy of 0.1%, which would make the measurements very reliable. However, as we have seen in logger 3, which gave strange misreadings, the accuracy of the loggers could be faltering at times. Their accuracy should be assessed more extensively.

Also, the measurements were performed over a longer period, capturing many different (tidal) conditions. This makes it possible to assess the difference in response of the groundwater table to, for example, the difference in neap and spring tides, but also rising and falling tides.

The limitations of this research are that the measurements can not very accurately be coupled to the tide or wave conditions, because there is no data available at the measurement site. Having this data would be very interesting, being able to quantify how much the phase of the tide shifts (is delayed) and how the amplitude dampens when moving landward.

Another limitation is that there are big gaps in the data because the sensors were removed after every day of measuring. Also, setting up and calibrating the equipment cost a lot of time, making that the actual measurements are around 6-8 hours long. Lots of data in between these slots is missing.

5.2.4. Suggestions for further research

The first suggestion for further research is installing the wells for a longer consecutive time. It would be very interesting to have one long data set of a given period. The only challenge here is making sure that the equipment does not get damaged or stolen. Additionally, it would be interesting to make measurements of the tidal and wave conditions while measuring the groundwater table, to be able to couple the two measurements.

In this study, no attention was paid to the hydraulic conductivity of the sand. Only the phreatic surface was measured, however, due to capillary rise Horn, 2002, moisture could enter the nests even above the groundwater table. This risk might be interesting to investigate further.

In this research, only three loggers were used to make the measurements, of which one was malfunctioning. To get a better idea of the groundwater table, more wells would have to be installed. They would have to be placed from the shoreline up to the water line.

In the measurements, no groundwater table variations due to long wave dynamics were found. It could be interesting to experiment more with other methods of measuring the groundwater table. For example, according to Turner (1998), when a sampling frequency of less than 1 minute is necessary, the best method is to use buried pressure sensors.

5.3. Collaboration

5.3.1. Key findings

The analysis of the collaboration in the TURTLE project resulted in several key insights into the collaboration dynamics, strengths, and challenges within the project. These include the following:

Collaborative strengths

The TURTLE project benefits from a strong lead organization model, with Delft University of Technology effectively coordinating sub-projects and leveraging partner expertise. This centralized structure ensures efficient oversight and alignment across diverse contributions.

A demand-driven engagement approach has also proven effective, allowing partners to contribute flexibly without overstretching resources. This flexibility is crucial for balancing project involvement with other responsibilities and should be preserved in future strategies.

Finally, the emphasis on interdisciplinary collaboration across conservation, biology, and engineering is a major strength, fostering innovation and holistic solutions. Retaining this focus while building on existing coordination and flexibility will ensure any new strategies enhance, rather than disrupt, these foundational strengths.

Disconnection and engagement challenges

While the TURTLE project benefits from its centralized lead organization model, this structure also contributes to challenges in fostering network-wide connectivity. Communication tends to flow through Delft University of Technology, with limited direct interaction between other partners. This centralization, while efficient for coordination, can leave partners feeling isolated from the broader collaboration, reducing opportunities for knowledge sharing and cross-disciplinary innovation.

Engagement levels across the network also vary with some partners feeling connected to the project, whereas others report limited engagement due to unclear opportunities for participation. These challenges underscore the need for strategies to increase inclusivity and ensure all partners can meaningfully contribute while maintaining flexibility to align with their capacities.

Opportunities for improvement

Addressing the disconnection and engagement challenges presents opportunities to strengthen the TURTLE project's collaboration framework. One key area is the development of ”weak links” to enhance indirect communication and facilitate broader partner interactions. By encouraging cross-partner engagement outside the central hub, the network can increase interdisciplinary collaboration and reduce reliance on Delft University as the sole point of connection.

Another significant opportunity lies in cultivating ambient awareness among partners. By increasing the visibility of ongoing activities, progress, and research outputs across the network, partners can remain informed even when not directly involved in specific sub-projects. This ambient awareness can be facilitated through digital tools, such as shared dashboards or regular project updates, enabling partners to identify areas to contribute and fostering a stronger sense of connection to the overall project. Enhancing visibility in this way helps maintain flexibility while improving engagement and collaboration across the network.

Finally, increasing the visibility of the TURTLE project's outcomes to the public and stakeholders offers dual benefits: boosting external support and funding opportunities while motivating partners by highlighting the impact of their work. These improvements can enhance engagement, build a more resilient network, and support the project's long-term success.

5.3.2. Interpretation

The TURTLE project its collaboration model shows the balance between centralized coordination and distributed expertise. While the lead organization model used drives efficiency and promotes flexibility, it inadvertently also restricts communication practices, with most interactions flowing through the Delft University of Technology. This dynamic highlights a double-edged sword, centralization ensures smooth coordination but risks limiting the number and diversity of interactions between partners in the project.

The disconnection and engagement challenges found suggest that while the project is effective using a demand-driven engagement model, it could benefit from a stronger sense of community among partners. This specific finding has significant implications, as there is a risk of limited innovation and limited contributions to the project by partners without stronger ties between them. Addressing ambient awareness, for example, is not just about improving communication but about creating an environment where ideas and insights can flow between partners, even those less actively engaged.

The project its interdisciplinary nature is a clear strength, but it also presents an opportunity that could be utilized further. During sub-projects, these different disciplines are leveraged effectively, but creating more spaces for cross-disciplinary connections outside of these projects could promote partner engagement and lead to new ideas and approaches within projects, instigated by partners not directly involved.

5.3.3. Unexpected findings

Several themes emerged during the interviews that, while outside the immediate scope of this research, offer valuable directions for future investigation.

One of the most frequently mentioned aspects during the interviews was funding, often perceived as a limiting factor for the project's development. Partners noted that their level of engagement in projects was constrained by the amount of funding available. Additionally, it was highlighted that research projects, in general, tend to struggle with securing adequate funding, which poses ongoing challenges for continuity and growth.

Including new partners was discussed in multiple interviews when interdisciplinary collaboration in projects was mentioned. Including new partners in the project is an excellent way to expand the initiative. During the fieldwork, a new potential partner was connected to the TURTLE project. The new strategies proposed within the framework of the results can help to effectively incorporate new partners into the project, by early establishment of the partner's needs for communication and engagement.

5.3.4. Limitations

The interviews conducted for this research involved representatives from the TURTLE project partners. Relying on representatives may introduce bias, as their perspectives are influenced by both their personal views and those of their organization. Among all the partners, only one representative per company was interviewed. Ideally, multiple individuals from each company would have been interviewed to provide a broader perspective and reduce potential biases.

The current framework represents an initial iteration. It would have been preferable to return to the partners to discuss the proposed framework and develop additional iterations. This process would have strengthened the framework, as feedback from the partners would help refine and improve the strategy. However, these limitations primarily arose due to the time constraints imposed by the defined project timeline.

5.3.5. Suggestions for further research

The framework developed should be implemented and tested in the field. To make this possible, further research into the practical application of the strategy and measures that are to be taken is necessary. As stated in the limitations, this is the first iteration of the framework, and it requires further refinement through practical application. Project management is an ever-evolving process, as project dynamics constantly change. Therefore, it is recommended to try and test the framework against these changes to ensure its adaptability and effectiveness.

From the unexpected findings, recommendations for further research in other directions can be derived. From the interviews, it is evident that there will always be a need for funding; eventually, every project must be financed in some way. All partners have different approaches to securing or delivering the necessary resources to the overarching project or sub-projects, and it would be beneficial to obtain a clear understanding of how these approaches can be utilized in the future. A research focus on funding and alternative ways to conduct research is proposed.

Since including new partners would contribute to the growth of the project, it is recommended to research how the project could include new partners sustainably and effectively. The current strategy can be used as a foundation for including new partners, listing some principles that are important for collaboration. It is however recommended to develop a complete, comprehensive strategy for including new partners.

5.4. Coastal squeeze mitigation

The people from Costa Rica are proud of their nature, this comes from meticulous conservation efforts (Central Intelligence Agency (CIA), 2024). As stated previously the beach of Ostional and the foreshore is a protected environment. Because of the conservation efforts etc., the people from Costa Rica do not like construction on the coast, especially when it could potentially change the natural processes. Therefore to respect the Costa Rican culture I would recommend no further research in hard engineering solutions to coastal squeeze, even though it is a thing that is happening on the coast on the beach of Ostional. I would also not recommend it since the building of a hard solution would probably be more expensive than relocating the village of Ostional. I would recommend close monitoring to adequately react to the conservation of the turtle nesting space. Also, the monitoring data could be used to further understand the coastal groundwater dynamics in a shifting or squeezed beach.

Only half of the protected beach environment was prone to coastal squeeze, the other half had a little green zone behind the beach. This was also true for the beaches north and south of Ostional. So to place this into, only half of the nesting beach in Ostional is prone to coastal squeeze in the near future. The green zones behind the beaches are good to mention because they are installed/preserved intentionally and this is already the solution the the problem.

5.5. Integration of the different disciplines

The findings from hydrodynamic analysis, collaborative strategies, and coastal engineering interventions reveal the critical interconnections necessary for sustaining turtle nesting beaches like Ostional. By integrating these disciplines, the study demonstrates how a holistic approach can address the challenges of managing such dynamic and sensitive ecosystems.

Hydrodynamic analysis, such as wave runup and groundwater table dynamics, provides a detailed understanding of physical processes impacting turtle nesting habitats. These insights are essential for identifying risks like flooding or erosion and informing potential interventions. However, implementing such findings effectively relies on robust collaborative strategies, where interdisciplinary teams and stakeholders co-develop solutions that respect ecological integrity and community values. Collaborative efforts ensure that scientific recommendations are actionable, culturally sensitive, and supported by those directly impacted.

Coastal engineering interventions, while often necessary to address coastal squeeze or other risks, must align with both the findings from hydrodynamic analysis and the priorities identified through collaboration. At Ostional, the emphasis on minimal human interference underscores the need for engineering solutions that adapt to natural processes rather than attempt to control them. This balance is achieved by using data-driven insights from hydrodynamic studies to anticipate changes and collaboratively plan interventions that prioritize retreat over rigid structures.

By linking these domains, the approach becomes not only technically sound but also socially and ecologically sustainable. Hydrodynamic data provides the ”why,” collaboration defines the ”how,” and coastal engineering interventions represent the ”what” of a comprehensive conservation strategy.

6 Conclusions

6.1. Wave runup findings

This study aimed to characterize wave run-up dynamics at Ostional Beach, Costa Rica, in the context of olive ridley sea turtle nests. By employing timestack imagery and comparing both manual and automated wave run-up extraction methods, the research provided valuable insights into the effectiveness of automated models in capturing wave run-up patterns in this unique coastal environment.

The entropy-only model demonstrated a higher level of accuracy, with a strong correlation to manually digitized data, making it a promising tool for future applications in similar settings. In contrast, the Entropy-Saturation model faced challenges, particularly in detecting the effluent line due to the dark volcanic sand. These findings emphasize the importance of tailored approaches when applying automated methods to coastal environments with distinct visual characteristics.

The spatial accuracy of the wave runup data was influenced by factors such as camera calibration, rectification, and environmental variables. These conditions, common in dynamic beach environments like Ostional, presented challenges for both extraction methods and require careful consideration in future studies.

Future research should focus on refining automated models to better accommodate the unique environmental and site-specific conditions of Ostional Beach. Additionally, a deeper exploration of the limitations identified in this study, particularly the impact of environmental factors on data accuracy, will be essential for improving the reliability of wave run-up measurements in similar coastal ecosystems. This comprehensive approach will further the understanding of coastal dynamics and contribute to informed conservation efforts, especially for vital nesting sites like Ostional.

6.2. Groundwater table findings

The groundwater table measurements were performed to increase our understanding of the dynamics of the beach groundwater table on Ostional Beach, how to accurately measure it, and its impact on the turtle nesting site. It was observed that the motion in the groundwater table was mainly dependent on the tide, where the amplitude dampens and the phase lag increases landward. During spring tide, the highest groundwater table that was measured was 86 cm below the sand, and was measured to be even deeper at the measuring location further landward up the beach.

The groundwater table was measured to generally be much deeper than the average depth of an olive ridley nest (40 cm). In the conditions and at the location of the measurements of this study, drowning by the groundwater table would not have posed a threat to the majority of the nests. However, this study only covered two measurement points, and during only one month. A lot of data can still be collected at different times and locations.

The measuring method was good enough to capture the tidal motion in the groundwater table well, however, fluctuations due to long waves were not captured in the measurements. This could be due to the logger not being sufficiently accurate, another possibility is that long waves have little to no influence on the groundwater table at Ostional Beach. More methods for measuring the groundwater table will have to be tested to determine this.

6.3. Collaboration findings

This research explored how collaboration in the TURTLE project can be enhanced by addressing current challenges while leveraging existing strengths. The key findings indicated that while the centralized lead organization model, demand-driven engagement, and interdisciplinary collaboration are core strengths, challenges related to disconnection, varying engagement levels, and communication gaps exist. These issues underscore the need for strategic improvements to make for more inclusive and effective collaboration within the project.

The analysis suggests that by enhancing ambient awareness among partners and cultivating weak links for broader engagement, the project can overcome communication barriers and foster stronger connections. These changes, when implemented alongside maintaining flexibility and interdisciplinary collaboration, will help balance operational efficiency with inclusivity and engagement. To ensure successful implementation of the proposed framework, it is recommended to further refine it based on project partners' feedback and ideas.

In conclusion, addressing the identified challenges while capitalizing on the existing strengths of the TURTLE project offers a clear path toward enhanced collaboration. This research provides a framework with actionable insights that can contribute to more effective and future-proof collaboration that not only benefits the project but future interdisciplinary initiatives as well.

6.4. Hydraulic structures findings

This research explored the possible mitigation measures for coastal squeeze on the beach of Ostional. Engineering mitigation measures where human intervention in the environment is needed are found to be not suitable for the beach in Ostional. Because the people of Costa Rica don't want it and because the integrity of the complicated beach processes is not guaranteed to stay the same. Therefore the recommendation is to prepare for retreat of the village inland when necessary. This way nature can run its course, as that is the purpose of a nature reserve. Close monitoring of the beach processes for a longer time is also recommended to see if these change.

6.5. Final reflection

The integration of hydrodynamic analysis, collaborative strategies, and coastal engineering interventions demonstrates the value of a multidisciplinary approach in addressing the challenges of conserving turtle nesting beaches. Each domain contributes essential perspectives: hydrodynamics enhances our understanding of coastal dynamics, collaboration ensures inclusive and adaptive planning, and engineering interventions provide actionable solutions that align with both environmental and community goals.

This study highlights the necessity of fostering synergy between disciplines. Hydrodynamic insights must guide engineering practices, while collaboration ensures that those practices are implemented in a way that respects local priorities and ecological principles. This interconnected approach enables the development of strategies that are not only scientifically robust but also socially and environmentally responsible.

References

Aarninkhof, S., Ruessink, B., & Roelvink, J. (2005). Nearshore subtidal bathymetry from time-exposure video images. *Journal of Geophysical Research: Oceans*, *110*(C6).

Abreu-Grobois, Plotkin, & IUCN. (2008, June 30). *Iucn red list of threatened species: Lepidochelys olivacea*. https://www.iucnredlist.org/species/11534/3292503

Bailey, D. G., & Shand, R. D. (1994). Determining wave run-up using automated video analysis. *Proceedings of the Second New Zealand Conference on Image and Vision Computing*, *2*, 1–2.

Baird, A. J., & Horn, D. P. (1996). Monitoring and modelling groundwater behaviour sandy beaches. *Journal of Coastal Research*, *12*(3), 630–640. http://journals.fcla.edu/jcr/article/view/80225/0

Battjes, J. (1974). Surf similarity. *Coastal Engineering 1974*. https://doi.org/10.1061/9780872621138.029

Beber, I., Sellés-Ríos, B., & Whitworth, A. (2024). Future sea-level rise impacts to olive ridley (lepidochelys olivacea) and green sea turtle (chelonia mydas) nesting habitat on the osa peninsula, costa rica. *Climate Change Ecology*, *7*, 100085. https://doi.org/10.1016/j.ecochg.2024.100085

Bézy, V. S., Putman, N. F., Umbanhowar, J. A., Orrego, C. M., Fonseca, L. G., Quirós-Pereira, W. M., Valverde, R. A., & Lohmann, K. J. (2020). Mass-nesting events in olive ridley sea turtles: Environmental predictors of timing and size. *Animal Behaviour*, *163*, 85–94. https://doi.org/10.1016/j.anbehav.2020.03.002

Bongarts Lebbe, T., Rey-Valette, H., Chaumillon, É., Camus, G., Almar, R., Cazenave, A., Claudet, J., Rocle, N., Meur-Ferec, C., Viard, F., et al. (2021). Designing coastal adaptation strategies to tackle sea level rise. *Frontiers in Marine Science*, *8*, 740602.

Bouguet, J.-Y. (2004). Camera calibration toolbox for matlab. *http://www. vision. caltech. edu/bouguetj/-calib_doc/*.

Bruder, B. L., & Brodie, K. L. (2020). Cirn quantitative coastal imaging toolbox. *SoftwareX*, *12*, 100582.

Cattaneo, C., Mainetti, G., & Sala, R. (2015). The importance of camera calibration and distortion correction to obtain measurements with video surveillance systems. *Journal of Physics: Conference Series*, *658*(1), 012009.

Central Intelligence Agency (CIA). (2024). *Costa rica - the world factbook* [Accessed: 2024-11-20]. https://www.cia.gov/the-world-factbook/countries/costa-rica/

Clarke, T. A., & Fryer, J. G. (1998). The development of camera calibration methods and models. *The Photogrammetric Record*, *16*(91), 51–66.

Da Silva, P. G., Coco, G., Garnier, R., & Klein, A. H. (2020). On the prediction of runup, setup and swash on beaches. *Earth-Science Reviews*, *204*, 103148. https://doi.org/10.1016/j.earscirev.2020.103148

De Bruijn, H., & Heuvelhof, E. T. (2018). *Management in networks* (2nd ed.). Routledge - Taylor & Francis Group. https://doi.org/10.4324/9781315453019

DeCelles, P. G., & Giles, K. A. (1996). Foreland basin systems. *Basin research*, *8*(2), 105–123.

Deltares. (n.d.). *Areas of expertise | deltares*. https://www.deltares.nl/en/expertise/areas-of-expertise

Dronkers, J. (2022). Climate adaptation measures for the coastal zone [Accessed: 2024-11-24]. https://www.coastalwiki.org/wiki/Climate_adaptation_measures_for_the_coastal_zone

Emerson, K., Nabatchi, T., & Balogh, S. (2011). An integrative framework for collaborative governance. *Journal of Public Administration Research and Theory*, *22*(1), 1–29. https://doi.org/10.1093/jopart/mur011

Emery, K. O., & Gale, J. F. (1951). Swash and swash mark. *Transactions American Geophysical Union*, *32*(1), 31–36. https://doi.org/10.1029/tr032i001p00031

Esteves, L. S., & Esteves, L. S. (2014). *What is managed realignment?* Springer.

Fish, M. R., Côté, I. M., Gill, J. A., Jones, A. P., Renshoff, S., & Watkinson, A. R. (2005). Predicting the impact of sea□level rise on caribbean sea turtle nesting habitat. *Conservation Biology*, *19*(2), 482–491. https://doi.org/10.1111/j.1523-1739.2005.00146.x

Fuentes, M., Limpus, C., & Hamann, M. (2011). Vulnerability of sea turtle nesting grounds to climate change. *Global Change Biology*, *17*(1), 140–153. https://doi.org/10.1111/j.1365-2486.2010.02192.x

Global Water. (n.d.). *Submersible pressure transducer & usb datalogger combination | ysi.com*. https://www.ysi.com/wl16

Google. (2023). *Google earth*. https://earth.google.com/

Gourlay. (1992). Wave set-up, wave run-up and beach water table: Interaction between surf zone hydraulics and groundwater hydraulics. *Coastal Engineering*, *17*(1-2), 93–144. https://doi.org/10.1016/0378-3839(92)90015-m

Granovetter, M. S. (1973). The strength of weak ties. *American Journal of Sociology*, *78*(6), 1360–1380. https://doi.org/10.1086/225469

Guza, R. T., & Thornton, E. B. (1982). Swash oscillations on a natural beach. *Journal of Geophysical Research Atmospheres*, *87*(C1), 483–491. https://doi.org/10.1029/jc087ic01p00483

Hartley, R., & Zisserman, A. (2003). *Multiple view geometry in computer vision*. Cambridge university press.

Holman, R. A., & Bowen, A. J. (1984). Longshore structure of infragravity wave motions. *Journal of Geophysical Research Atmospheres*, *89*(C4), 6446–6452. https://doi.org/10.1029/jc089ic04p06446

Horn, D. P. (2002). Beach groundwater dynamics. *Geomorphology*, *48*(1-3), 121–146. https://doi.org/10.1016/s0169-555x(02)00178-2

Horn, D. P. (2006). Measurements and modelling of beach groundwater flow in the swash-zone: A review. *Continental Shelf Research*, *26*(5), 622–652. https://doi.org/10.1016/j.csr.2006.02.001

Howd, P. A., Oltman□Shay, J., & Holman, R. A. (1991). Wave variance partitioning in the trough of a barred beach. *Journal of Geophysical Research Atmospheres*, *96*(C7), 12781–12795. https://doi.org/10.1029/91jc00434

Huisman, C. E., Bryan, K. R., Coco, G., & Ruessink, B. (2011). The use of video imagery to analyse groundwater and shoreline dynamics on a dissipative beach. *Continental shelf research*, *31*(16), 1728–1738.

Ikeuchi, K. (2021). *Computer vision*. Springer International Publishing. https://doi.org/10.1007/978-3-030-63416-2

Instituto Meteorológico Nacional de Costa Rica. (2024a). *¿quiénes somos?* [Accessed: 2024-10-29]. https://www.imn.ac.cr/quienes-somos

Instituto Meteorológico Nacional de Costa Rica. (2024b). *Estación meteorológica automática de garza* [Accessed: 2024-10-29]. https://www.imn.ac.cr/especial/estacionGarza.html

Instituto Meteorológico Nacional de Costa Rica. (2024c). Estación meteorológica cigefi - ucr [Accessed: 2024-10-29]. https://www.imn.ac.cr/especial/estacionCigefi.html

IUCN-SSC Marine Turtle Specialist Group. (n.d.). *Red list assessments | iucn-ssc marine turtle specialist group*. https://www.iucn-mtsg.org/statuses

Jones, C., Hesterly, W. S., & Borgatti, S. P. (1997). A general theory of network governance: Exchange conditions and social mechanisms. *Academy of Management Review*, *22*(4), 911–945.

Kim, K., Kim, H., Lim, J. H., & Lee, S. J. (2016). Development of a desalination membrane bioinspired by mangrove roots for spontaneous filtration of sodium ions. *ACS nano*, *10*(12), 11428–11433.

Leonardi, P. M. (2015). Ambient awareness and knowledge acquisition: Using social media to learn ”who knows what” and ”who knows whom”. *MIS Quarterly*, *39*(4), 747–762. https://doi.org/10.25300/misq/2015/39.4.1

Longuet-Higgins & Stewart, R. (1964). Radiation stresses in water waves; a physical discussion, with applications. *Deep Sea Research and Oceanographic Abstracts*, *11*(4), 529–562. https://doi.org/10.1016/0011-7471(64)90001-4

Lutz, P. L., Musick, J. A., & Wyneken, J. (2002, December 17). *The biology of sea turtles, volume ii*. CRC Press. https://doi.org/10.1201/9781420040807

Madison, G. (2020). *Sensor logger* (Version 1.6.5) [Mobile app, available on App Store]. https://apps.apple.com/us/app/sensor-logger/id1531582925

Mazaris, A. D., Matsinos, G., & Pantis, J. D. (2009). Evaluating the impacts of coastal squeeze on sea turtle nesting. *Ocean & Coastal Management*, *52*(2), 139–145.

McIvor, A., Möller, I., Spencer, T., & Spalding, M. (2013). Mangroves as a sustainable coastal defence. *7th International Conference on Asian and Pacific Coasts (APAC). The Nature Conservancy, University of Cambridge, and Wetlands International, Bali, Indonesia, September*, 24–26.

Miche, M. (1951). Le pouvoir réfléchissant des ouvrages maritimes exposés à l'action de la houle. *Annales des Ponts et Chaussées*, 285–319. https://resolver.tudelft.nl/uuid:959b3a89-cb91-477a-9a74-4de83f088652

Milkman, K. L., & Berger, J. (2014). The science of sharing and the sharing of science. *Proceedings of the National Academy of Sciences*, *111*(supplement 4), 13642–13649. https://doi.org/10.1073/pnas.1317511111

Morrison-Smith, S., Chilton, L. B., & Ruiz, J. (2021). Ambiteam: Providing team awareness through ambient displays. *Graphics Interface*. https://doi.org/10.20380/gi2021.04

NIST. (n.d.). *Nist internet time service*. https://tf.nist.gov/tf-cgi/servers.cgi

Oceana. (2010, July). *Why healthy oceans need sea turtles: The importance of sea turtles to marine ecosystems*. https://oceana.org/reports/why-healthy-oceans-need-sea-turtles-importance-sea-turtles-marine-ecosystems/

Olson, J. S., & Olson, G. M. (2014). Bridging distance: Empirical studies of distributed teams. *Human-Computer Interaction in Management Information Systems*, 117–134. https://doi.org/10.4324/9781315703626-14

Orton, J. D., & Weick, K. E. (1990). Loosely coupled systems: A reconceptualization. *Academy of Management Review*, *15*(2), 203–223. https://doi.org/10.2307/258154

Park, N. S. H. (1996). Managing an interorganizational network: A framework of the institutional mechanism for network control. *Organization Studies*, *17*(5), 795–824. https://doi.org/10.1177/017084069601700505

Pike, D. A., Roznik, E. A., & Bell, I. (2015). Nest inundation from sea-level rise threatens sea turtle population viability. *Royal Society Open Science*, *2*(7), 150127. https://doi.org/10.1098/rsos.150127

Provan, K. G., & Kenis, P. (2007). Modes of network governance: Structure, management, and effectiveness. *Journal of Public Administration Research and Theory*, *18*(2), 229–252. https://doi.org/10.1093/jopart/mum015

Raubenheimer, B., & Guza, R. T. (1996). Observations and predictions of run□up. *Journal of Geophysical Research Atmospheres*, *101*(C11), 25575–25587. https://doi.org/10.1029/96jc02432

Ricolfe-Viala, C., & Sánchez-Salmerón, A.-J. (2011). Using the camera pin-hole model restrictions to calibrate the lens distortion model. *Optics & Laser Technology*, *43*, 996–1005. https://doi.org/10.1016/j.optlastec.2011.01.006

Serafin, K. A., Ruggiero, P., & Stockdon, H. F. (2017). The relative contribution of waves, tides, and nontidal residuals to extreme total water levels on u.s. west coast sandy beaches. *Geophysical Research Letters*, *44*(4), 1839–1847. https://doi.org/10.1002/2016gl071020

Simarro, G., Bryan, K. R., Guedes, R. M., Sancho, A., Guillen, J., & Coco, G. (2015). On the use of variance images for runup and shoreline detection. *Coastal Engineering*, *99*, 136–147.

SOKKIA Europe. (n.d.). *Grx1 gnss receiver | sokkia europe*. https://eu.sokkia.com/sokkia-care-products/grx1-gnss-receiver

Stockdon, H. F., Holman, R. A., Howd, P. A., & Sallenger, A. H. (2006). Empirical parameterization of setup, swash, and runup. *Coastal Engineering*, *53*(7), 573–588. https://doi.org/10.1016/j.coastaleng.2005.12.005

Sturm, P. F., & Maybank, S. J. (1999). On plane-based camera calibration: A general algorithm, singularities, applications. *Proceedings. 1999 IEEE Computer Society Conference on Computer Vision and Pattern Recognition (Cat. No PR00149)*, *1*, 432–437.

SWOT. (2021). *Swot report vol xvi*. https://www.seaturtlestatus.org/swot-report-vol-16

TKI Deltatechnologie. (n.d.). *Tki delta technologie – achtergrond en werkwijze*. https://tkideltatechnologie.nl/achtergrond-werkwijze/

TKI Deltatechnologie. (2024, July 25). *Nature-based solutions for flood proof sea turtle nesting beaches (turtle) – tki delta technologie*. https://tkideltatechnologie.nl/project/nature-based-solutions-for-flood-proof-sea-turtle-nesting-beaches-turtle/

Trullas, S. C., & Paladino, F. V. (2007). Micro□environment of olive ridley turtle nests deposited during an aggregated nesting event. *Journal of Zoology*, *272*(4), 367–376. https://doi.org/10.1111/j.1469-7998.2006.00277.x

Tsai, R. (1987). A versatile camera calibration technique for high-accuracy 3d machine vision metrology using off-the-shelf tv cameras and lenses. *IEEE Journal on Robotics and Automation*, *3*(4), 323–344.

TU Delft. (2024). *Tu delft presents the nine best climate action & energy papers* [Accessed: 2024-11-06]. https://www.tudelft.nl/en/2024/tu-delft/tu-delft-presents-the-nine-best-climate-action-energy-papers

Turner, I. L. (1998). Monitoring groundwater dynamics in the littoral zone at seasonal, storm, tide and swash frequencies. *Coastal Engineering*, *35*(1-2), 1–16. https://doi.org/10.1016/s0378-3839(98)00023-4

UHSLC. (2024). *Uhslc stations*. https://uhslc.soest.hawaii.edu/stations/?stn=087#tidecal

Uunk, L., Wijnberg, K., & Morelissen, R. (2010). Automated mapping of the intertidal beach bathymetry from video images. *Coastal Engineering*, *57*(4), 461–469.

Valverde, R. A., Orrego, C. M., Tordoir, M. T., Gómez, F. M., Solís, D. S., Hernández, R. A., Gómez, G. B., Brenes, L. S., Baltodano, J. P., Fonseca, L. G., & Spotila, J. R. (2012). Olive ridley mass nesting ecology and egg harvest at ostional beach, costa rica. *Chelonian Conservation and Biology*, *11*(1), 1–11. https://doi.org/10.2744/ccb-0959.1

Van De Ven, A. H. (1976). On the nature, formation, and maintenance of relations among organizations. *Academy of Management Review*, *1*(4), 24–36. https://doi.org/10.5465/amr.1976.4396447

van der Grinten, M. J. (2024). *Enhancing wave runup extraction on a dissipative beach through machine learning and image preprocessing techniques*. Delft University of Technology. https://resolver.tudelft.nl/uuid:8882db80-2627-4762-89ab-19daaeb163a0

Verheem, R., & Laeven, M. (2009). Sea for flood protection in the netherlands: A case study. *Report for the Netherlands Commission for Environmental Assessment, http://api. commissiemer.nl/docs/mer/diversen/views_experiences_2009_p20-25. pdf*.

Ware, M., Long, J. W., & Fuentes, M. M. (2019). Using wave runup modeling to inform coastal species management: An example application for sea turtle nest relocation. *Ocean & Coastal Management*, *173*, 17–25. https://doi.org/10.1016/j.ocecoaman.2019.02.011

Whiting, S. D., Long, J. L., Hadden, K. M., Lauder, A. D. K., & Koch, A. U. (2007). Insights into size, seasonality and biology of a nesting population of the olive ridley turtle in northern australia. *Wildlife Research*, *34*(3), 200. https://doi.org/10.1071/wr06131

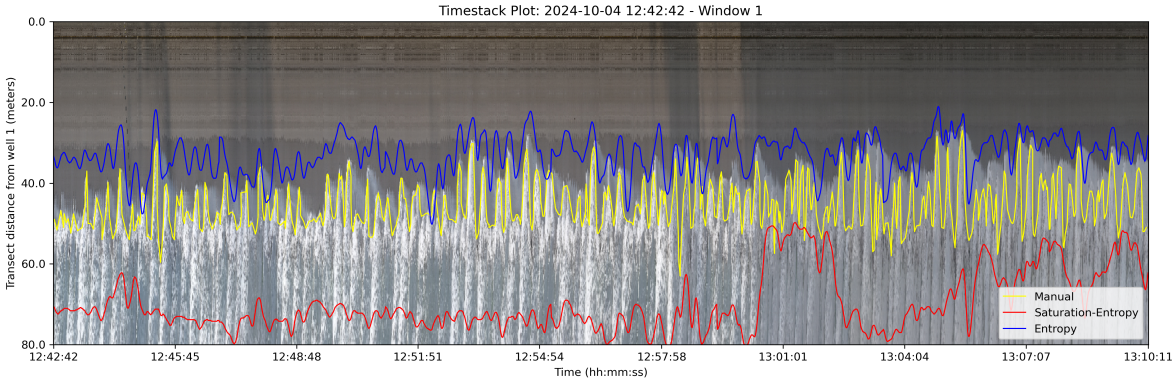
Zhang, S., & Zhang, C. (2009). Image analysis for wave swash using color feature extraction. *2009 2nd International Congress on Image and Signal Processing*, 1–4.

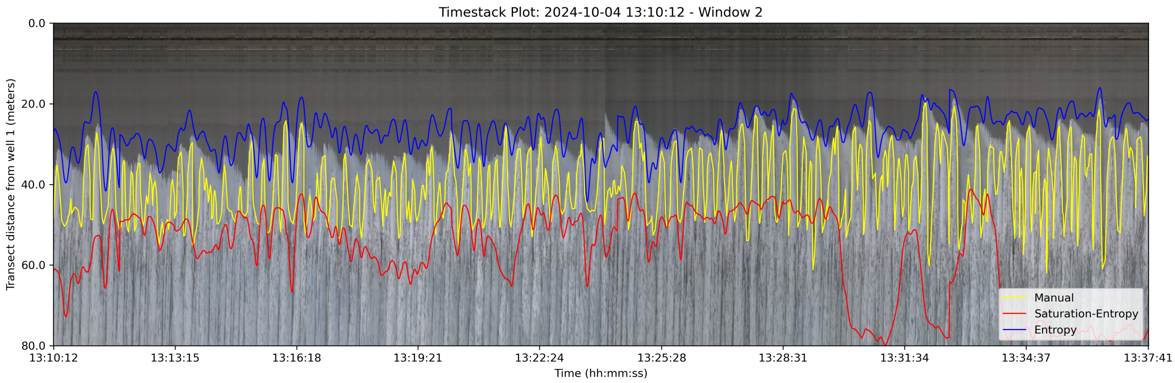
Zhang, Z. (1999). Flexible camera calibration by viewing a plane from unknown orientations. *Proceedings of the seventh ieee international conference on computer vision*, *1*, 666–673.

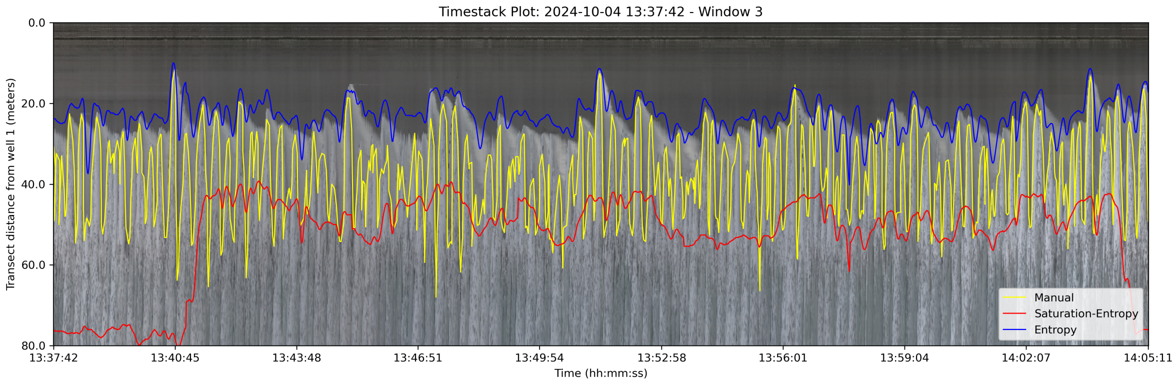
A

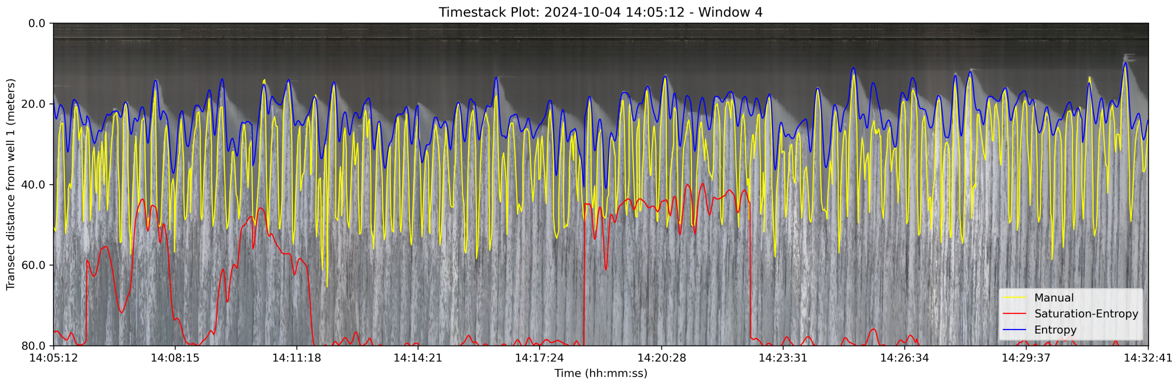
Timestacks

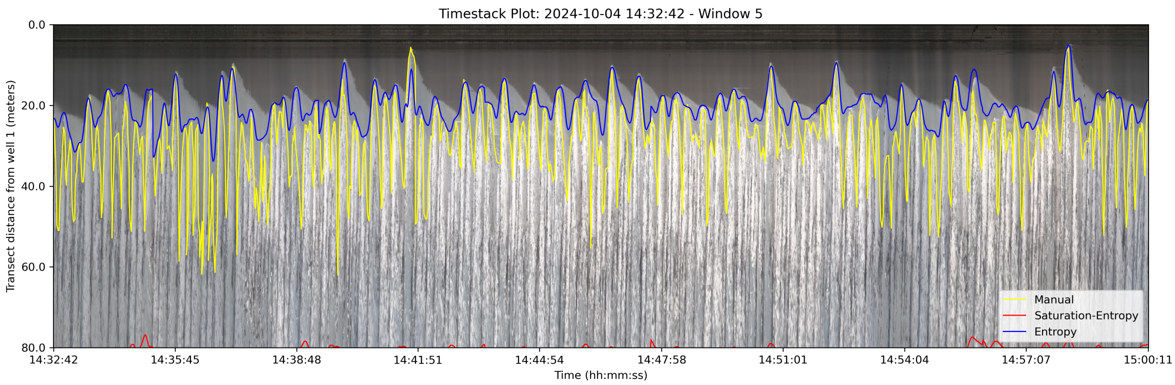
A.1. Timestack data plots from 4 October 2024

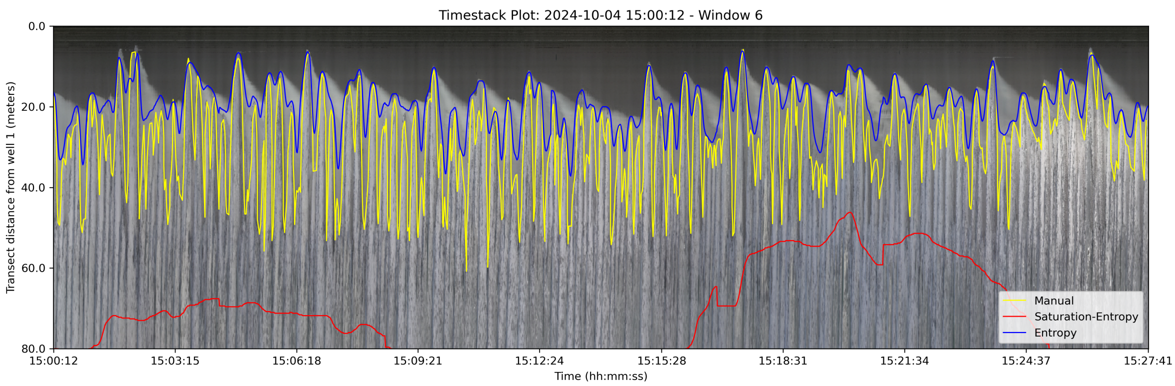


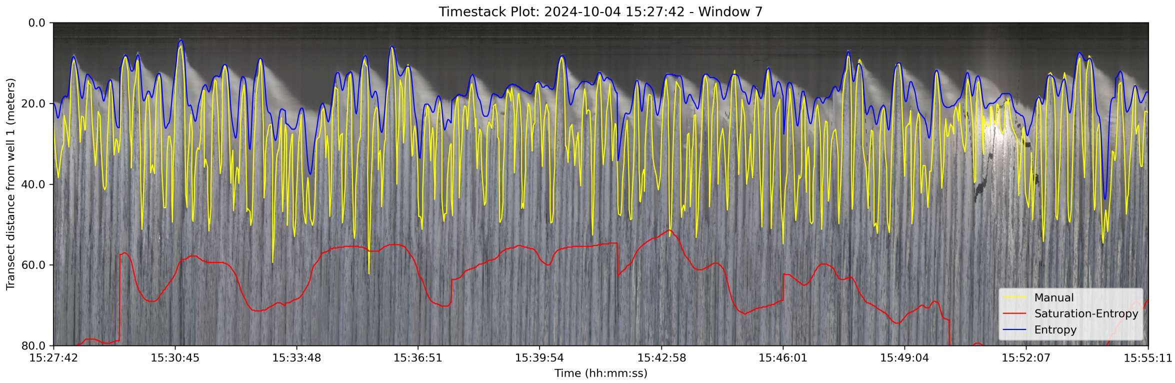


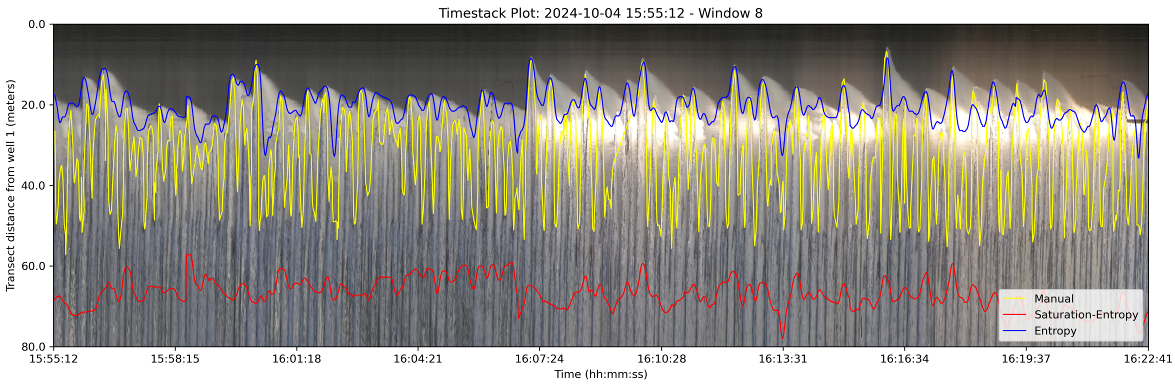

Timestack Plot: 2024-10-04 13:37:42 - Window 3
Transect distance from well 1 (meters)
0.0
20.0
40.0
60.0
80.0
13:37:42
13:40:45
13:43:48
13:46:51
13:49:54
13:52:58
13:56:01
13:59:04
14:02:07
14:05:11
Time (hh:mm:ss)
Manual
Saturation-Entropy
Entropy

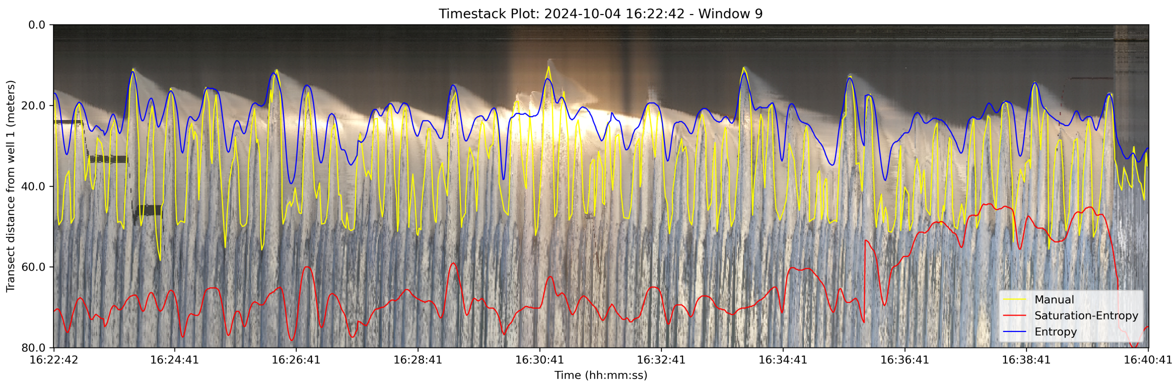

Timestack Plot: 2024-10-04 14:05:12 - Window 4
Transect distance from well 1 (meters)
0.0
20.0
40.0
60.0
80.0
14:05:12
14:08:15
14:11:18
14:14:21
14:17:24
14:20:28
14:23:31
14:26:34
14:29:37
14:32:41
Time (hh:mm:ss)
Manual
Saturation-Entropy
Entropy


Timestack Plot: 2024-10-04 14:32:42 - Window 5
Transect distance from well 1 (meters)
0.0
20.0
40.0
60.0
80.0
14:32:42
14:35:45
14:38:48
14:41:51
14:44:54
14:47:58
14:51:01
14:54:04
14:57:07
15:00:11
Time (hh:mm:ss)
Manual
Saturation-Entropy
Entropy


Timestack Plot: 2024-10-04 15:00:12 - Window 6
Transect distance from well 1 (meters)
0.0
20.0
40.0
60.0
80.0
15:00:12
15:03:15
15:06:18
15:09:21
15:12:24
15:15:28
15:18:31
15:21:34
15:24:37
15:27:41
Time (hh:mm:ss)
Manual
Saturation-Entropy
Entropy


Timestack Plot: 2024-10-04 15:27:42 - Window 7
Transect distance from well 1 (meters)
0.0
20.0
40.0
60.0
80.0
15:27:42
15:30:45
15:33:48
15:36:51
15:39:54
15:42:58
15:46:01
15:49:04
15:52:07
15:55:11
Time (hh:mm:ss)
Manual
Saturation-Entropy
Entropy


Timestack Plot: 2024-10-04 15:55:12 - Window 8
Transect distance from well 1 (meters)
0.0
20.0
40.0
60.0
80.0
15:55:12
15:58:15
16:01:18
16:04:21
16:07:24
16:10:28
16:13:31
16:16:34
16:19:37
16:22:41
Time (hh:mm:ss)
Manual
Saturation-Entropy
Entropy


Timestack Plot: 2024-10-04 16:22:42 - Window 9
Transect distance from well 1 (meters)
0.0
20.0
40.0
60.0
80.0
16:22:42
16:24:41
16:26:41
16:28:41
16:30:41
16:32:41
16:34:41
16:36:41
16:38:41
16:40:41
Time (hh:mm:ss)
Manual
Saturation-Entropy
Entropy

B
Groundwater Table Measurements

B.1. Individual measurements

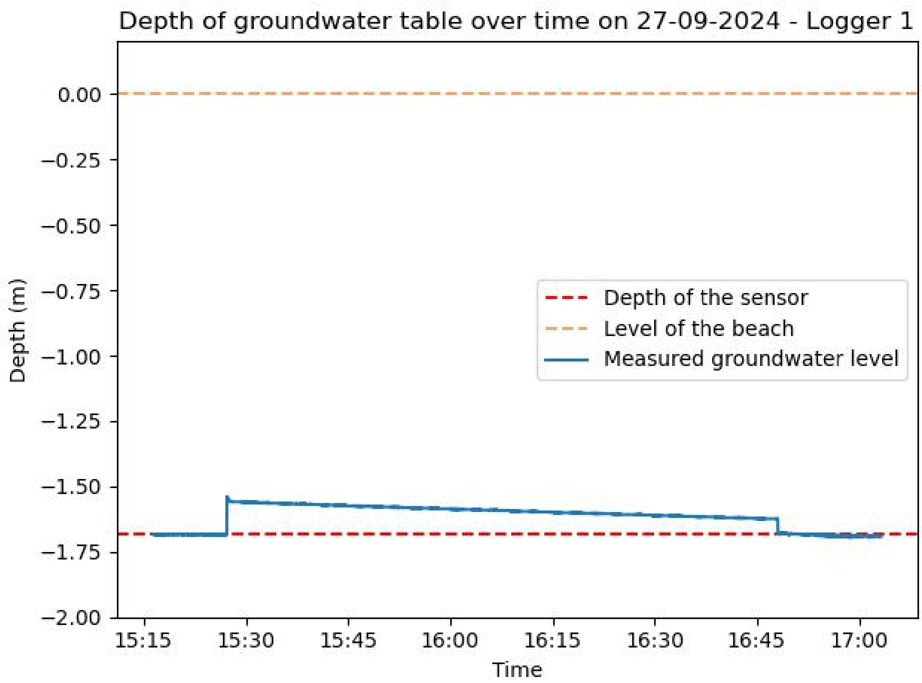


Figure B.1: Logger 1 placed in well 1

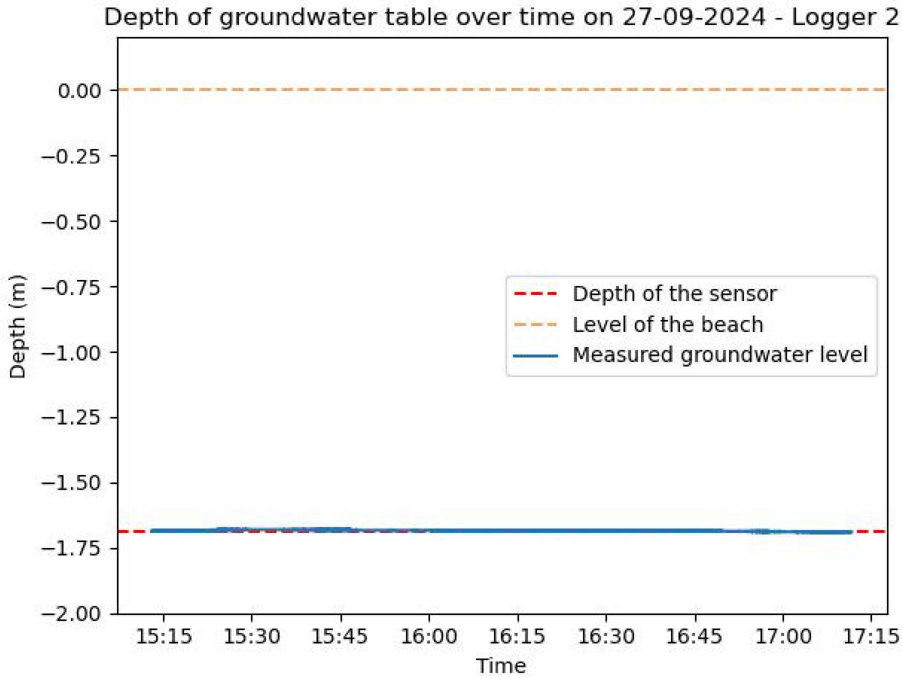


Figure B.2: Logger 2 placed in well 2

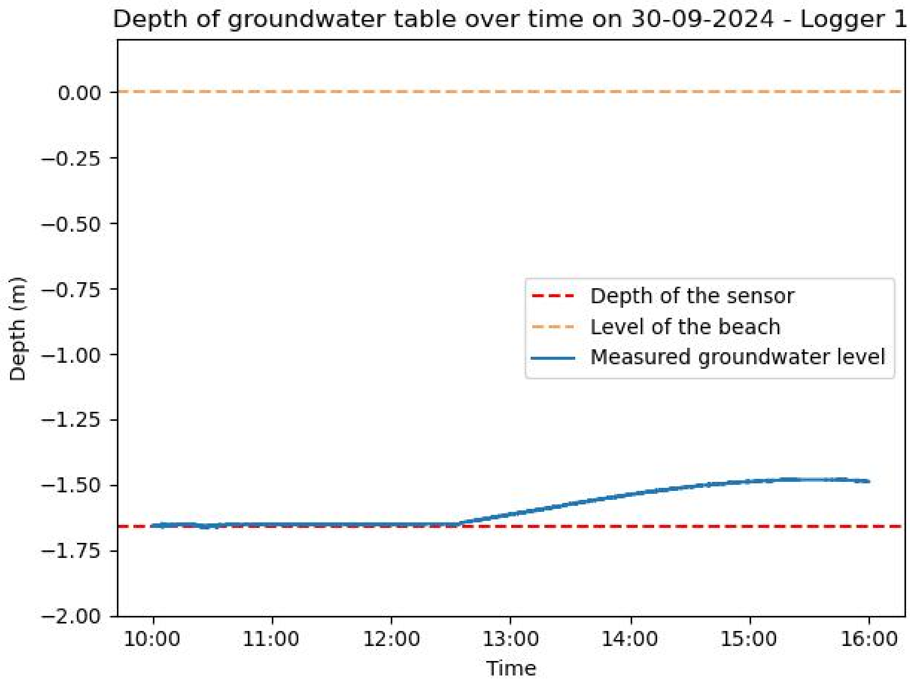


Figure B.3: Logger 1 placed in well 2

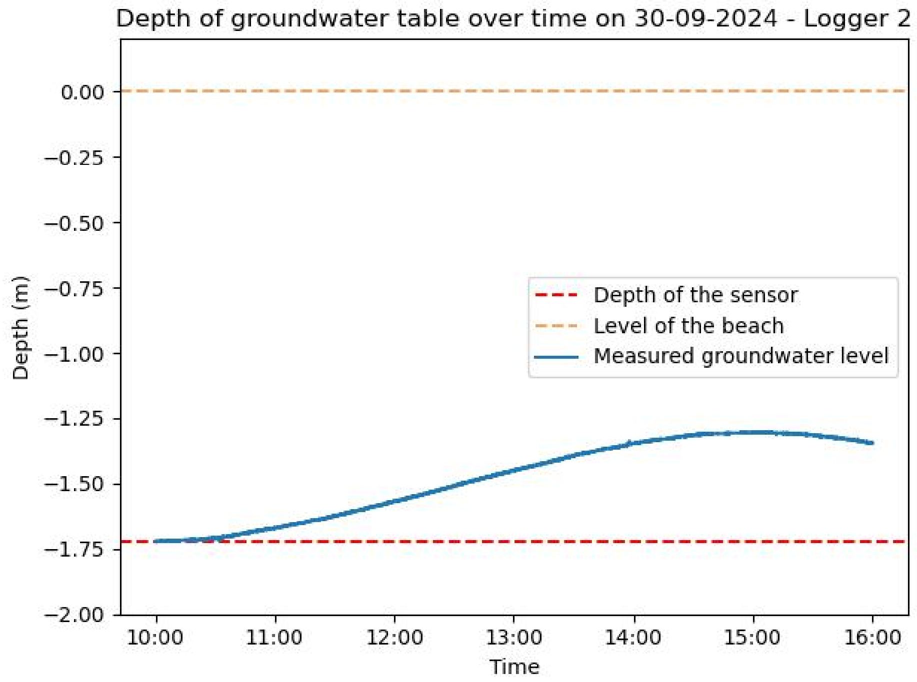


Figure B.4: Logger 2 placed in well 1

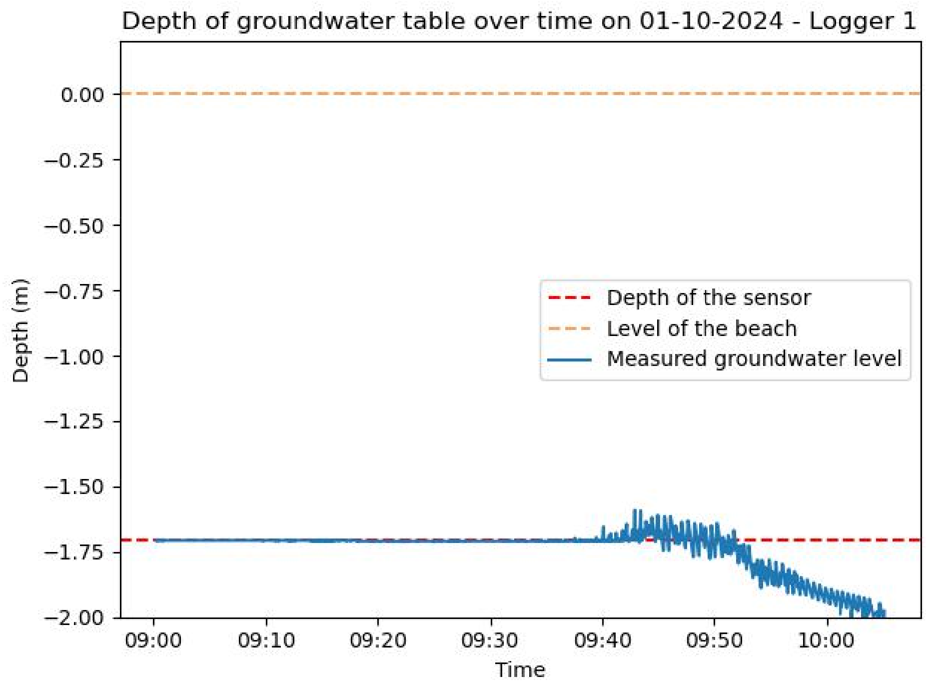


Figure B.5: Logger 1 placed in well 2

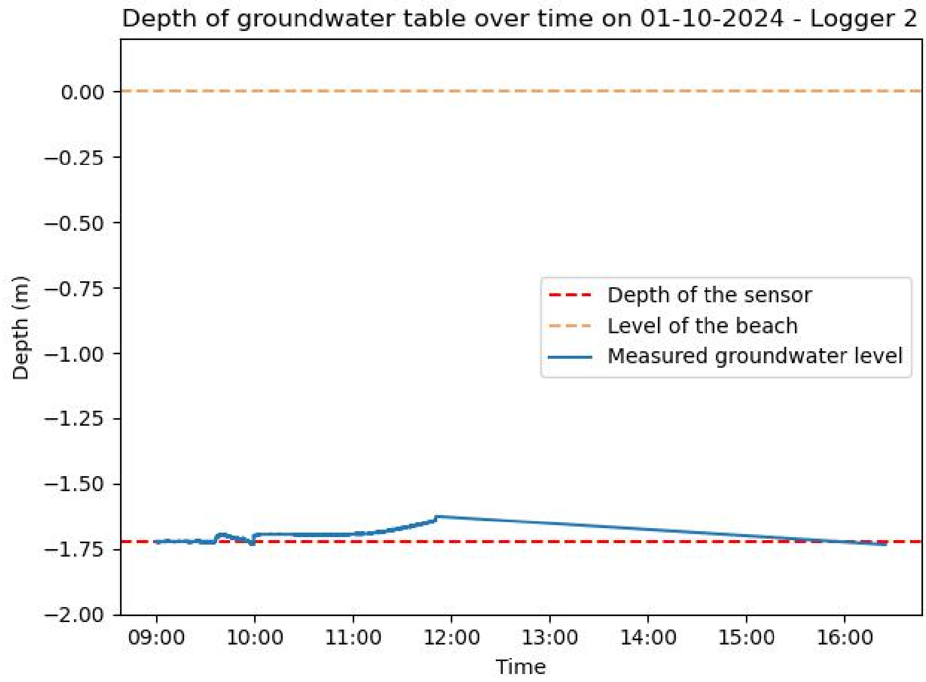


Figure B.6: Logger 2 placed in well 1

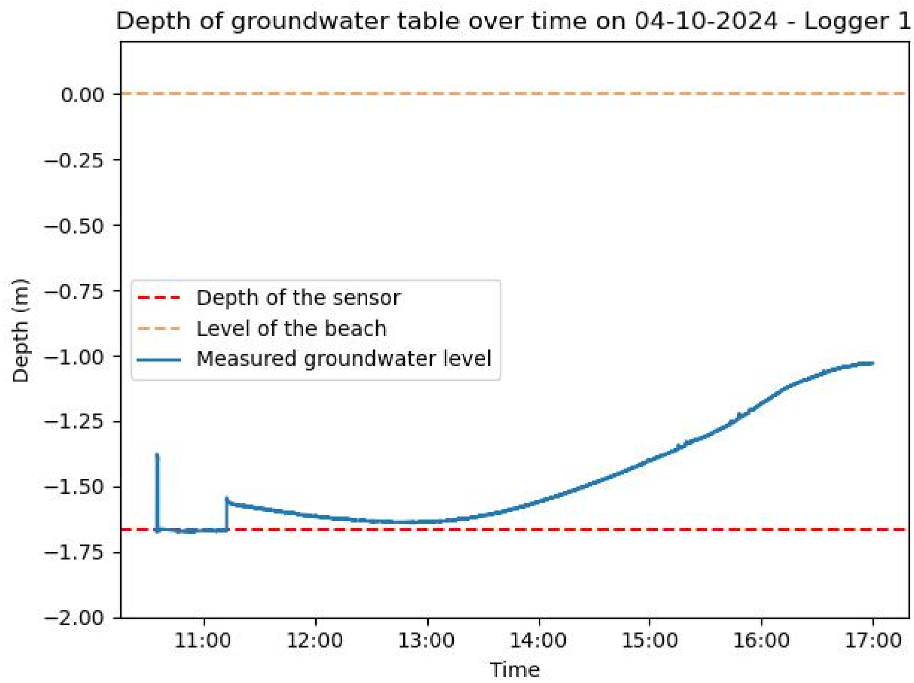


Figure B.7: Logger 1 placed in well 1

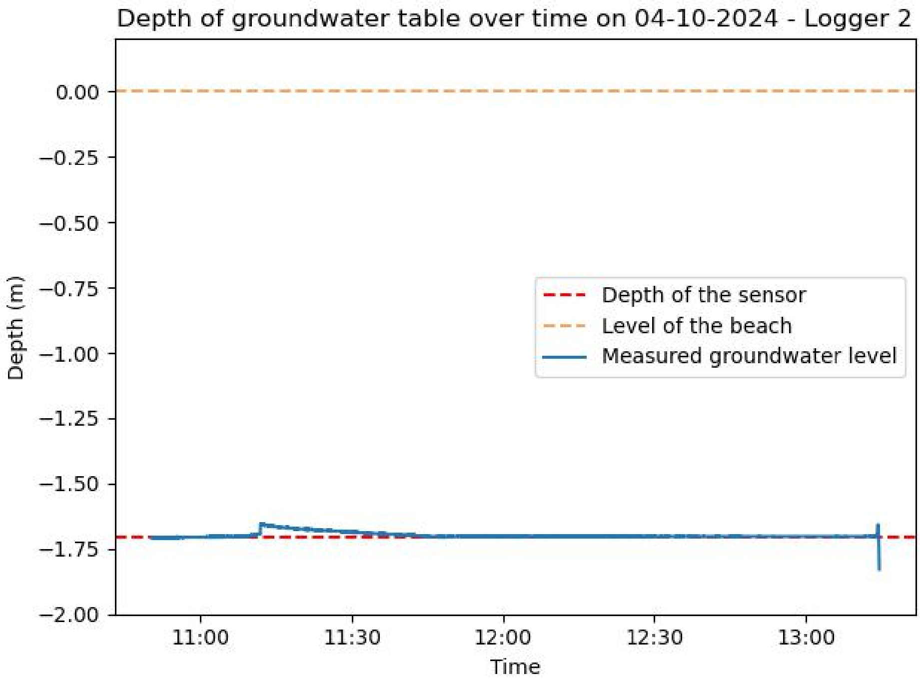


Figure B.8: Logger 2 placed in well 2

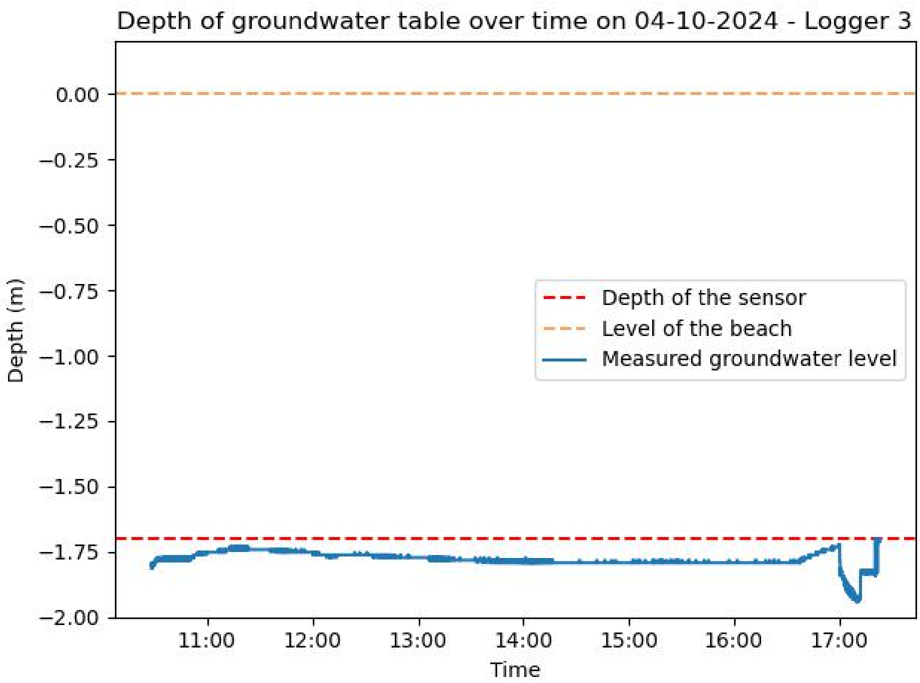


Figure B.9: Logger 3 placed in well 3

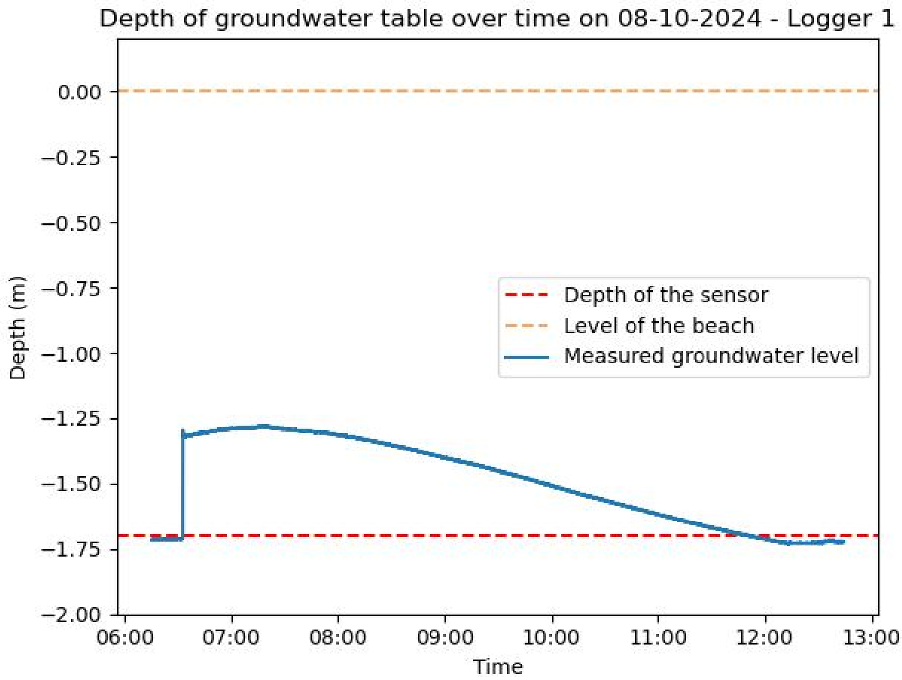


Figure B.10: Logger 1 placed in well 1

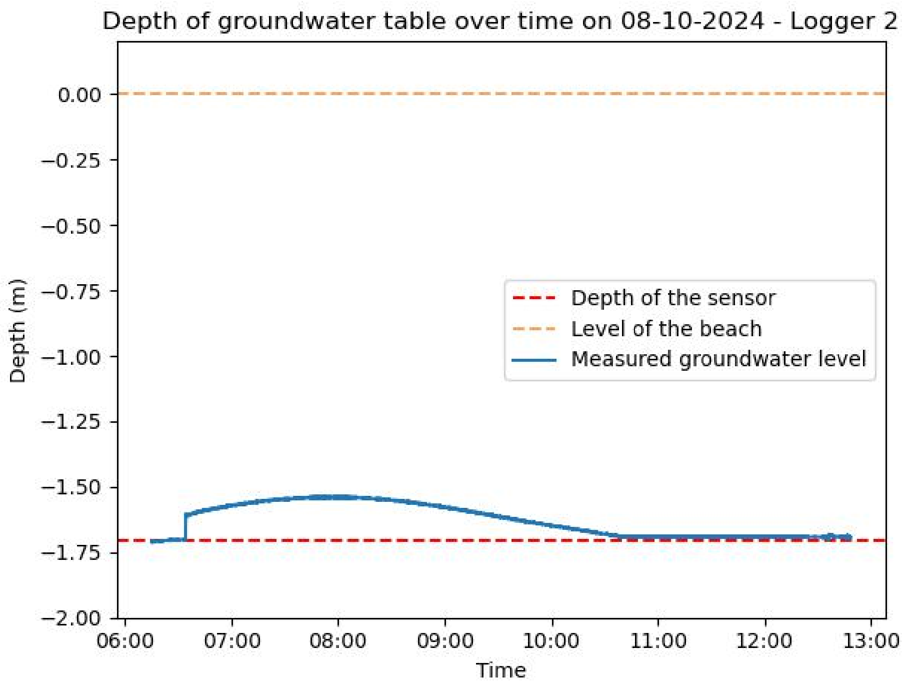


Figure B.11: Logger 2 placed in well 2

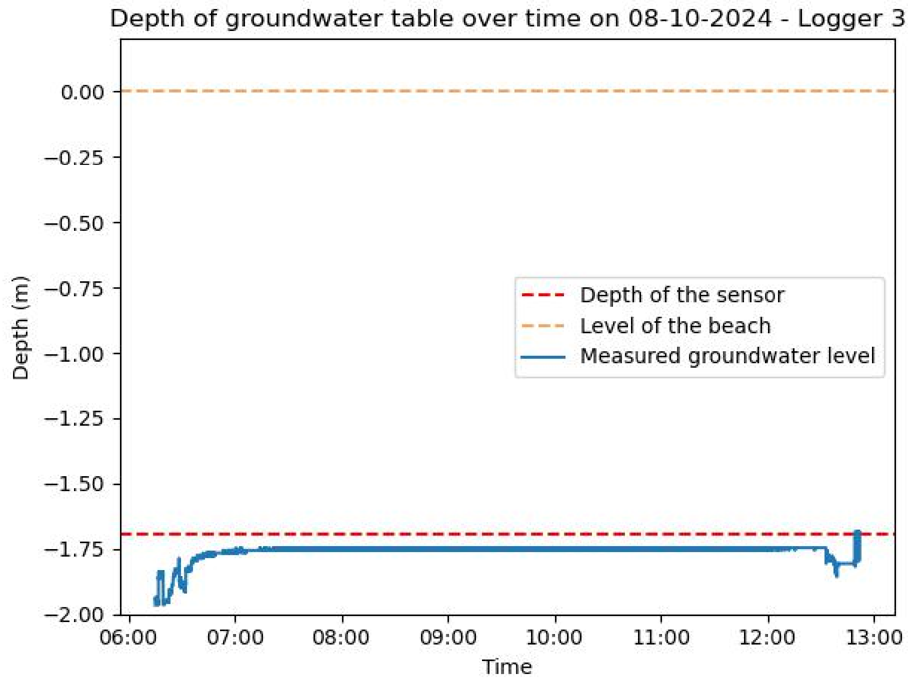


Figure B.12: Logger 3 placed in well 3

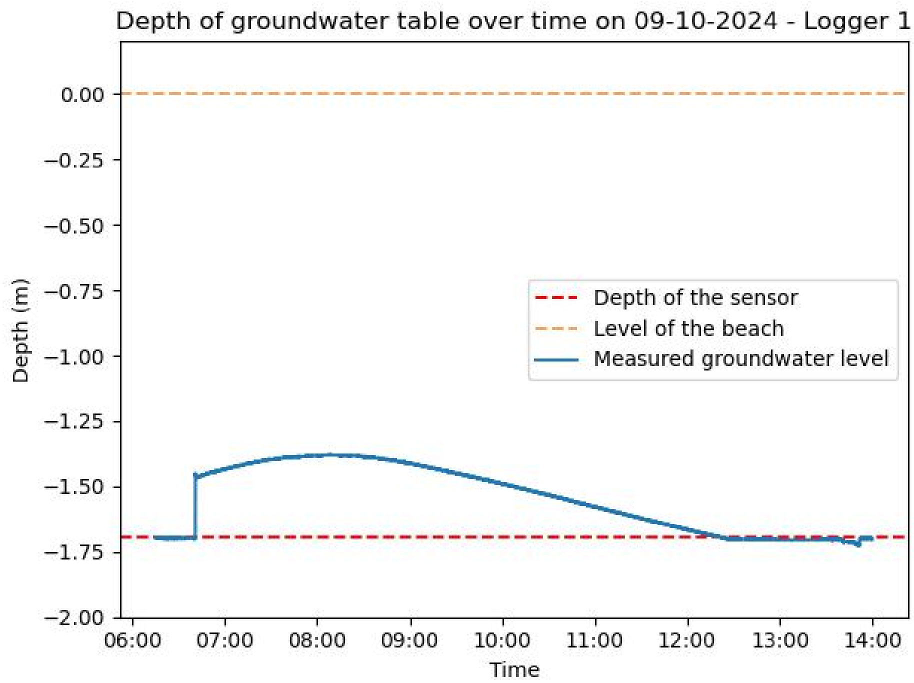


Figure B.13: Logger 1 placed in well 1

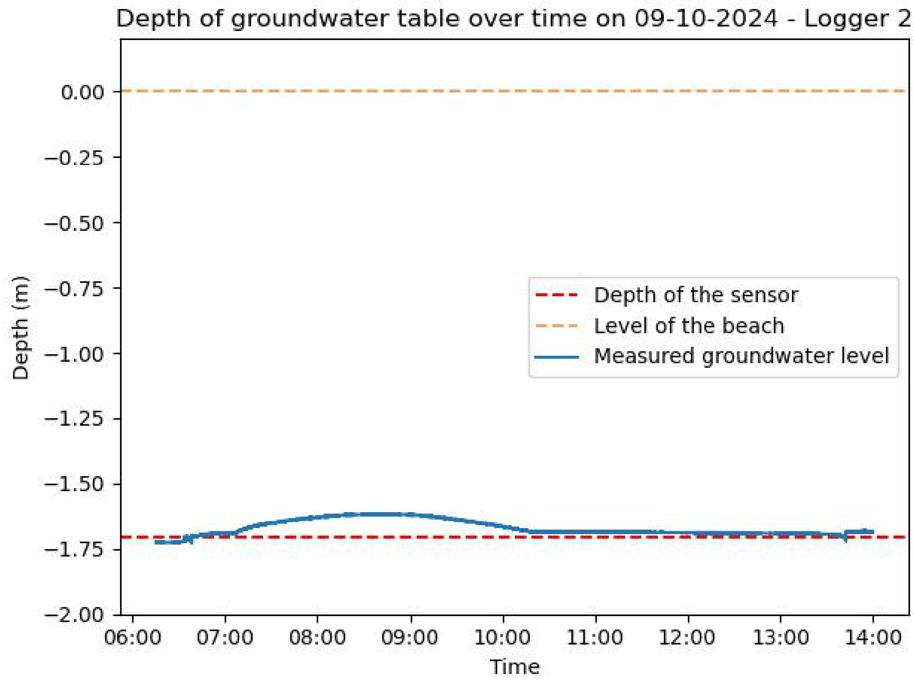


Figure B.14: Logger 2 placed in well 2

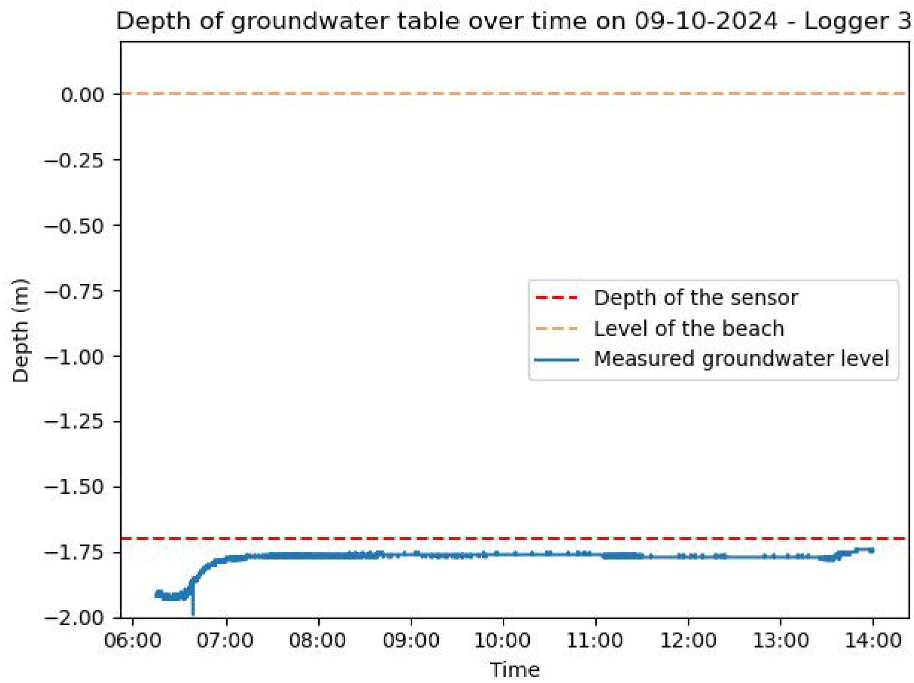


Figure B.15: Logger 3 placed in well 3

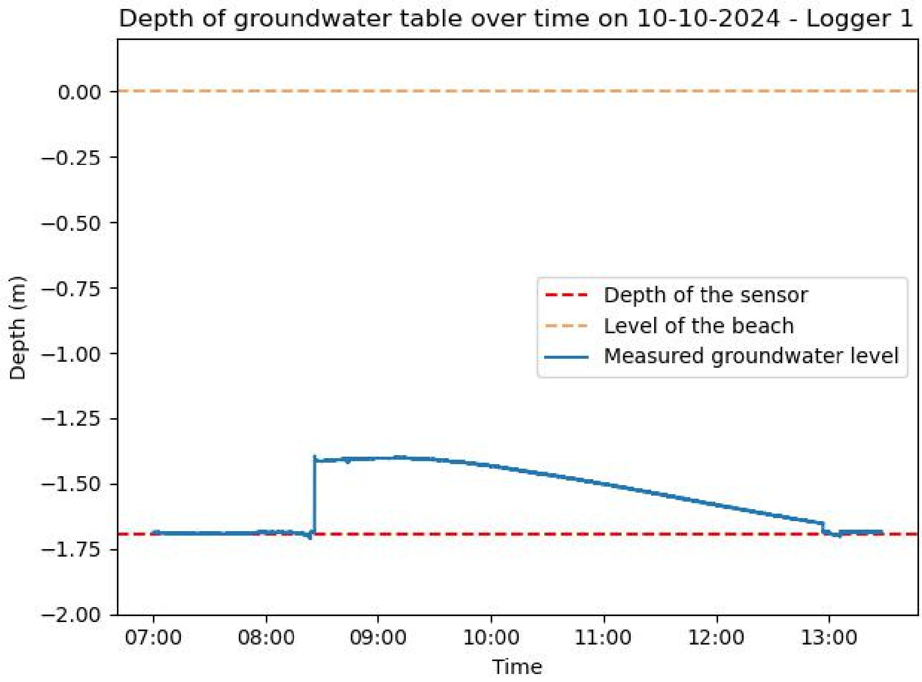


Figure B.16: Logger 1 placed in well 1

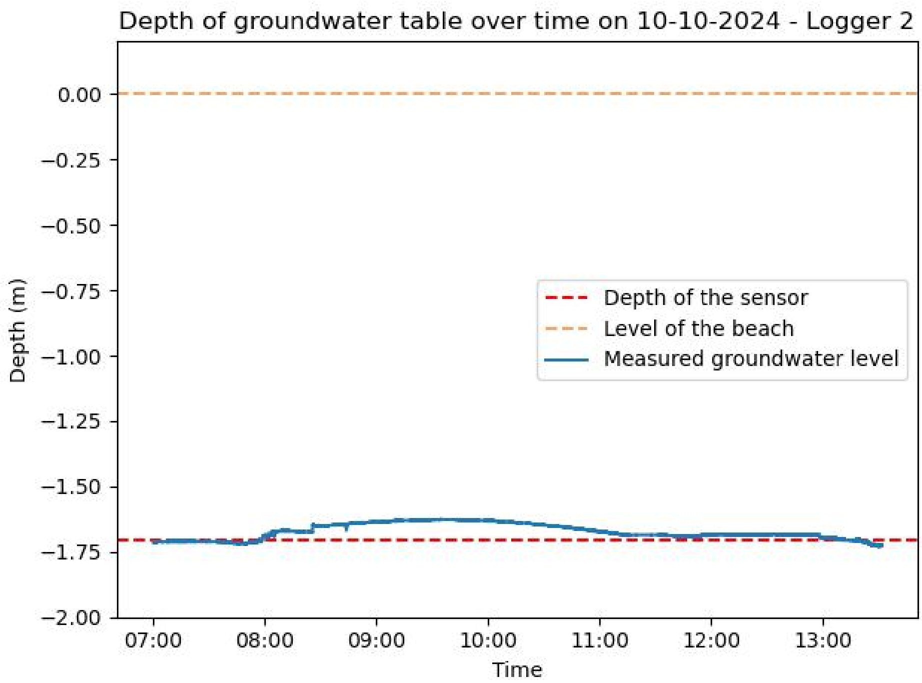


Figure B.17: Logger 2 placed in well 2

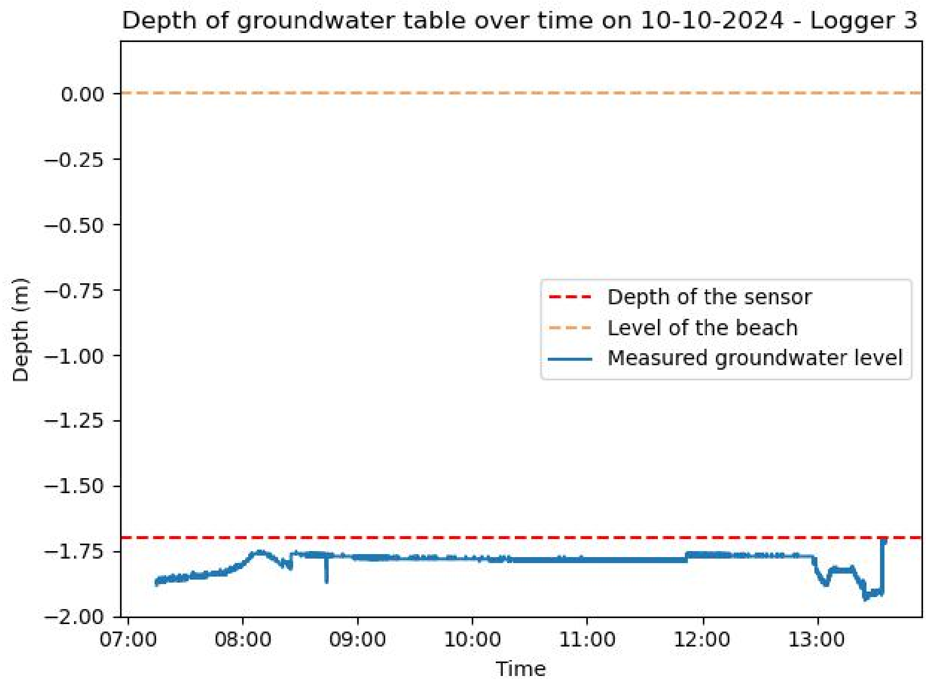


Figure B.18: Logger 3 placed in well 3

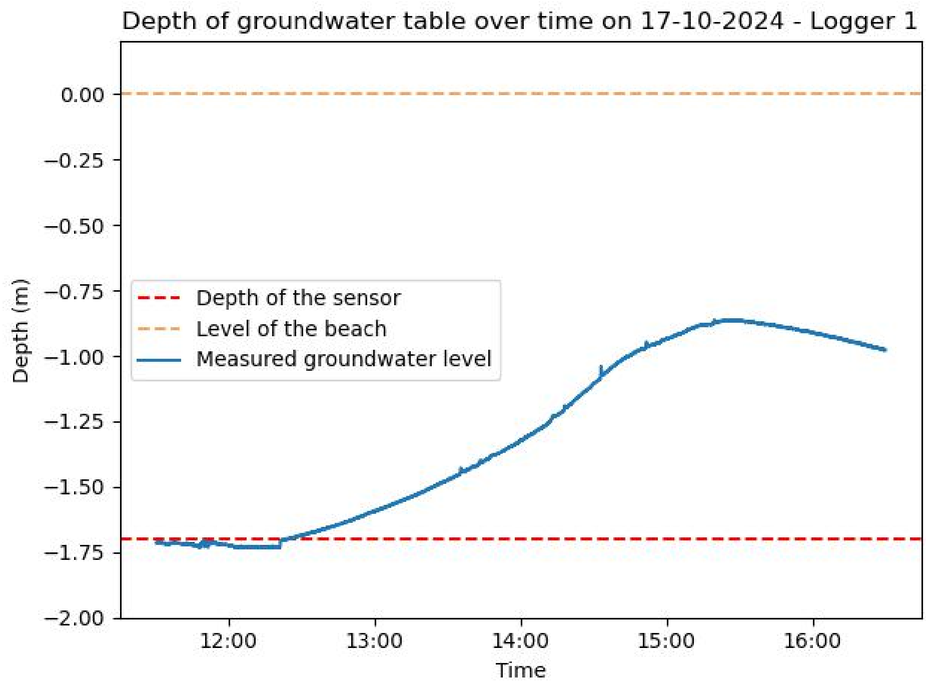


Figure B.19: Logger 1 placed in well 1

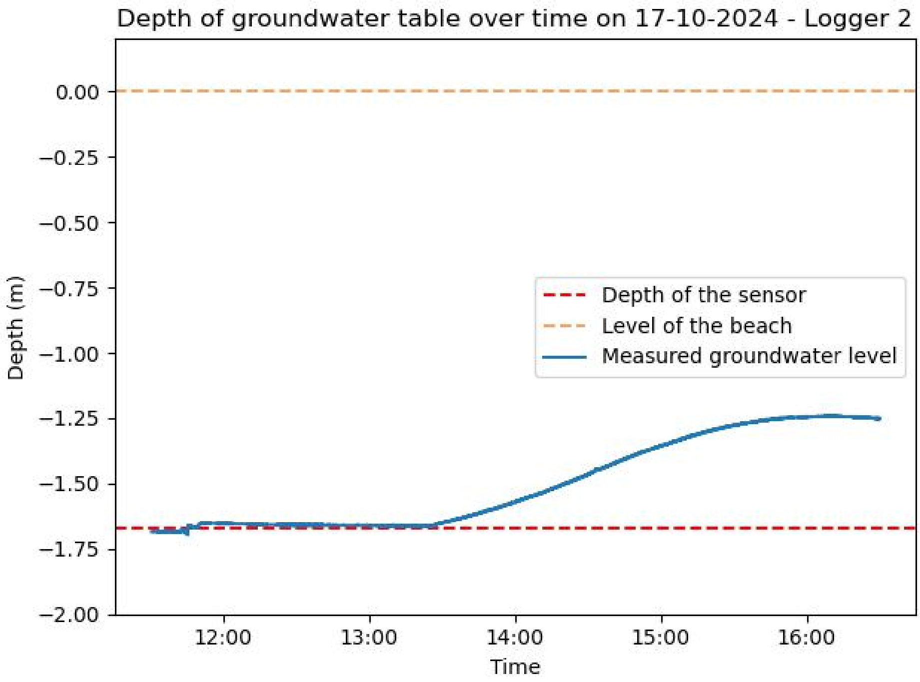


Figure B.20: Logger 2 placed in well 2

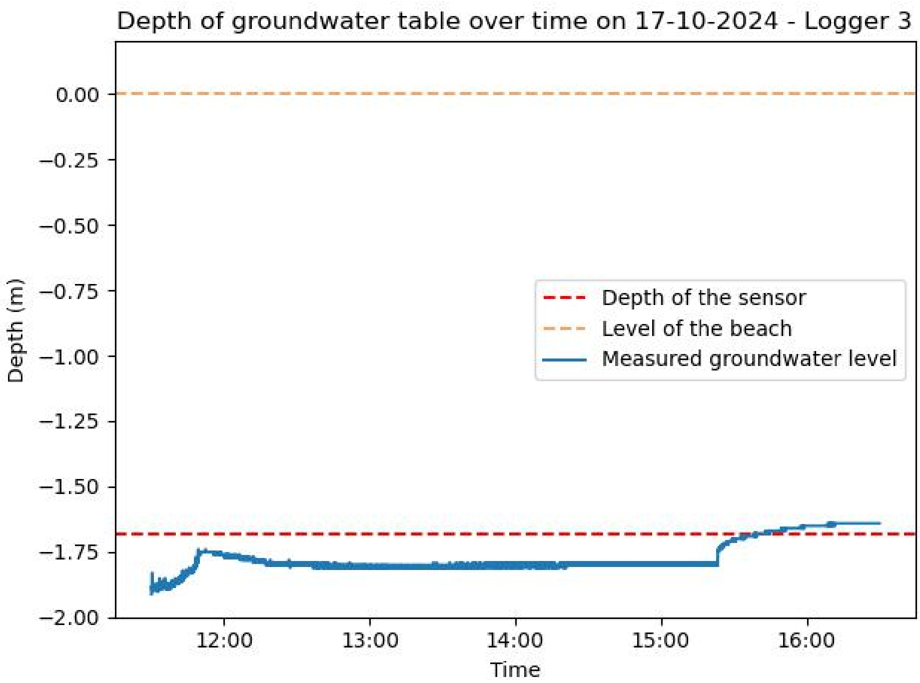


Figure B.21: Logger 3 placed in well 3

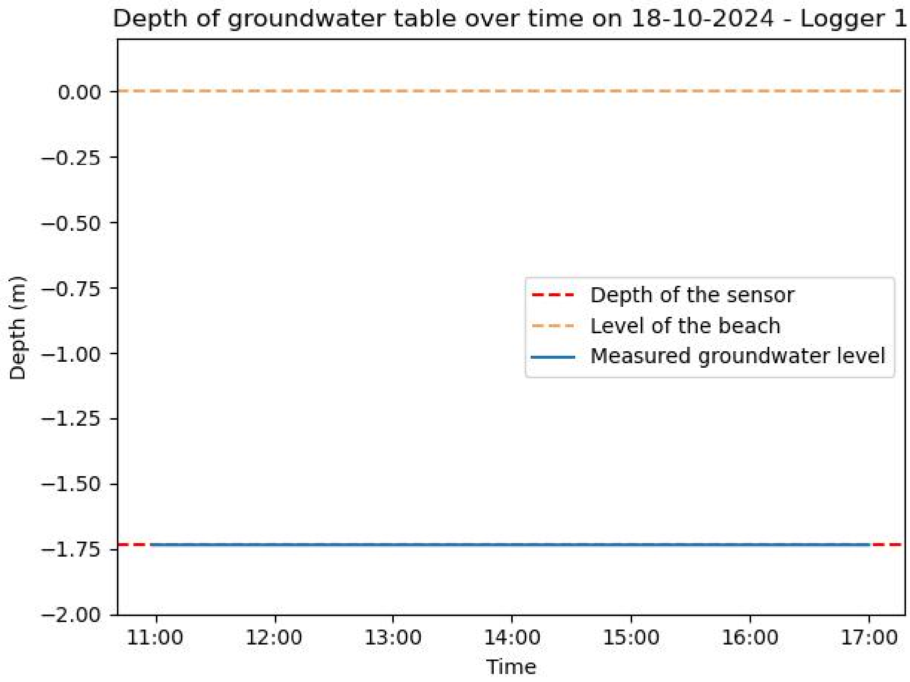


Figure B.22: Logger 1 placed in well 1

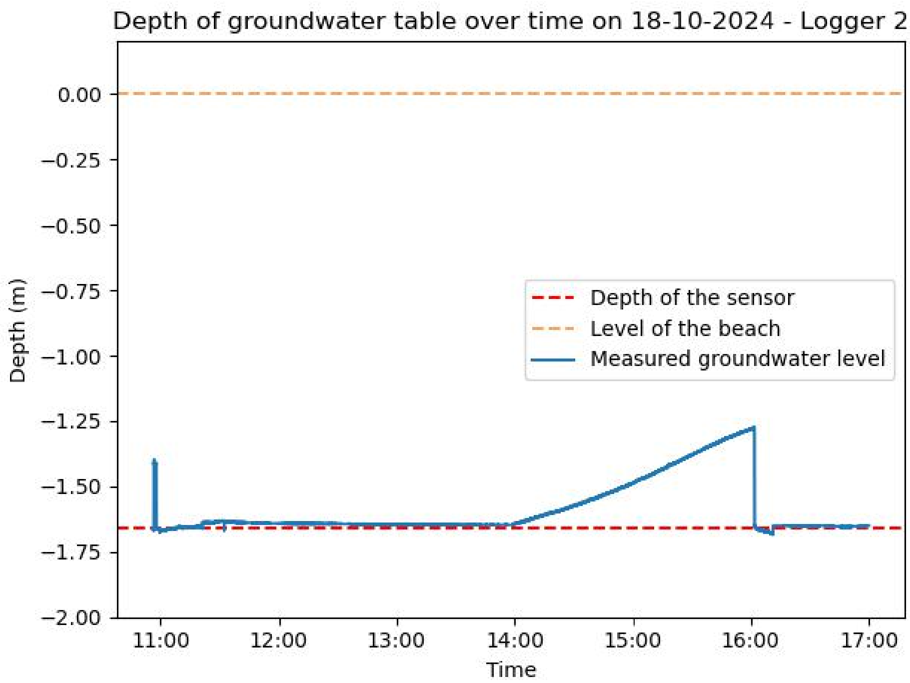


Figure B.23: Logger 2 placed in well 2

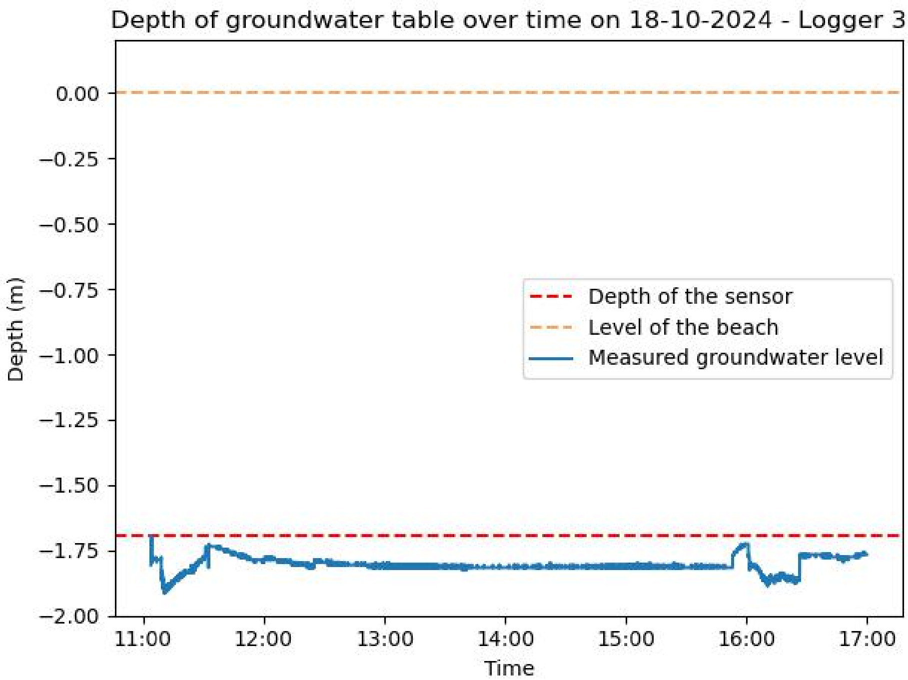


Figure B.24: Logger 3 placed in well 3

B.2. Daily measurements

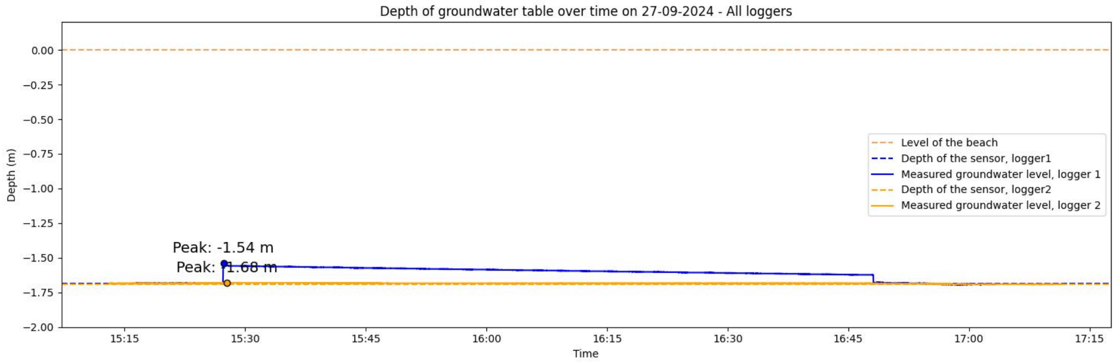


Figure B.25: All measurements on 27-09-2024

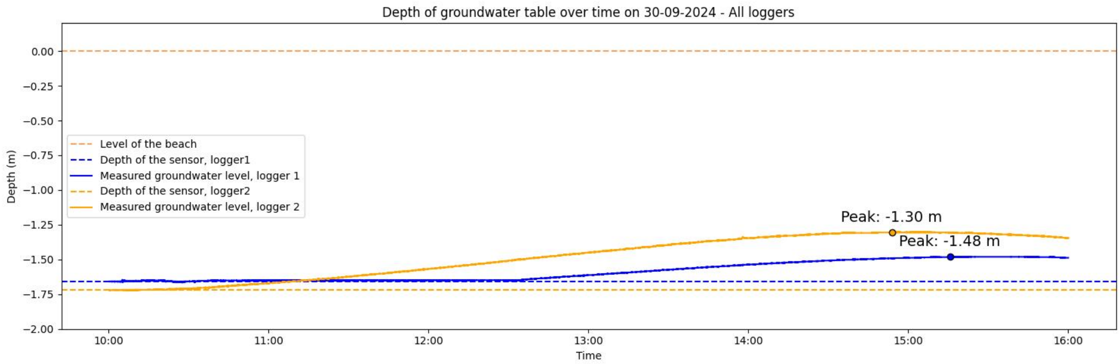


Figure B.26: All measurements on 30-09-2024

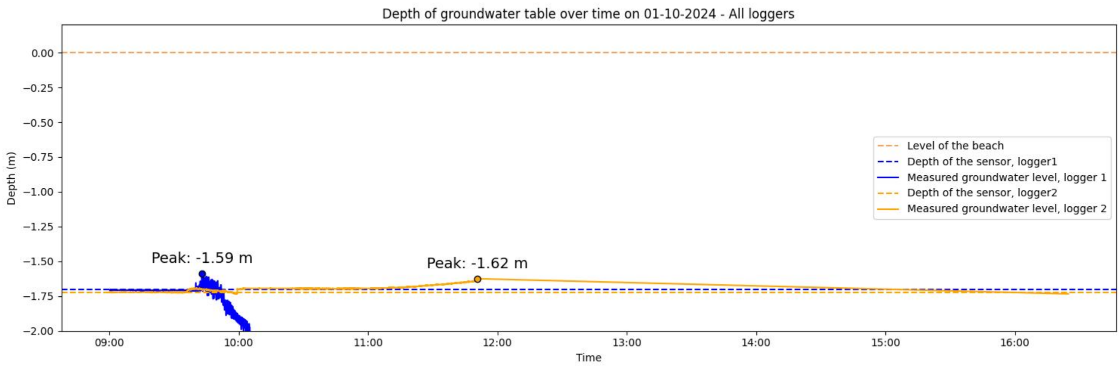


Figure B.27: All measurements on 01-10-2024

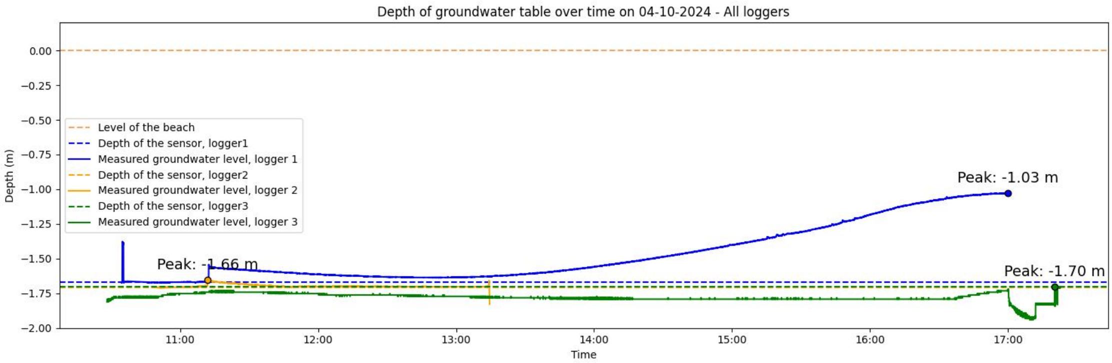


Figure B.28: All measurements on 04-10-2024

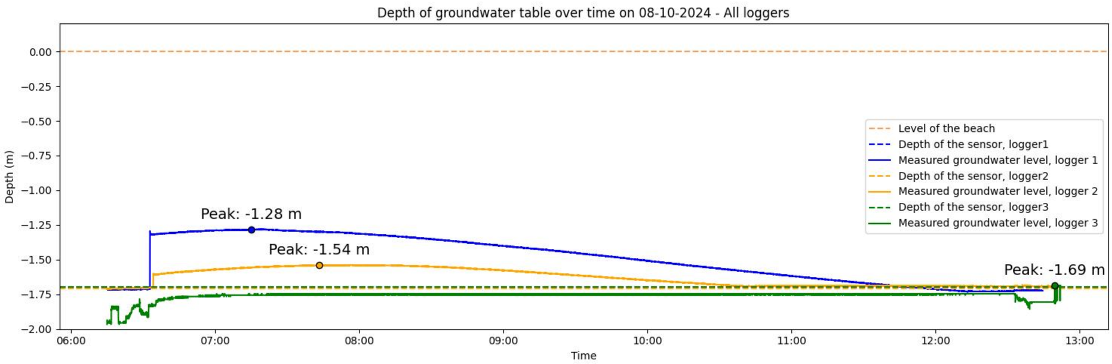


Figure B.29: All measurements on 08-10-2024

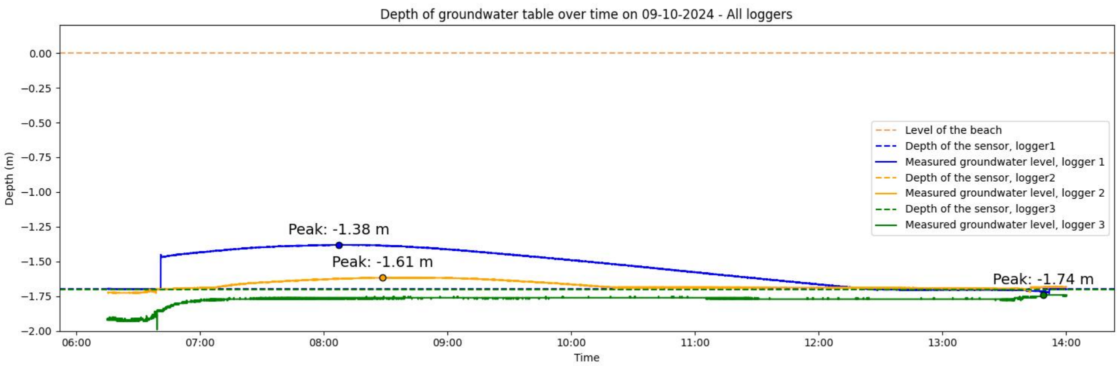


Figure B.30: All measurements on 09-10-2024

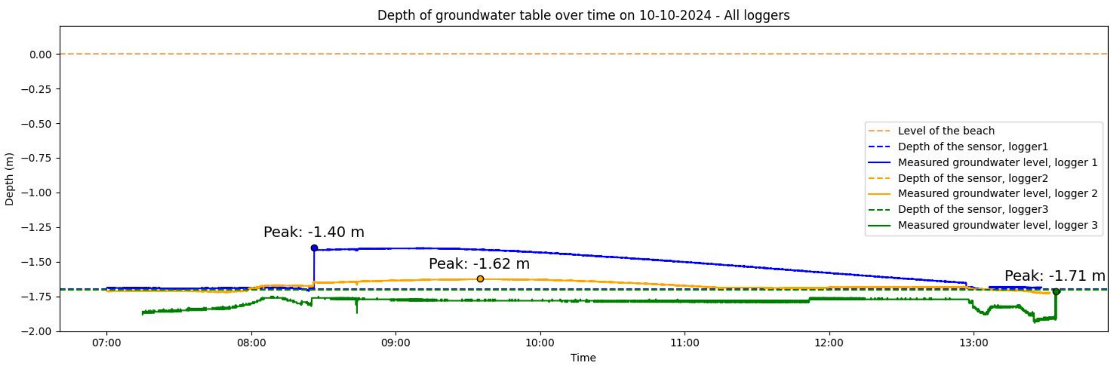


Figure B.31: All measurements on 10-10-2024

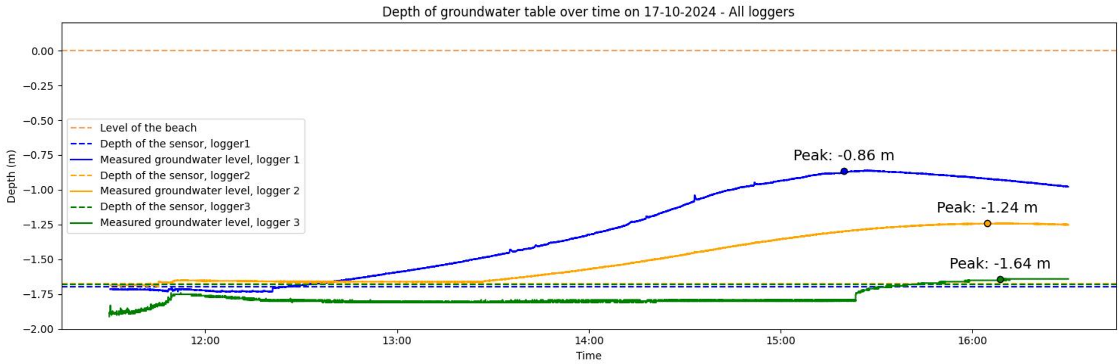


Figure B.32: All measurements on 17-10-2024

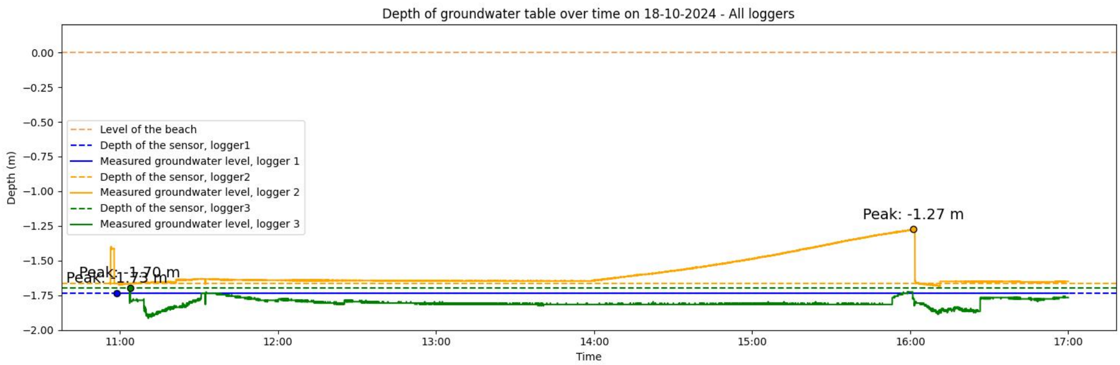


Figure B.33: All measurements on 18-10-2024

C

Manual for constructing and installing wells

C.1. Purpose

These wells are designed to be placed in the sand on a beach and house sensors that measure groundwater pressure.

C.2. Materials Needed for One Well (2-Meter Length)

In Table C.1, the materials required for one well are listed. The dimensions provided correspond to the wells used in Ostional, but other dimensions can be used depending on the requirements.

Material	**Amount**	**Unit**	**Dimensions**
PVC pipe	1	–	$D = 5$ cm, $l = 200$ cm, $t = 0.2$ cm
PVC round cap (internal diameter of the pipe)	1	–	$D = 5$ cm
PVC flat caps (matching outer diameter)	2	–	$D = 5$ cm
Metal rod (for sensor attachment)	1	–	$D = 0.7$ cm, $l = 190$ cm
Metal rod (for pushing plug)	1	–	–
Nuts	2	–	M10 / M8
Submersible pressure transducer	1	–	$D = 2$ cm
block of foam	1	–	All sides = 5 cm
Duct tape	1	Roll	–
Electrical tape	1	Roll	–
Geotextile fabric	1	Roll	$l = 200$ cm, $b = 50$ cm
Zip ties	1	Bag	$l = 20$ cm

Table C.1: Materials needed for one well.

C.3. Tools needed

The tools used for making the wells and what use they have are shown in Table C.2.

Tool	Use
Heat gun	To shape tip
Drill	To drill holes
Vise	To secure pipe for drilling
Measuring tape	To measure
Marker or pencil	To mark
Hand auger soil drill	To make the pilot hole
Water pump with long hose	To liquefy sand
Steel tap	To tap steel thread
Long rod	To push foam down the well

Table C.2: Tools needed for the wells

C.4. Step-by-step instructions

Step 1: Preparing the PVC pipe

Measure and cut the PVC pipe to the appropriate length for your well. Cut the end of the well where the tip needs to be 6 cm. See Figure C.1.

Figure C.1: Well with cuts

Step 2: Shaping the bottom of the pipe

Use a heat gun to soften the bottom end of the PVC pipe. Mold it into a tapered shape to make it easier to drive into the sand. This will help the well penetrate the beach surface during installation. Use a mold or glove to shape the tip, then tape the end to close the seams. See Figure C.2.

Step 3: Drilling holes in the pipe

Use a drill to create evenly spaced holes along the length of the pipe, allowing water to flow through. For the well shown in the picture, 8 mm holes were drilled with 8 cm spacing on 2 sides, and 4 mm holes on the other 2 sides with the same spacing, but offset from the 8 mm ones. On 4 sides, additional 4 mm holes were drilled every 4 cm. See Figure C.3.

Figure C.2: Well tip shaped with heatgun

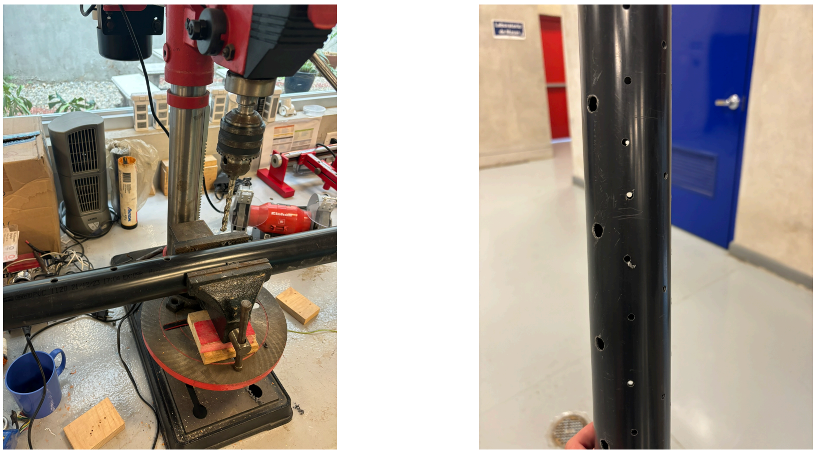


Figure C.3: Drilling holes in the well

Step 4: Wrapping the well with geotextile fabric

Wrap the PVC pipe in geotextile fabric to act as a filter that prevents sand from entering the well but allows water to flow through. Wrap the fabric around the well 3 times. Tape the seams with duct tape and secure the fabric at the ends. Use zip ties at regular intervals to ensure the fabric is tightly secured. See Figure C.4.

Figure C.4: Wrapping the well

Step 5: Attaching metal rod to cap

In one flat cap, drill a small hole to close off the well when the sensor is not in place. In the other flat cap, drill two holes: one for attaching the metal rod and one for the sensor to go through. The size of these holes will depend on the diameters of the rod and the sensor. Attach the metal rod to the cap using nuts. If the rod lacks threading, use a steel tap to create threads. See Figure C.5.

Figure C.5: Metal rod attached to cap

Step 6: Attaching the sensor to the metal rod

Attach the groundwater pressure sensor securely to the metal rod using duct tape, ensuring it will make contact with groundwater once installed. See Figure C.6.

Figure C.6: Sensor attached to the rod

C.5. Installing the well

Step 1: Drilling the hole

Use a hand auger soil drill to create a hole in the sand. Drill until the hole begins to collapse, at which point the well will be inserted. See Figure C.7a

Step 2: Using the pump to liquefy the sand

Place the well into the hole, then insert a water pump with a long hose down to the well's tapered bottom. Pump water to liquefy the sand and move the well up and down to sink it deeper until reaching the desired depth.

Step 3: Plugging the well to block sand

After reaching the desired depth, remove the hose and insert the foam and the round cap into the top of the well, pushing them to the bottom. This prevents sand from entering while still allowing water to flow through the holes. See Figure C.7b.

Step 4: Sealing the top of the well

Once the foam and round cap are in place, seal the top using a PVC cap. See Figure C.7c

Step 5: Measuring

To take measurements, insert the metal rod with the sensor into the PVC well.

(a) Step 1: Drilling a hole for the well **(b)** Step 3: Plugging the well **(c)** Step 4: Top of the well, sealed

Figure C.7: Steps one, three, and four

D

Interview questions

Phase 1: Introduction and Establishing Background

1. Could you tell me a bit about yourself and your role in the TURTLE project?
    a) Which projects have you contributed to, and what expertise or experience do you think has been most relevant to your role?
    b) What motivates you and your organization to be involved in the project?
    c) Who do you typically collaborate with within the project, and how does that collaboration usually work?
2. How do you usually communicate with other actors in the project?
    a) Are there certain channels or tools that work best?
3. How involved do you feel in the overall direction of the project? Are there areas where you feel more or less engaged?
4. Have you faced any challenges in working with others in the project?
    a) How have those been handled, or what could help in the future?
5. How do you feel about the current project structure, particularly how the teams and actors collaborate?

Phase 2: Collaboration Moving Forward

1. How do you see your involvement in the project progressing in the future?
2. Looking to the future, what do you think is most important for improving collaboration across the project?
3. What are changes or additional support that you can think of that would help you feel more connected or effective in your role within the project?
4. What do you think could be done to make the TURTLE project have a bigger impact, within your field and more broadly speaking?
5. How do you think the project's outcomes could be shared more effectively within the project and with external parties?
6. What challenges do you see the project facing in the future, and how do you think we could

prepare for them?

7. How important do you think adaptability is, and what would help the TURTLE project stay flexible and resilient in the long run?
8. Is there anything we haven't covered that you think is important to discuss or additional comments on questions that we posed?