

# DuneFront

Deliverable 13.1

December 2025





# Predictive Digital Twin

Deliverable 13.1 – D13.1

## Deliverable information

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## Cover page

The DuneFront project aims to enhance coastal protection and safety by optimizing coastal solutions that combine natural elements, such as dunes, with man-made structures like dikes and seawalls, known as hybrid dune-dike systems. In the scope of the DuneFront project, the goal of Work Package 13: Predictive Digital Twin (WP13) is to develop a user-friendly tool called Predictive Digital Twin (PDT) to assist in the design and evaluation of these systems. A predictive digital twin for hybrid dune–dike systems is a virtual representation of a real coastal protection system composed of dunes and dikes that work together to reduce flooding risk. This digital version brings together data and computer models to simulate how the coast behaves. Because it updates continuously and can run future scenarios, the digital twin helps us predict how the system changes over time and how it responds to storms, sea-level rise, climate change scenarios, and human interventions such as breakwaters, groynes, nourishments, and dikes. Also, it can help on defining which combination of natural elements and man-made structures would lead to a better overall design. Ultimately, the PDT is designed to inform the blueprints developed by WP14 and also to be used by engineers, coastal managers, and other relevant stakeholders for planning of future hybrid-solution strategies at different coastal environments.

This report is the first deliverable of WP13. Within this report, we describe the conceptualization of the PDT, the numerical models chosen together with the rationale behind the model choices, explain the adaptation we needed to do in these models, and show how the models are currently simulating different site studies in the scope of the project.

The development of the PDT involved societal interaction with different stakeholders and potential users from different European countries early in the project. The users informed their needs, which were accordingly considered when building the PDT architecture in terms of internal technical needs and support. This also tailored the choices of the models and the needed adaptations to those. The current version has been tested at different demonstrator locations, and the results indicate that the chosen modelling approach performs well for the intended scale and application.

In conclusion, the work presented here shows the first step toward building a fully functional PDT for hybrid dune–dike systems. By defining the concept, selecting and adapting suitable models, and testing them at real demonstration sites, we show the general concept of a PDT prototype, providing a starting point for the next development stages within the DuneFront project.

# Table of Content

1.	Introduction .....	7
1.1	Overview of Work Package 13 .....	7
1.1.1	Tasks of Work Package 13 .....	7
1.1.2	Milestones and Deliverables of Work Package 13 .....	8
1.2	Aims and objectives .....	8
2.	Predictive Digital Twin development .....	8
2.1	Conceptualization and Design (T13.1) .....	8
2.1.1	Definition of a Predictive Digital Twin .....	8
2.1.2	Conceptualization of a Predictive Digital Twin for DD-Hybrid NbS .....	10
2.1.3	User definition and architecture design of the PDT software .....	10
2.1.4	Selection of existing models and extensions .....	17
2.2	Calibration (T13.2) .....	19
2.2.1	Inclusion of Vegetation Effects in the CS-Model .....	19
2.2.2	Inclusion of Hard-Structures in the CS-Model .....	21
2.2.3	Coupling Shorelines and CS-Model .....	24
2.2.4	Sensitivity Analysis .....	26
2.3	Validation (T13.3) .....	30
2.3.1	Overview of validation cases .....	30
2.3.2	Oosterover (BE) – Vegetation .....	30
2.3.3	Katwijk (NL) – Hard structures .....	33
2.3.4	Hondsbosche Duinen (NL) – Coupling method and 2D .....	36
2.3.5	Wadden Islands (NL) – Ecotope definition .....	37
3.	Code access instructions .....	39
4.	Conclusions .....	40
5.	Acknowledgments .....	41
6.	References .....	42

## List of abbreviations

Abbreviation	Explanation
DD-hybrid NbS	Dune-Dike Hybrid Nature-Based Solutions
WP	Work Package (in the scope of the internal organization of DuneFront project)
PDT	Predictive Digital Twin

# 1. Introduction

## 1.1 Overview of Work Package 13

The objective of Work Package 13 is to develop a physics- and ecology-based Predictive Digital Twin (PDT) for hybrid dune-dike systems that will feed the DuneFront decision support system developed in WP14. The PDT will be used to evaluate the effectiveness of designs and provide Model Performance Indicators (MPIs) for different demonstrators.

### 1.1.1 Tasks of Work Package 13

Work Package 13 is divided into 7 main tasks:

- Task 13.1 - Predictive Digital Twin (PDT) design (Lead: TU Delft; Involved partners: LU, DELTARES, UGENT-B, M1-M12): Construct the DuneFront Predictive Digital Twin (PDT) for DD-hybrid NbS based on the existing process-based component description of the morphological evolution of beaches and dunes
- Task 13.2 - PDT calibration (Lead: TU Delft; Involved partners: UGENT-B, UGENT-M, LU, DELTARES, M12-M24): Incorporate evidence-based process understanding in the DD-hybrid NbS response (WP5-9) in combination with available physical and ecological process-based knowledge, to build a PDT that can provide robust predictions of sediment transport fluxes in the presence of vegetation and hard structures. This will be achieved by implementing behaviour-based rules and dedicated reduced-order process-based descriptions: 1) to include the effects of vegetation and dike material on both dune growth and dune erosion, and 2) to include for the first time the presence of hard structures and the associated impacts on the DD-hybrid Nbs during extreme storm conditions
- Task 13.3 - PDT validation (Lead: TU Delft; Involved partners: LU, DELTARES, UGENT-B, M12-M24): Validate the PDT with observations at the existing demonstrator sites. This is achieved by hindcasting the evolution of existing DD-hybrid NbS at selected demonstrator sites with respect to vegetation, sedimentation, and erosion of the beach and concurrent dune development
- Task 13.4 - Key MPIs of the PDT (Lead: UGENT-M, Involved partners: TU Delft, LU, DELTARES, DEME, JAN DE NUL NV, M1-M32): Define Key Model Performance Indicators (MPIs) for DD-hybrid NbS representing biodiversity, flood safety, environmental, economic, and societal effects to assess the performance of the DD-hybrid NbS for co-creation purposes under different climate change scenarios.
- Task 13.5 - PDT Climate Change impact (Lead: UGENT-E; Involved partners: TUDelft, UGENT-B; M32-M48): Perform multidecadal PDT simulations using the Key MPIs to demonstrate the effectiveness of a DD-hybrid NbS coastal protection system under climate change scenarios compared to hard-only and soft-only solutions
- Task 13.6 - Integrated validation (Lead: DELTARES; Involved partners: TU Delft, LU, M32-M48): Drive the PDT with physical, ecological, economic, and societal boundary conditions (WP4),

allowing for an integrated evaluation of DD-hybrid NbS on a palette of coastal functions (D13.2). An applied version of the PDT will be ready by M34 to be used in the Decision-Support System.

- Task 13.7 - Visualisation within the PDT (Lead UGENT-E; Involved partners: TU Delft, LU, DELTARES, M36-M48): Disseminate state-of-the-art techniques on assessing DD-hybrid NbS performance (and introduce evidence-based knowledge) in simple, yet very practical and comprehensive, visualisation modules of the PDT that can be used for demonstration of the PDT capabilities, as input for the Decision-Support System (WP14), the co-creation process (WP15), and for communication purposes (WP16). In addition, a shared environment will be created for the continued development of the Open-Source PDT

### 1.1.2 Milestones and Deliverables of Work Package 13

Work Package 13 is composed of two deliverables and two milestones, described below:

The deliverables include:

- **Deliverable D13.1 (this report) – Predictive Digital Twin architecture preparing to feed the DSS.** This deliverable is of type ‘DEM’ (Demonstrator, pilot, prototype, plan design) and consists of the description of the construction, calibration, and validation of Predictive Digital Twin for DD-hybrid NbS. Tasks 13.1, 13.2, and 13.3 are described in D13.1.
- **Deliverable D13.2 – PDT model open.** This deliverable is of type ‘OTHER’ and consists of the application and dissemination of the validated Open-Source PDT. Tasks 13.4, 13.5, 13.6, and 13.7 will be described in D13.2

The milestones include:

- Milestone M13.1 – Model Performance Indicators (MPIs) selected. M13.1 is associated with task 13.4.
- Milestone M13.2 – PDT application (also first feedback loops to fine-tune it). M13.2 is associated with task 13.6.

### 1.2 Aims and objectives

The main objective of this report is to present the construction phases of the PDT, starting from the architecture build, choice of models, implementation of physical and ecological process description, calibration, and validation of the model.

## 2. Predictive Digital Twin development

### 2.1 Conceptualization and Design (T13.1)

#### 2.1.1 Definition of a Predictive Digital Twin

The definition of a Digital Twin (DT) differs considerably in the literature depending on the context and field (Miedtank et al., 2024, Wright and Davidson, 2020). Conceptually, DTs can be loosely defined as a virtual representation of a system/product that mirrors a corresponding physical counterpart (Sabri et al., 2024). However, different definitions emerge with particularities that make it fit better in each domain. Nonetheless, most definitions agree on specific characteristics that the digital representation must have to be considered a DT (Miedtank et al., 2024, Lepper et al., 2025, Wright and Davidson, 2020, Chen et al., 2023): (1) DT requires a physical entity (e.g. a turbine, a room, a bridge) to be modelled, be it a system or an object; (2) an evolving set of data that describes the object or system in time and space (e.g., temperature, size, structural integrity); and (3) means of dynamically updating the digital counterpart according to the set of data and vice-versa (Figure 1). Hence, some aspects are inherent in these characteristics, such as the need for a real-time connection (or a connection in an appropriate time scale to your system), the bidirectionality of the data exchange between the digital and physical counterparts, and an interactive layer.

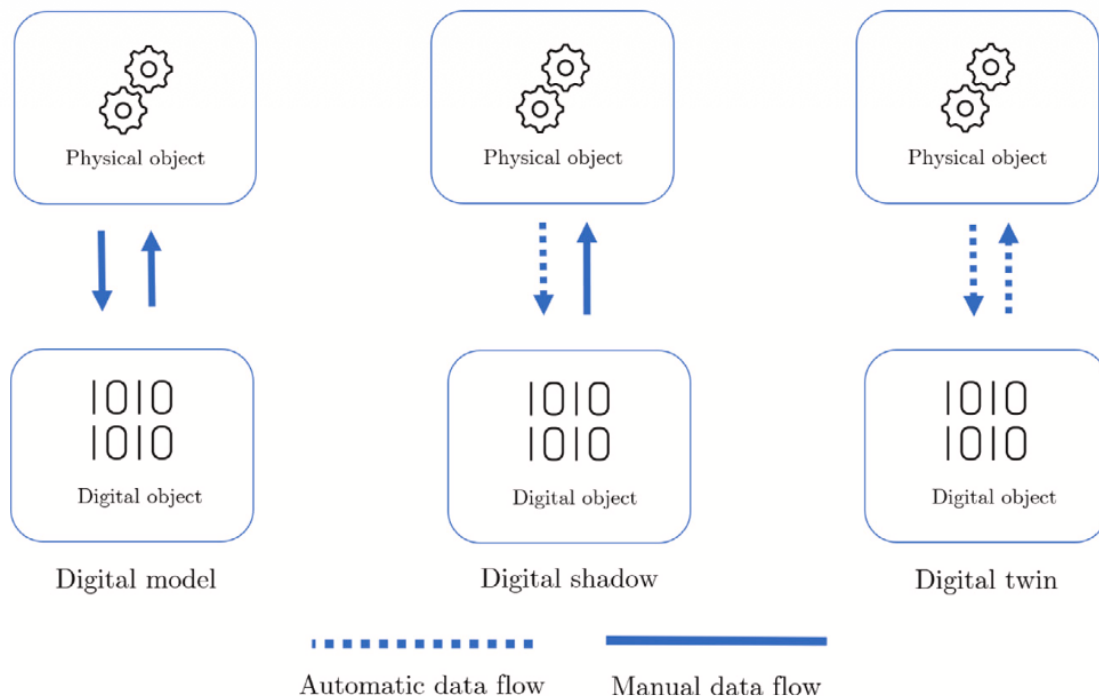


Figure 1: Three levels of digital interaction reproduced from Miedtank et al. (2024), representing the different levels of interaction between physical and digital objects, highlighting how these interactions differentiate Digital Twins.

DTs can also be applied in a planning context (i.e., test of changes on a physical object or design). In such cases, foreseen changes in the physical object are applied in the digital context, and information gathered from the physical counterpart is used to simulate future changes in the object. In those specific cases, the

terminology *Predictive Digital Twin* (PDT) can be used, though other nomenclatures have also been employed (e.g., Digital prototype).

Even though DTs have been successfully applied in industry and manufacturing fields, they have recently moved to applications in Earth Science and Marine fields, such as the *European Digital Twin of the Ocean* program (EDITO, 2025), NorthSat-X (Miedtank et al., 2024), AI4DTE (Schneider et al., 2023), to name a few. However, applying DT concepts in marine and coastal environments presents significant challenges. Those challenges are associated with the size and complexity of the system (Tzachor et al., 2023), associated computational demand (Li et al., 2023, Chen et al., 2023), and the inherent inability to introduce bi-directionality at a system level (i.e., the digital counterpart cannot control the boundaries in the physical system), relying on indirect feedback through stakeholder actions and interventions (Miedtank et al., 2024, Lepper et al., 2025).

### 2.1.2 Conceptualization of a Predictive Digital Twin for DD-Hybrid NbS

For the case of a Predictive Digital Twin for DD-Hybrid NbS, challenges are similar to those related to marine DTs, namely the size and complexity of the system and the associated computational demand. The bi-directionality component on the foreseen PDT is inherently loose, as the tool is made to test designs that are to be implemented on different sites (thus closing the bi-directionality loop). In addition, choices regarding the level of complexity to be included in the digital counterpart need to be considered at an early stage. In coastal areas, due to their complexity, different numerical models are typically built to represent different processes at different time-space scales. Which model would be appropriate is based on different aspects, such as user needs, type of intervention, scale of interest, uncertainty, and so forth.

In the current PDT, a top-down approach is chosen to build a digital counterpart, where models are selected that can sufficiently represent large-scale, decadal changes in the system, before including detailed processes. Apart from user cases that are known within the project, such as the expectation of using PDT outputs to feed the Decision Support System being developed in Work Package 14, general information on potential usage was initially vague. Two workshops were organized with different potential users to gather information on user needs and feedback on early prototypes, so that we could align the architecture design.

### 2.1.3 User definition and architecture design of the PDT software<sup>1</sup>

Two workshops were organized to better delineate user needs: one in October/2024 with the project partners, composed of a mix of engineers, scientists, ecologists, and stakeholders/policymakers; and another one in March/2025, composed mostly of coastal managers from EU countries, in collaboration with the EU-funded MANABAS project (MANABAS, 2025). Both workshops had between 30 and 40 participants each and consisted of walking through early prototypes of a PDT to show potential capabilities and a set of questions to define user needs and gather feedback on usage potential (Figure 2). Information

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<sup>1</sup> The architecture design described in this section was supported with additional resources of the TU Delft Digital Competence Centre (<https://www.tudelft.nl/digital-competence-centre>).

was collected using Mentimeter, with participants answering anonymously a set of pre-defined questions regarding the prototype shown and general questions on how the tool could be useful and what would be needed for proper use in each case. Responses were subsequently summarized qualitatively during a WP13 meeting, where we identified the necessary information for the architecture design.



*Figure 2: Picture taken at the MANABAS workshop, exemplifying the general concept we used for interactions with a Mentimeter approach.*

From the workshops, important insights and feedback were gathered and implemented in the architectural design. Firstly, three key users were defined who each have different requirements that affected the general architecture: coastal managers, engineers, and researchers (Figure 3). Coastal Managers are users who see the PDT as a tool for quick assessment of predefined scenarios on evaluation of the DD-Hybrid NbS solution and a communication tool (mostly between stakeholders, but also at a lower level for public communication). They see the tool as a potential component in decision-making, but note that policies and choices are not made solely based on this tool. They also shared concerns that this

tool is not meant to substitute detailed modelling. Coastal Engineers are users who see this tool to forecast design choices, whereas Coastal Researchers are users who will also use this tool for system understanding.

Regarding the time scale of interest, both workshop groups stated an interest in predictions in the order of years to decades, while simulation time was preferred in the order of minutes to hours. Another important aspect highlighted in both workshops was the interactivity layer, which should be efficient and simple, while providing users with the necessary choices and output. Another important requirement raised was that different users should be able to access information from not only previous simulations, but also across all the different Demonstrator sites.

The user definition is important to tailor the development of the architecture design, but other users mentioned in Figure 3, (e.g., decision-makers, data scientists) could also benefit from the tool. For example, coastal ecologists could use these tools and the access to different scenarios to evaluate potential effects on general trends in vegetation growth.

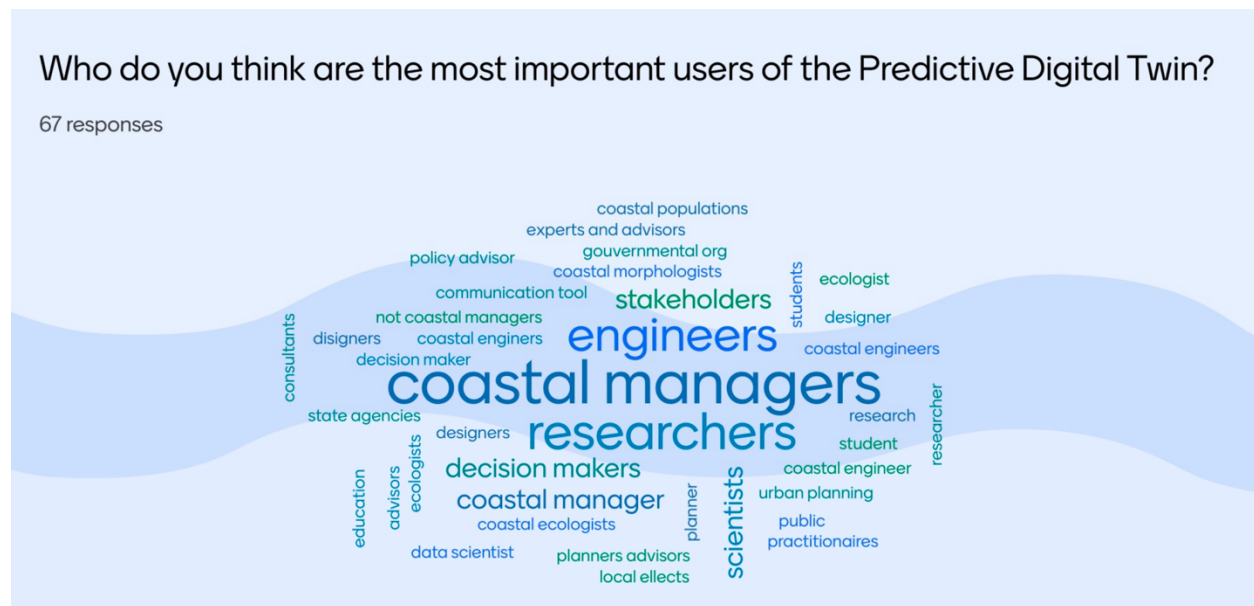


Figure 3: Result from one of the user definition questions for the workshop in the MANABAS meeting in March/2025. Results are similar to those of the first workshop, with Coastal Managers as the main user group, followed by researchers and engineers. The figure is a direct result of the Mentimeter; subgroups and typos have been considered in post-analysis.

Based on this feedback, we designed the general software architecture based on the C4 Model for software architecture, which describes a system at increasing levels of detail (Context, Container, Component, Code) to provide a structured and visual representation of the system’s architecture. The general overview of the user level is presented in Figure 4. The main considerations in defining the different interaction blocks, considering the user needs, were:

- Design that allows for a centralized deployment, so that different users can access information from different demonstrators.

- Construction of a database.
- Choice of models that allow for year-to-decadal predictions with a relatively fast processing time.
- An interactive layer (i.e., frontend) in a web-based format for easy access.
- Input potential for pre-defined conditions and detailed prompts.
- Modular backend, so that technical development on the numerical modelling (e.g., inclusion of detailed processes or functionalities) could happen without major drawbacks on the overall relationship between containers.
- Prioritize open-source programming languages to ensure global compatibility.

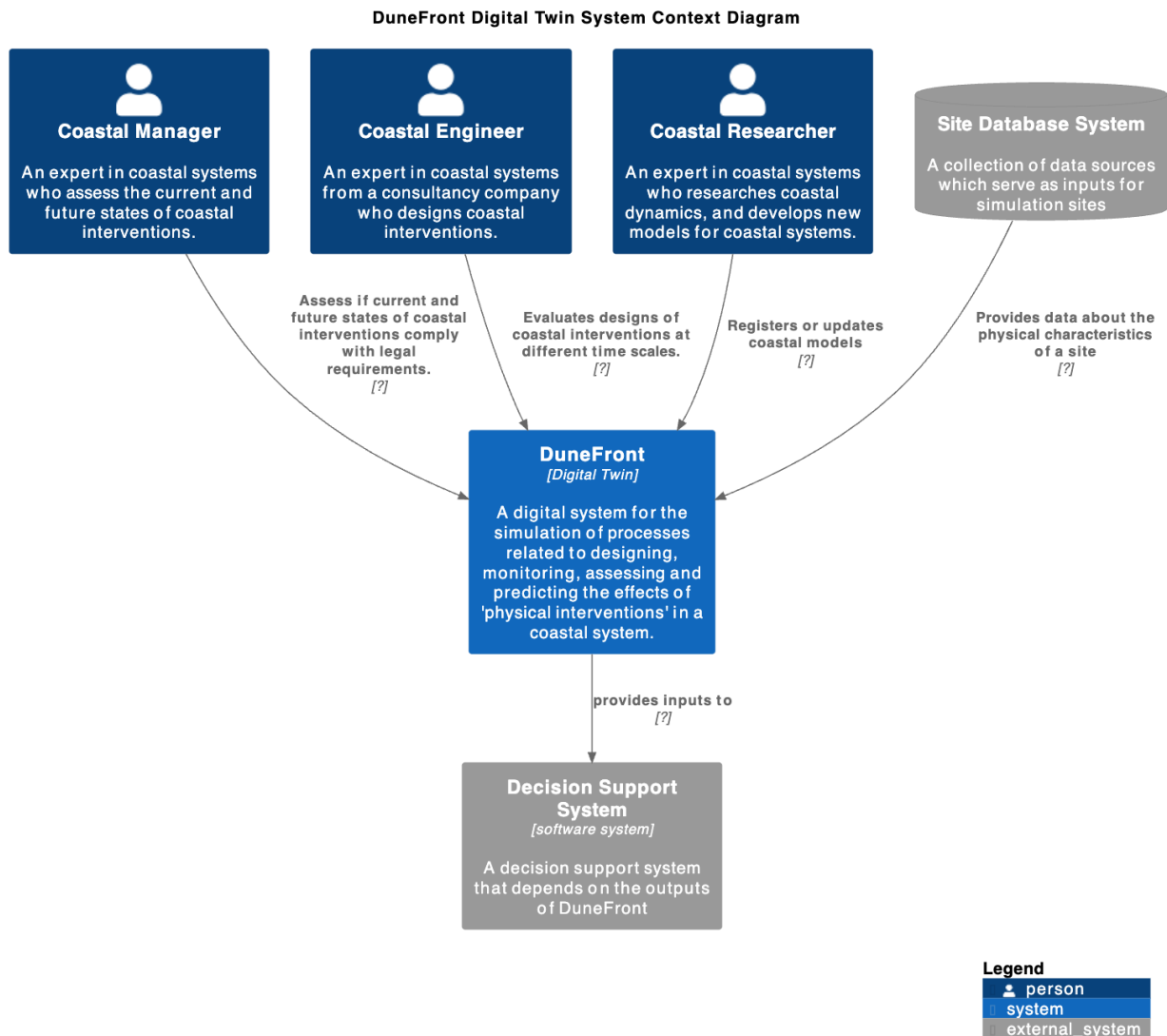


Figure 4: Context diagram for the PDT, highlighting the interaction of all three different users and how output from the system interacts with the Decision Support System developed in Work Package 14.

The final elaborated architecture design is shown in Figure 5. The shown architecture is from the perspective of the Coastal Manager-type user, as it is the one who requires the most complex architecture design. Nonetheless, the architecture for Coastal Engineers and Researchers is very similar, with small changes on the access point, as those users may bypass the access management and web-GUI interface to work directly on the code. The current prototype is based on a basic version of this architecture, where post-processing tools and data feed from external sources are not yet implemented directly (Figure 6). A basic prototype was required for several reasons. Firstly, several containers must be aligned with other WPs, which are still in progress, such as the Decision Support System (WP14), limiting our full post-processing implementation. Secondly, the increased user needs considerably raised complexity, making it necessary to develop a basic version that prioritizes the most important aspects for initial use. Thirdly, some components can only be developed upon central deployment (e.g., shared server or cluster, so users have access to all previous simulations and operational simulations), which is foreseen only in a later stage, once the package passes its alpha version state.

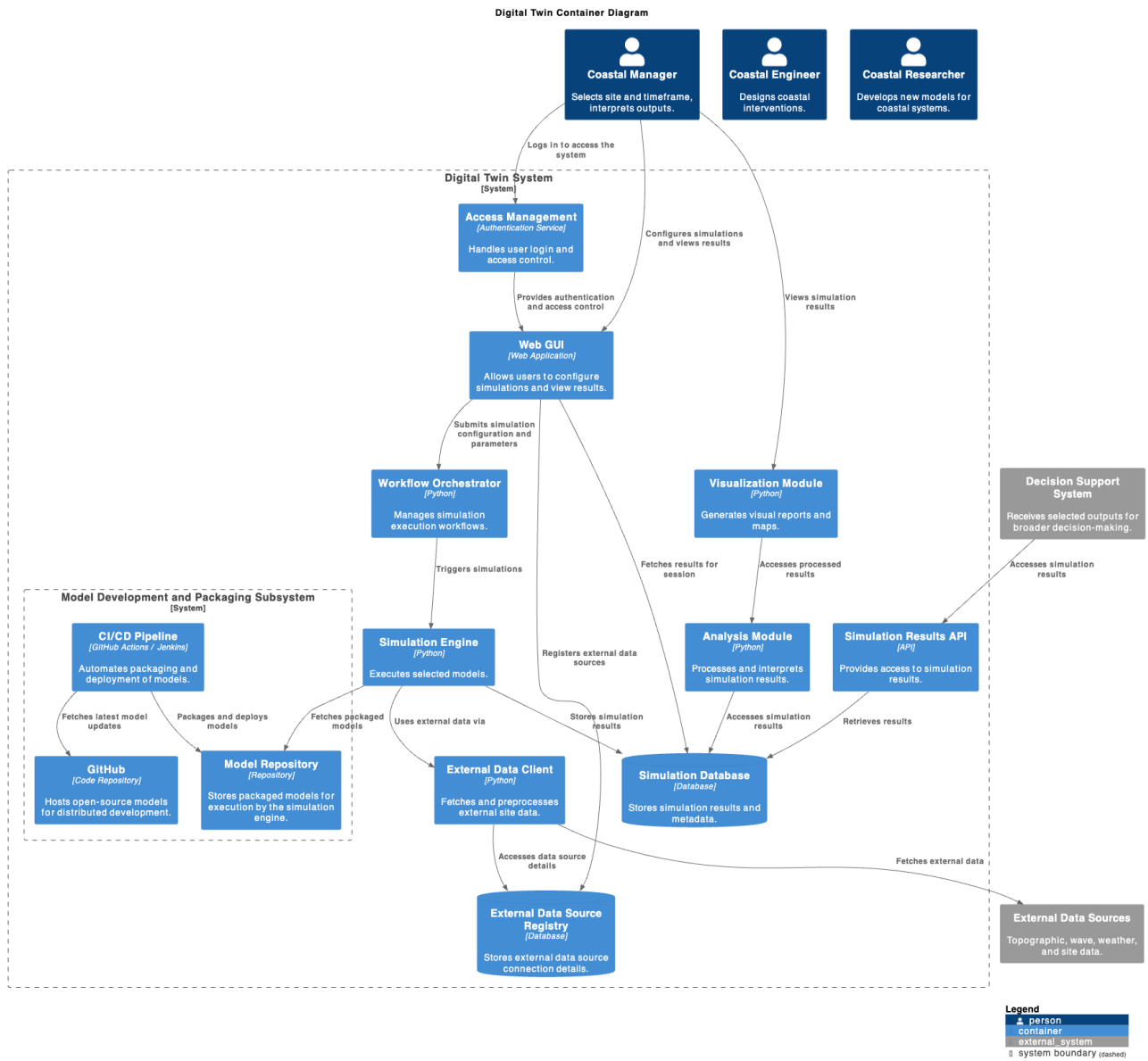


Figure 5: Final container diagram, where the system has been broken down into containers (i.e., applications, databases) and their relationships.

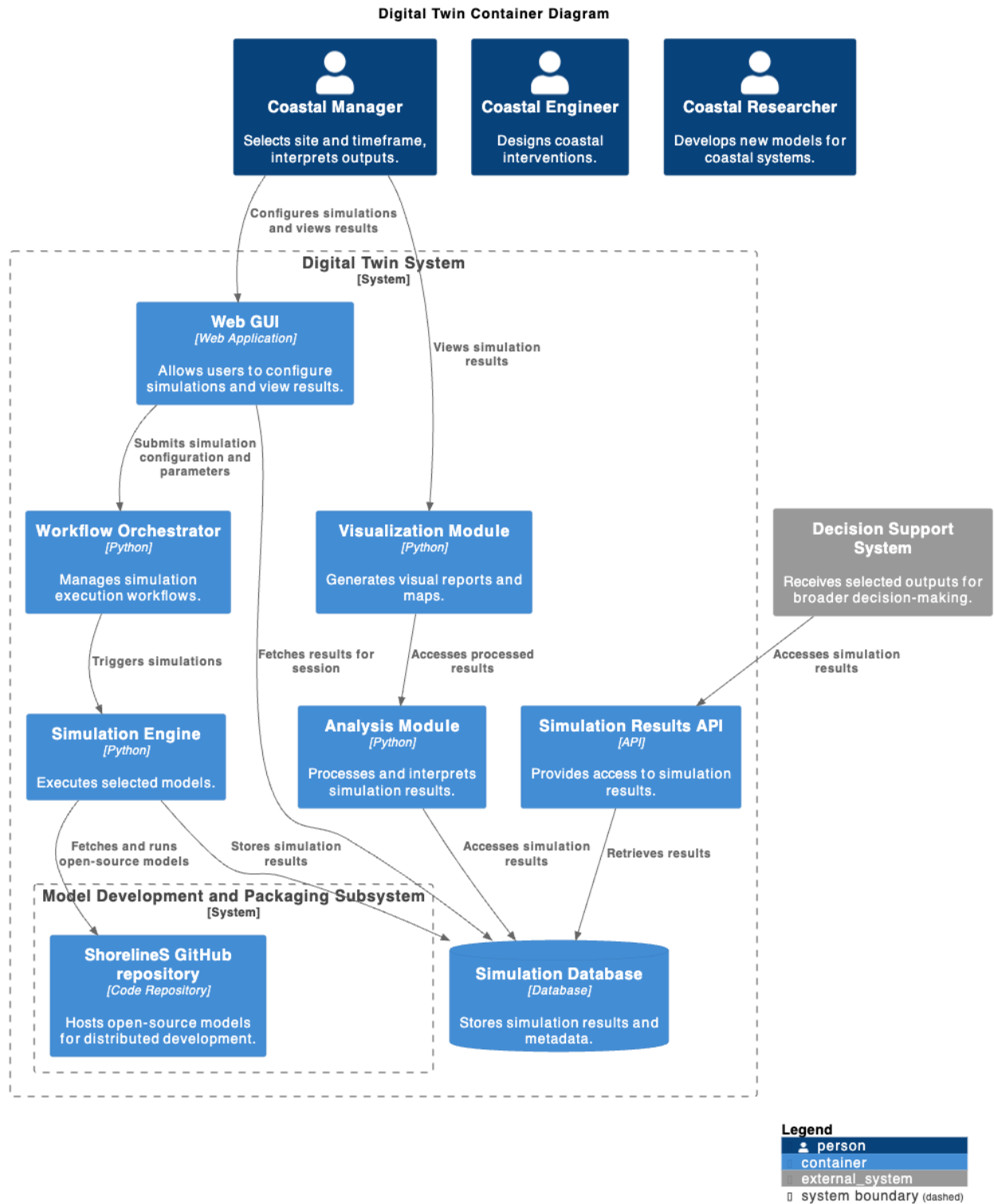


Figure 6: Final Diagram for the minimal prototype. This container diagram is a reduced form of the full architecture.

#### 2.1.4 Selection of existing models and extensions

The two models selected as the core of the digital component are the ShorelineS model (Roelvink et al., 2020) for alongshore processes and the CS model (Hallin et al., 2019) for cross-shore processes. Apart from being well-known models, both were chosen as they can work on similar timescales and could be directly coupled without much change to their modelling structure.

The ShorelineS model (Roelvink et al., 2020) is a vector-based alongshore coastline model that represents the coast with movable nodes and simulates sandy shoreline evolution on time scales of years to centuries. It uses sediment conservation to update the shoreline location based on gradients in wave-driven alongshore transport and includes an active cross-shore profile extending from the depth of closure to the dune crest. Because of the node-based formulation, the model can capture erosion, accretion, and the development of coastline complex formations like spits or islands at relatively low computational cost. It is particularly suitable to simulate systems with expected alongshore variability due to wave-driven transports at time-scales of years to decades.

The CS-model (Hallin et al., 2019) is a semi-empirical, supply-driven cross-shore model designed to simulate decadal to centennial beach–dune evolution. The profile is schematized using a set of morphological pivot points (e.g., shoreline, dune toe, dune crest), which shift horizontally and vertically depending on the sediment exchange between the different profile compartments (beach, dune, bar) (Figure 7). Sediment exchanges due to aeolian transport, dune erosion, overwash, sea-level rise, or nourishments are redistributed among these compartments, and the profile geometry is updated accordingly at each time step. Despite all these complexities, the model needs very little computation capacity.

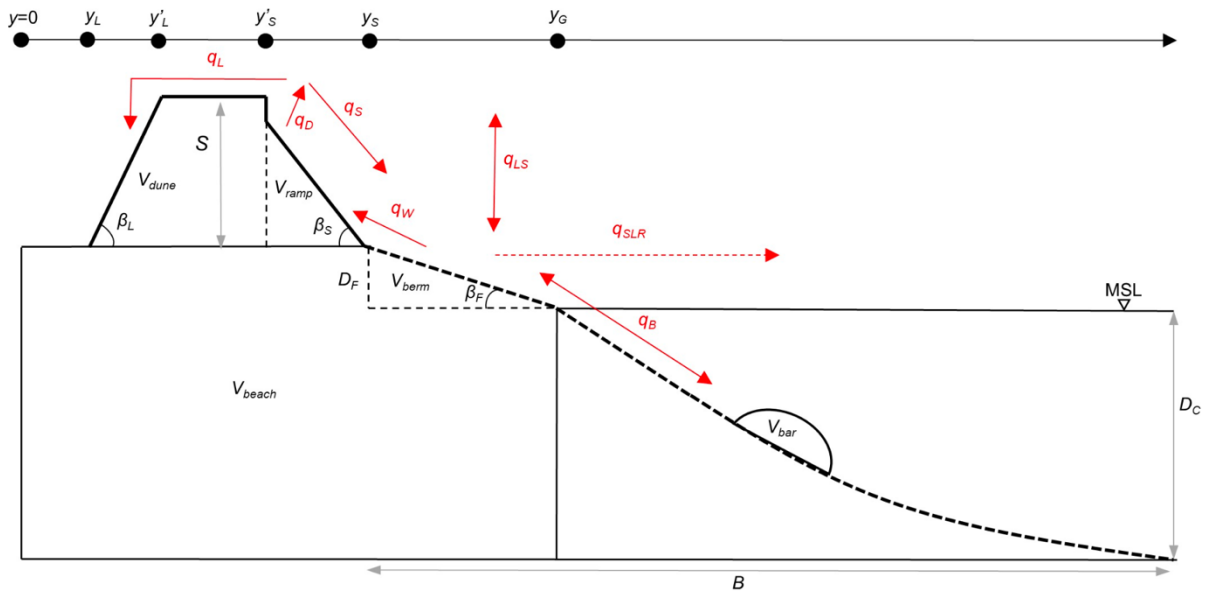


Figure 7: Profile schematization of the CS-model reproduced from Hallin et al. (2019). Red arrows represent transport components, whereas black dots represent pivot points, cross-shore locations that change as a function of the volumes. List of the terms in Table 1.

Table 1: List of symbols and terms related to the CS-model.

<b>Term</b>	<b>Description</b>
$Y_L$	Dune lee cross-shore position
$Y'_L$	Crest cross-shore position at the lee side
$Y'_S$	Crest cross-shore position at the sea side
$Y_S$	Dunefoot cross-shore position
$Y_G$	Shoreline position
$S$	Dune height
$\beta_L$	Angle of repose on the lee side
$\beta_S$	Angle of repose on the seaward side
$\beta_F$	Swash angle
$V_{dune}$	Dune volume
$V_{beach}$	Beach volume
$V_{ramp}$	Dune ramp volume
$V_{berm}$	Berm volume
$V_{bar}$	Bar volume
$D_F$	Dunefoot height
$D_C$	Depth of closure
$Q_L$	Overwash transport
$Q_D$	Transport of eroded sediment from the dune
$Q_S$	Transport of eroded sediment from the dune to the beach

$Q_W$	Onshore aeolian transport
$Q_B$	Beach-bar transport
$Q_{SLR}$	Transport to compensate for SLR assuming Brunn's rule
$Q_{LS}$	Longshore-driven gradients
B	Width of the active profile

Both models have been tested and validated on different settings (Larson et al., 2016, Palalane and Larson, 2019, Yoo et al., 2022, Mao et al., 2025, Elghandour et al., 2023) and proved suitable to simulate the year-to-decadal evolution of shoreline development and beach-dune dynamics. Nonetheless, in the context of DD-Hybrid-NbS, some critical limitations of these models need to be addressed based on information gathered on other WPs, user needs, or parametrizations to represent processes that are not included in the models. Generally, there are three main extensions: (1) inclusion of vegetation on the CS-Model; (2) inclusion of hard structures on the CS-Model; and (3) coupling the CS-model with the ShorelineS, so that alongshore variability is properly reflected in the beach-dune profile. Another important modification was the translation of both models from their native programming languages (Fortran for CS-Model, and MATLAB for ShorelineS) to Python to ensure optimal compatibility and usability between different WPs. A detailed description of the improvements done in the model is provided in the next session.

## 2.2 Calibration (T13.2)

### 2.2.1 Inclusion of Vegetation Effects in the CS-Model

Vegetation is an important driver of beach-dune development, especially on year-to-decadal time-scales. Not only do changes in vegetation drive morphological behavior of the dune profile, but also information on vegetation development is an important aspect for decision-making in DD-Hybrid-NbS projects. Given the user requirements and the nature of the CS-model, reduction-order parametrizations of vegetation growth and development are implemented to give a first-order estimate of vegetation development and the effects on beach-dune development in these environments.

There are three main considerations in terms of vegetation implemented: (1) vegetation growth and decay, (2) the influence of vegetation on sediment deposition, and (3) the influence of vegetation on dune erosion during storms.

For vegetation growth and decay, we adapt the rationale and parametrizations used in the DECAL model (Nield and Baas, 2008), and later implemented in the cellular automata model for beach-dune systems DUBEVEG (Keijsers et al., 2016). In this approach, vegetation growth or decay responds directly to sediment surface change rather than to explicit environmental drivers such as moisture or nutrients. The vegetation is incorporated by a dimensionless value  $r$  ranging from 0 (bare sand) up to 1 (full coverage), which mimics how vegetation affects the potential for aeolian sand transport and deposition and can be conceptually related to vegetation cover (Nield and Baas, 2008). The dimensionless value is a generalization, hence while detailed processes are not accounted for, it represents general trends of vegetation and their effects on transport. Different species can be incorporated individually, as long as

there is a relationship between growth and decay and bed level change (Figure 8). This is a common trait for some dune species, such as pioneer species (*Ammophila arenaria*) that present peak growth when there is a certain burial level, and conservative species (e.g., *Hippophae rhamnoides*), which are more stable species.

This parametrization is reduced in complexity but proved sufficient for an overview of vegetation evolution trend in coastal dunes (Keijsers et al., 2016, Galiforni Silva et al., 2019, Poppema et al., 2022). Different time scales for updating vegetation have been used in different studies, but mostly at the yearly scale. In the present study, as seasonality is important, we adapt the values of the curve from Nield and Baas (2008) to a monthly scale and update some of the growth values based on recent studies (Bonte et al., 2021, Nolet et al., 2018). Also, we limit growth during the winter period and apply a reduction of about 6% per month of the vegetation coverage during winter to account for browning, frosting, reduced light, and so forth. These values can be site-specific and could be adjusted on a case-by-case basis. As a reduced form of parametrization, characteristics that are relevant for a more detailed representation of the vegetation development (e.g., nutrient availability, humidity, salt spray) are not directly incorporated at the present stage but might be considered if needed for specific demonstrators.

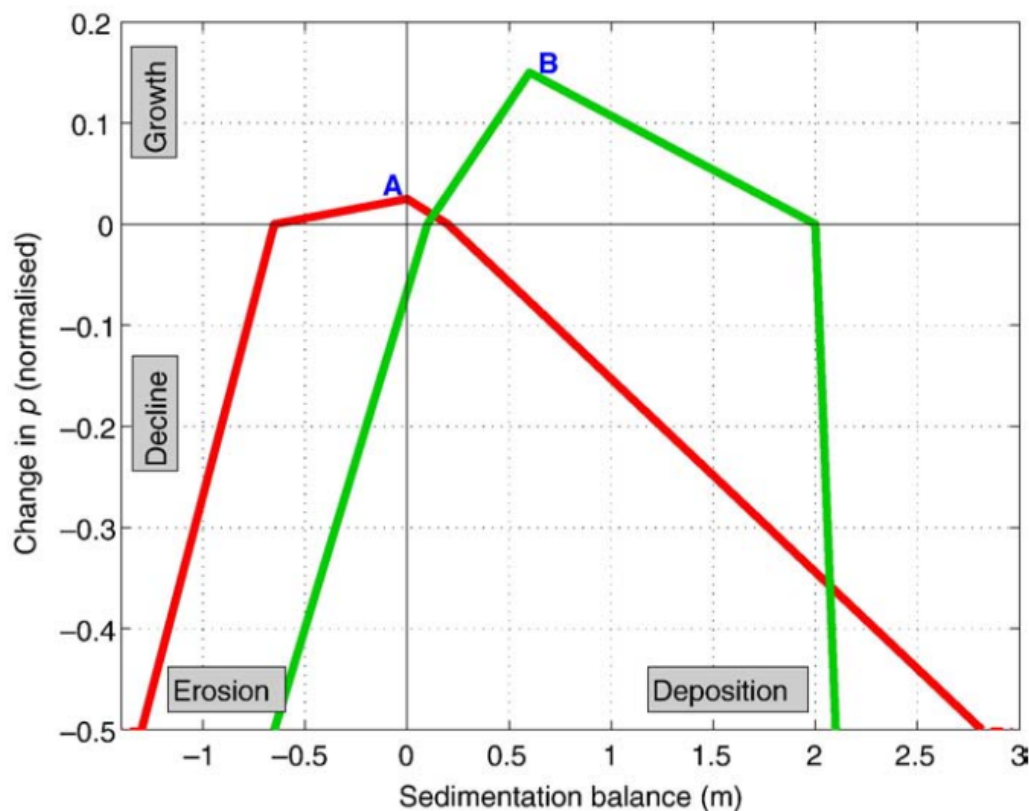


Figure 8: Example of relationship between yearly sedimentation balance and change in normalized “vegetation coverage”, reproduced from Nield and Baas (2008). Curve A represents a conservative species, whereas curve B represents a pioneer species.

Another important implementation regarding vegetation is the influence on dune erosion. Such an influence has been reported in previous studies (Figlus et al., 2022) and is being explored in experiments conducted in WP12. The main concept is that belowground biomass would influence the resistance of dunes to wave-driven erosion, thus a vegetated dune would better resist the impact of waves compared to bare dunes. Figlus et al. (2022) on flume experiments observed that the volume of eroded sand decreased approximately linearly with increasing vegetation frontal area density (defined as the total projected plant area per unit alongshore length). Across a range of experiments, the erosion potential was reduced by up to ~28 % for the highest vegetation densities tested.

In the model, the approximate total frontal area per alongshore unit is computed as:

$$A_v = \sum_i K_i \rho_{v,i}$$

where  $\rho_v$  is the normalized vegetation coverage (dimensionless, varying from 0 for bare sand to 1 for full cover) for each cross-shore zone  $i$  (e.g., dune foot, crest, and lee), and  $K_i$  is a species-specific scaling factor representing the characteristic frontal area at full cover, expressed in  $\text{cm}^2$  per cm alongshore (to match Figlus et al. (2022) scaling). This is separated per zone because each zone has its own vegetation value, but the erosion location still follows the same CS order.  $A_v$  is expressed in  $\text{cm}^2$  per cm alongshore.

The erosion reduction factor is then defined as

$$\text{vegred} = 1 - \min(0.021 A_v, 0.28),$$

where:

- 0.021 = 2.1 % reduction in potential erosion per ( $\text{cm}^2/\text{cm}$ ) of vegetation (Figlus et al., 2022)
- 0.28 = maximum reduction (28 %) observed in the flume data.

Hence, a bare dune ( $A_v = 0$ ) yields  $\text{vegred} = 1$  (no reduction), while dense vegetation saturates at  $\text{vegred} = 0.72$  (28 % less erosion potential).

It is expected that these values will be fine-tuned based on the experiments conducted by WP12 in 2026.

### 2.2.2 Inclusion of Hard-Structures in the CS-Model

In the previous version of the CS-model, hard structure schematization was absent, which made simulation on hybrid systems not possible. All beach and dune profile evolution due to sediment redistribution happened assuming a completely movable bed, which is not the case for a hybrid system, where hard structures do not move.

In the presence of hard structures, morphological redistribution should consider the presence of hard structures that act as non-erodible layers in the profile. Thus, for example, the same amount of sediment

that would move the dune toe a certain distance seaward would move the dune toe differently if the dune is moving over a dike surface, as less volume would be needed to fill the same volume due to the presence of the hard structure (Figure 9).

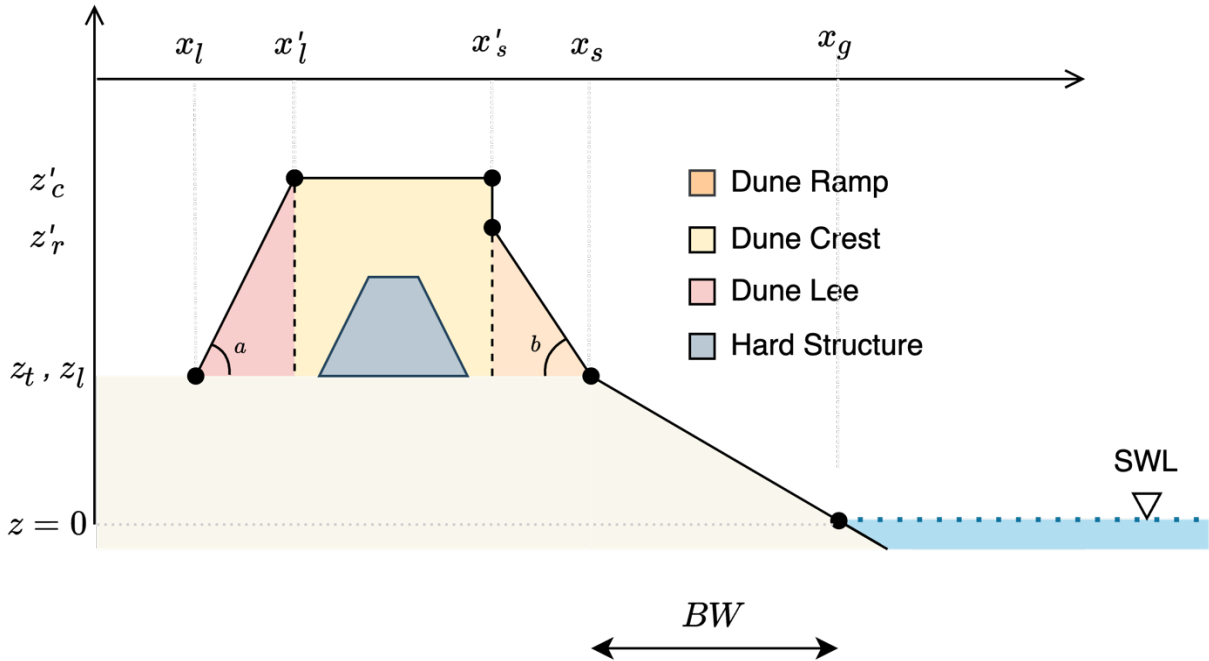


Figure 9: Schematization of the profile, following a similar description made by Hallin et. al. (2019) for the base CS-model. Here, we highlight the dune morphological units where we calculate volumes with different colors, as well as the non-erodible hard structure. Pivot points that are movable as a function of the unit volume are highlighted in black circles.  $a$  and  $b$  represent the angle of repose of the lee and ramp side, respectively, which are set constant throughout the simulation.

Realistically, several hard structure characteristics would influence the interaction between sediment and the hard structure (e.g., surface roughness). Given the scale of our simulations, we adopt a simplified approach, where the influence of the hard structure relies mostly on the area occupied and its non-erodibility characteristic.

In the current implementation, hard structures are defined as a non-erodible surface over which dunes can develop. As dune volume increases, dike geometry constrains the position and elevation of pivot points. The target dune volume is satisfied by locating pivot points (e.g., dune toe, dune crest) along the hybrid profile that meet geometric constraints using a root-finding function based on Brent's method (Brent, 1971). This method allows for calculating pivot changes on several different configurations of DD-hybrid systems (e.g., dune before dike, dike within dune). The presence of dikes may also limit the transport to the lee side of the dune, given that no space for development between the dune and dike exists.

In general terms, the process follows the following step-by-step approach:

1. Determine the target volume for the morphological unit of the dune (i.e., dune ramp, crest, or lee) based on availability from the neighboring unit downwind (e.g., for the dune ramp, sediment that comes from the beach).
2. Define a geometric function that expresses the volume of the morphological unit as a function of one or more pivot points (e.g., ramp height, crest height, or lee pivot).
3. Solve the volume constraint using a root-finding method (Brent's method) to find the pivot point(s) that satisfy the target volume.
4. Update all dependent positions of the block (e.g., ramp toe, ramp crest, seaward crest, lee pivot, or lee foot) according to geometric relationships.
5. Check for constraints imposed by hard structures or the substrate and adjust the pivot positions accordingly.
6. Redistribute excess volume laterally or between neighboring morphological units if the target volume cannot be fully accommodated within the primary block.

This approach is applied consistently across the dune ramp, crest, and lee blocks, with each section having tailored logic to handle specific geometric limitations or interactions with hard structures. By using a combination of volume-based constraints, geometric relationships, and root-finding, the model ensures mass conservation and realistic dune morphology evolution while respecting physical and structural constraints.

Hard structures also limit dune erosion. In erosion conditions, sediment is removed from the dune and transported to the beach and bar, calculated as in the original CS model. When a structure (e.g., a dike) is present, potential dune erosion is capped by the intersection between the dune profile and the structure. At each time step, the model computes the erosion volume available without intersecting the structure, applies the erosion, and updates the dune geometry. This available volume is defined by the area between the dune and the structure and depends on the runup, which sets the cross-shore bounds for the calculation. After the ramp is eroded, erosion capacity depends on how much the runup exceeds the dune–structure intersection. If no volume remains due to the structure, no erosion is applied.

In case of overwash, some of the sediment eroded moves landward instead of seaward towards the beach and bar. The first step is to determine how much of the dune crest can be eroded without violating geometric constraints. The model computes the full dune volume and subtracts the volume after a hypothetical erosion to match the overwash target. A root-finding algorithm (Brent's method) is used to find the potential reduction in crest height that satisfies this volume condition. This ensures that the erosion applied to the crest corresponds exactly to the intended overwash volume.

If a hard structure, such as a dike, exists landward of the crest, the erosion is limited so that the dune does not erode below the top of the structure. In such cases, any excess sediment that would have been removed is added to the lee side. The new crest elevation is calculated to maintain the correct geometric slope between the ramp, seaward crest, and lee crest, ensuring the dune profile remains physically consistent. The overwashed sediment is then added to the lee portion of the dune. The model calculates

the target lee volume by summing the current lee volume with the incoming overwash volume. To achieve this target, a root-finding function is applied to determine the new lee crest position that satisfies the updated volume.

The lee slope is assumed to extend linearly from the new crest down to a theoretical flat toe. If this line intersects a hard substrate (such as a dike or the original dune foot), the intersection is used to adjust the lee foot location, preventing the lee from penetrating the substrate. This guarantees that all overwash sediment is accommodated within physically feasible bounds. An example of how the dune evolves under overwash conditions can be seen in Figure 10.

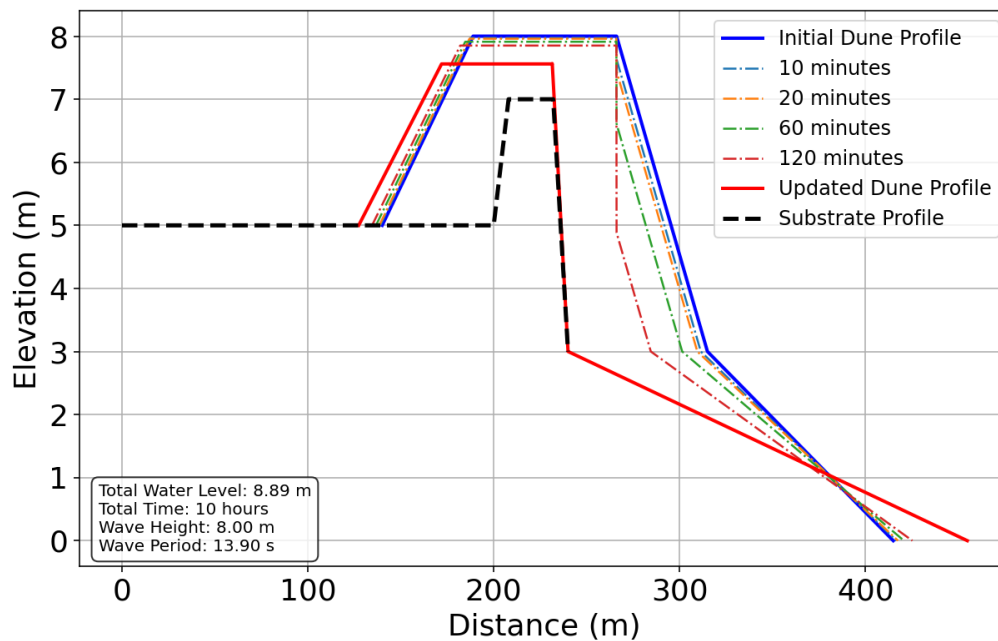


Figure 10: Example of a storm simulation, with boundary characteristics displayed in the lower left of the figure. The plot exemplifies how the profile changes over time with continuous erosion, with sediment being eroded to the beach and overwashed to the lee side. The blue line represents the initial condition, while the red line shows the final profile after the storm. As the beach increases, more dissipation occurs, yielding a reduction in the erosion.

### 2.2.3 Coupling ShorelineS and CS-Model

To ensure that both the alongshore and cross-shore development of the DD-Hybrid-NbS solution are present both models need to be coupled. Changes in the alongshore component by wave-driven transport gradients are translated to the cross-shore model, and effects are translated to the dune development. As both models compute shoreline position, this parameter can be used to directly couple the two models. We implemented three different approaches (Figure 11).

Initially, the ShorelineS model determines the shoreline position at every time step, and its vector-based grid is overlaid with the CS-model profiles. The volume change resulting from alongshore transport gradients is passed to the CS-model, which redistributes this sediment across the cross-shore

compartments of its schematized profile. The resulting gains or losses in beach volume are then returned to ShorelineS and added to the alongshore gradients to obtain a net sediment flux. This net flux determines the shoreline movement for that time step, completing the loop. From our test, this works best for sites where high alongshore variability exists within the timeframe simulated, though mass inconsistencies may appear over very long simulations.

In a second iteration, all morphological adjustments and shoreline calculations are made in the CS-model. ShorelineS computes the alongshore sediment transport but only passes the transport rates to the CS-model instead of the updated shoreline position. The CS-model incorporates these fluxes, applies its own cross-shore redistribution, and updates the profile and shoreline position directly. The updated shoreline is then used by ShorelineS. This coupling strategy proved best for sites with low alongshore variability, as it simulates the cross-shore evolution well with more balanced control on the mass conservation, as all changes happen within the same model.

Finally, a hybrid approach was made, where ShorelineS computed the changes in shoreline position driven by alongshore gradients, whereas the CS model computed the changes induced by cross-shore changes. Instead of exchanging fluxes, the models exchange geometric changes in shoreline position in Cartesian space, which are combined to obtain the updated shoreline for the next step. This coupling strategy is particularly useful on sites/time scales where shoreline position is highly dependent on both alongshore gradients and cross-shore contribution from the dunes (e.g., erosion)

Across all approaches, maintaining sediment conservation is important. Differences in discretization, interpolation, and the internal assumptions used by each model (e.g., shoreline defined via active profile height in ShorelineS versus beach volume in the CS-model) can introduce small imbalances that accumulate over long simulations. To minimize these effects, we track sediment volumes throughout the domain and ensure that mass errors remain below 1%.

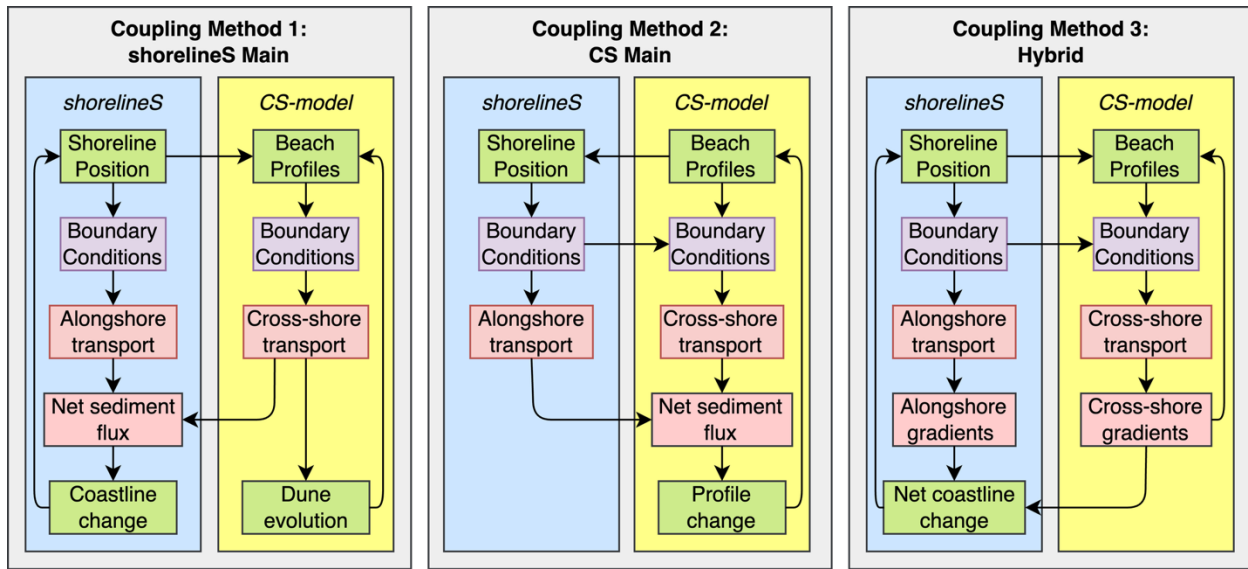


Figure 11: Flowcharts of the three coupling methods tested and implemented. Green boxes represent morphological aspects, whereas purple and red boxes represent external forcings and resulting processes, respectively

## 2.2.4 Sensitivity Analysis

To better understand the effects of the implementations described on previous sections and check whether the expected behavior is being reproduced, different sensitivity tests were carried out, focusing mostly on the new add-ons (i.e., vegetation, hard structure, and coupling).

For the effects of vegetation on sediment deposition and the newly introduced deposition scheme, two tests were carried out: one on the effect of vegetation coverage on the deposition location along the dune profile, and another on the sensitivity of the calibration parameters related to the wind adjustment term to the profile shape and, consequently, the behavior of sediment transport over the dune. For the effects of hard structure, the test examines the effects of different setup values on the time series of different parameters during a 10-hour storm, for different vegetation coverages. The final profiles for each setup value and vegetation coverage are also checked.

For the first test, results show the expected behavior of bare dunes tending to accumulate sediment near the crest and the lee side, similar to what is observed in desert dunes (Walker et al., 2022). On bare dunes, morphology predominantly controls the deposition patterns. Along the ramp, the flow accelerates, creating a zone that is not prone to deposition of near-bed transported sediment (i.e., creep, reptation, and saltation). As the flow reaches the dune crest, it decelerates, producing a region where this type of sediment more readily deposits. On the lee side, the flow separates from the surface and forms a separation bubble. Sediment transported close to the bed that is not deposited at the crest typically deposits within this recirculation zone. As vegetation is introduced in the model, sediment increasingly deposits on the ramp portion as vegetation decelerates the flow, controlling it more than the acceleration of the ramp. Walker et al. (2017) shows that wind speed is topographically accelerated upslope above the

vegetation, while within the vegetation, drag increases upslope, and speeds decelerate. Consequently, more deposition in the ramp should occur as dune height increases, which is also seen in Figure 12

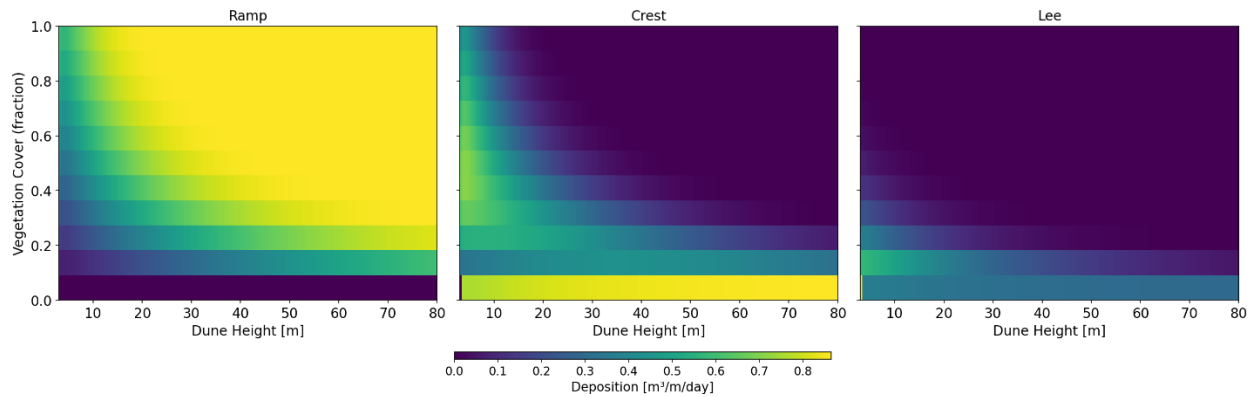


Figure 12: Effects of vegetation coverage on the deposition pattern on the dune profile.

For the second test, the analysis examines the effects of calibration parameters that control how topography affects the flow. The test varies two coefficients:  $\alpha$ , which controls the amplitude of bed slope gradient influence, and  $\beta$ , which controls the relative weight of the local slope term for each compartment unit of the dune. The purpose of this test is to evaluate whether these parameters affect only the magnitude of changes (hence not the general deposition patterns) or if they can induce changes in patterns. It also evaluates the extent of control these parameters have on certain aspects, such as maximum dune height and capacity of aeolian landward transport. Results show that these coefficients only control the magnitude of the deposition and not the overall pattern, with larger  $\alpha$  values inducing a smoother transition towards a total deposition in the ramp as the dune becomes higher (Figure 13). The combination of  $\alpha$  and  $\beta$  can make the ramp completely retain all aeolian transport from the beach when dunes reach an elevation of 20 meters up to about 65 meters.

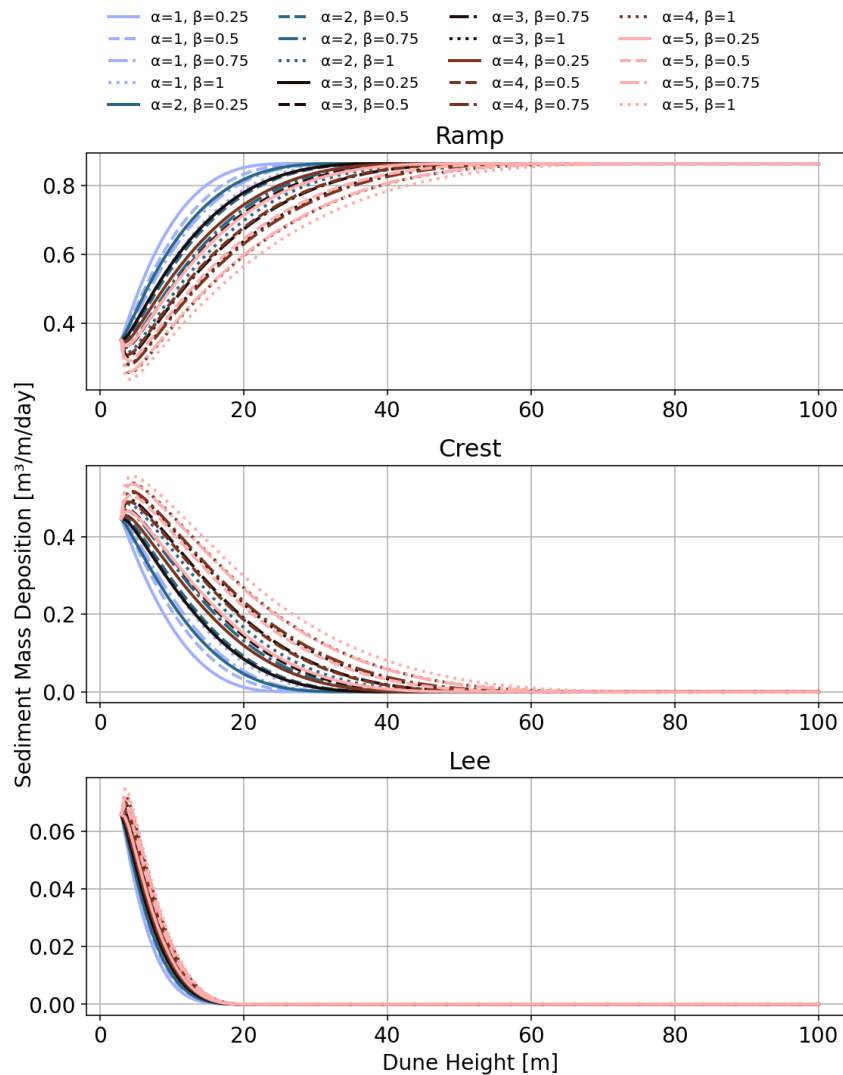


Figure 13: Effects of coefficients alpha and beta on deposition patterns along a vegetated dune. Vegetation coverage used is 0.1

For the test with a hard structure, effects are milder in the presence of vegetation, while erosion capacity increases with higher total water level values (i.e., setup + runup + surge + tide). Also, eroded volumes halt once they reach the hard structure, which can be seen for setup values of 5 and 6 meters (Figure 14). Moreover, the total water level (TWL) tends to reduce as beach volume increases due to increased dissipation of waves and, consequently, reduction of runup. Another important note is that overwash erosion only occurs for larger setup values, where the total water level reaches the top of the dune. Final profiles also show how vegetation reduces the erosive capacity for each setup. Effects are very visible at lower TWL values that do not reach the top of the dune, where, without the vegetation, some values were able to reach the hard structure portion (Figure 15).

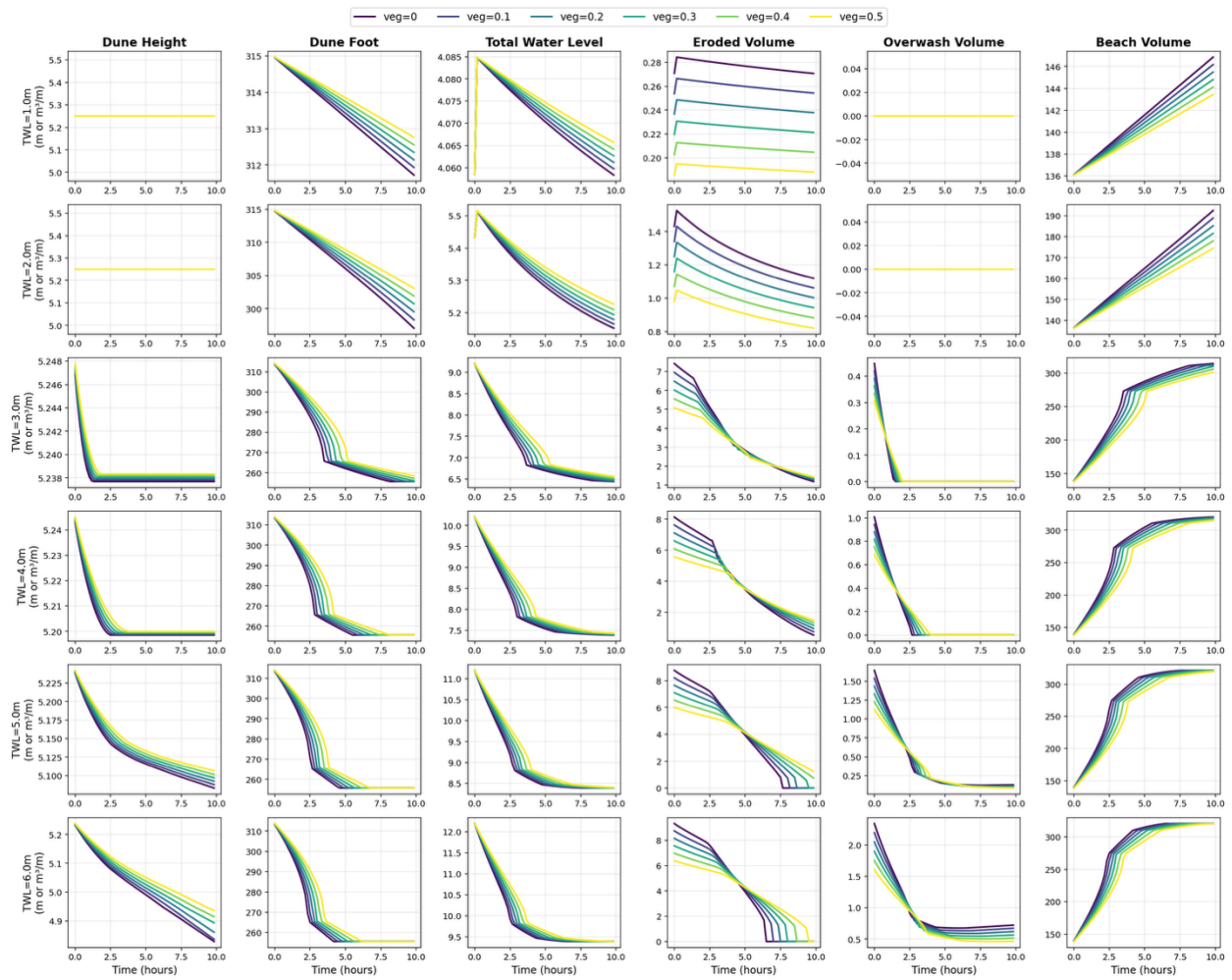


Figure 14: Sensitivity analysis on the effect of vegetation, TWL, and hard structure on erosive patterns during a 10-hour storm simulation. Initial profile and wave parameters ( $H_s = 8$  meters and  $T_p = 13,9$  seconds) were kept the same for all simulations.

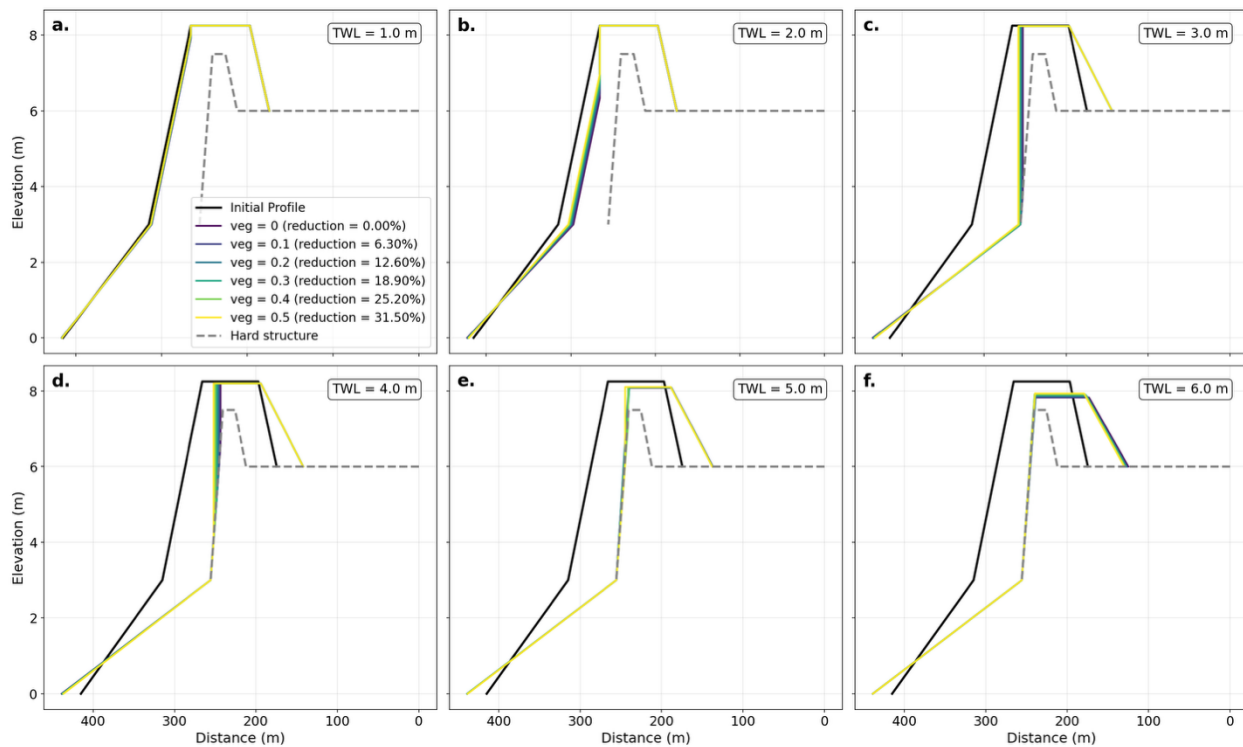


Figure 15: Final profiles for different vegetation coverage and TWL values after a 10-hour storm.

## 2.3 Validation (T13.3)

### 2.3.1 Overview of validation cases

Three demonstrators were selected to validate the added parametrizations: Oosterover (BE) for the relation between vegetation and dune growth, Katwijk (NL) for the presence of hard structures (in this case, a dike-in-dune system) during erosive events, and Hondsbossche Duinen (NL) for the coupling methods and the 2D approach. Selection prioritized cases with sufficient available data for validation and that effectively represent the specific characteristics targeted by the new parametrizations.

### 2.3.2 Oosterover (BE) – Vegetation

To test the vegetation component introduced, we apply the updated CS-model in the demonstrator of Oosterover, BE. Oosterover is a coastal stretch north of Ostend on the Belgian coast, where a pilot hybrid dune–dike system has been implemented. The project involves planting marram grass on the upper beach to limit sand accumulation against the dike and to improve understanding of early dune formation under active aeolian conditions. Due to beach nourishment, the site currently features a relatively wide beach (approximately 320 m), providing great sediment availability for dune initiation.

The Oosterover pilot, initiated in 2021, has been thoroughly monitored and described in several studies (Strypsteen et al., 2024, Derijckere et al., 2023), offering a well-documented setting with controlled vegetation plots. As such, this pilot represents a suitable case for testing the influence of vegetation on incipient dune development within our newly implemented vegetation module.

We apply the model on a 1-D version of the CS-model, so alongshore-driven variability is not considered in this test. We simulate the period comprising the monitoring period shown in Strypsteen et al. (2024). For the boundary conditions of waves and wind, we gathered the same information used in the paper, which was gathered at Ostend weather station and Ostend Oosterstaketsel wave buoy, though data pre-processing may have differed (Figure 16). For a 3-year simulation, the model took less than one minute. Initial conditions are displayed in Table 2.

*Table 2: Initial conditions and parameters used on the Oosterend test case.*

<b>Parameter</b>	<b>Unit</b>	<b>Value</b>
Median grain size	meters	$2.5 \cdot 10^{-4}$
Seaward dune slope	degree	0.47
Landward dune slope	degree	0.26
Initial dune height	meters	0.1
Initial normalized vegetation coverage	-	0.15
Beach Width	meters	320
Shoreface normal	degree	330
Empirical coefficient in aeolian equilibrium transport formula ( $K_w$ )	-	4.2
Empirical coefficient to account for fetch effect	meters <sup>-1</sup>	0.1

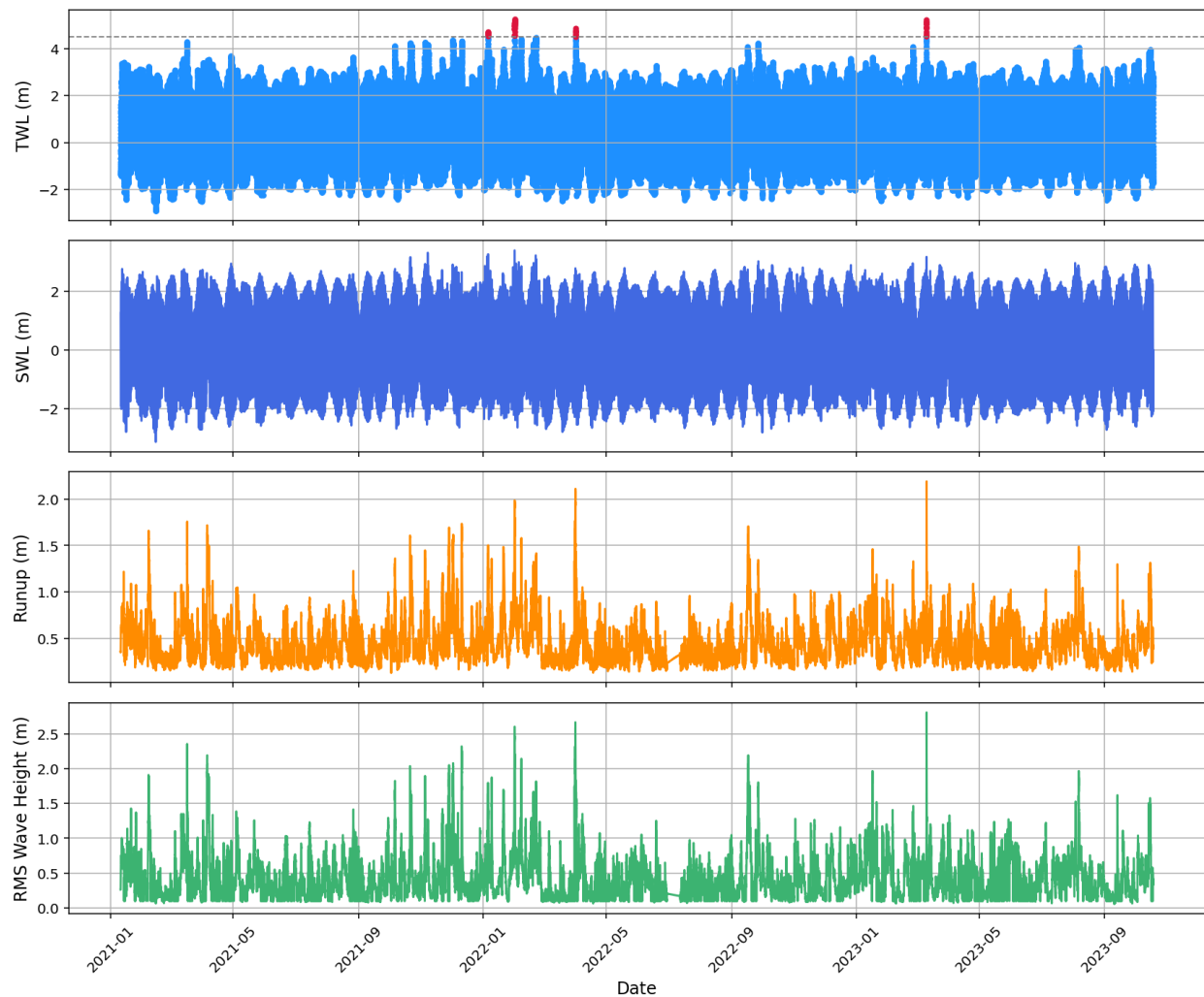


Figure 16: Boundary conditions used in the model. Red dots represent storm conditions, whereas runup and, consequently, TWL values are calculated by the model.

In terms of volume, the model captured the overall trend relatively well (Figure 17). The order of magnitude was respected, as well as the variability in height and dune length. Differences between modelled and measured are related to the speed of growth in some periods, such as the measured steeper growth between Jan-23 to Sep-23 and the modelled steeper growth between Jan-22 and May-22. Several hypotheses can explain these changes, such as the lack of alongshore component, supply changes on the beach face (e.g., armoring, surface moisture), and other environmental conditions (e.g., rain) that are not present in the reduced-order modelling by nature. Also, the site showed a prominent embryonic dune growing in front of the wooden fences, creating a more complex morphology that may have induced changes in how sediment is deposited that are currently not implemented in the model. It should be noted that these results do not include coupling with the alongshore component, which can introduce another source of variability to sediment supply from the beach.

In terms of vegetation, differences are more prominent, though several trends could be simulated by the simplified parametrization implemented. The overall order of magnitude was kept in place for most of the simulation, apart from the period between Jan-23 and Sept-23, which saw a prominent increase in vegetation, most probably following the increased sediment input in the same period that was not captured in the model and, therefore, not passed to the coverage growth. The simulated variability was notably lower than the measured vegetation coverage, though it was expected as vegetation dynamics are also affected by several parameters that are not implemented in the reduced-order model (e.g., nutrient depletion, rain). Nonetheless, qualitatively, the simplified parametrization showed much potential for application on the different demonstrators.

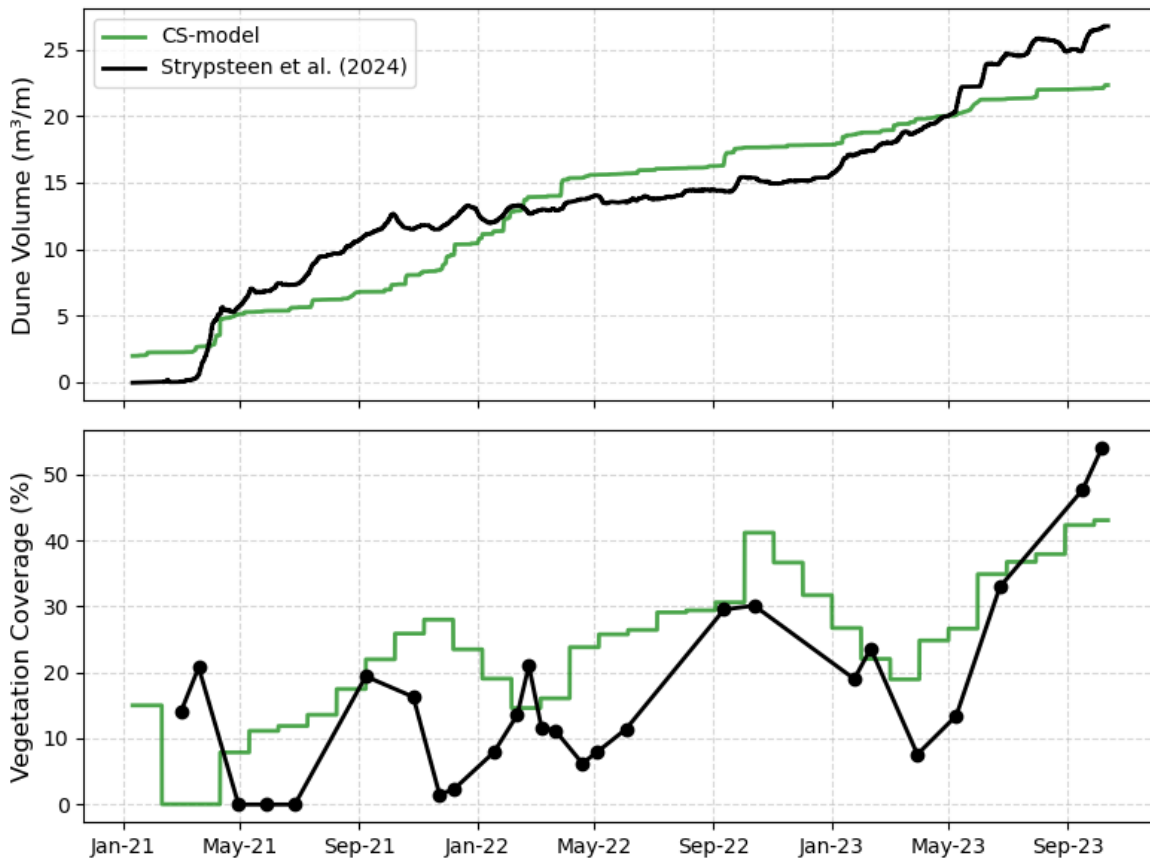


Figure 17: Comparison between modeled and measured dune growth and vegetation coverage in Oosteroever (BE). Values are based on Strypsteen et. al. (2024).

### 2.3.3 Katwijk (NL) – Hard structures

To test the hard structure adaptation, we apply the adapted CS-model to the demonstrator of Katwijk (NL). The Katwijk demonstrator has a dune-on-dike hybrid coastal structure system in which a buried hard dike is integrated within an artificial dune of about 40 meters wide and 1,5 kilometers long.

Even though the area has been monitored for changes on a yearly scale, data on the role of the dune-on-dike system during extreme events (i.e., events that lead to sufficient erosion so that the interaction between hard structure and dune becomes relevant) is very scarce. Thus, to test our model implementation, we rely on simulations done using XBeach modelling on the scope of WP12 by the PhD Student Cem Sevindik at TU Delft. Considering the conceptual differences in the model, we aim for a qualitative check on the effects of the storm in the hybrid system and the relationship between the dike and dune when the dune is eroded sufficiently during the storm so as to reach the dike (i.e., dike exposed). Aspects such as landward transport due to overwash, the reduction of erosion over time as the beach gets wider, and the erosive trends in the dune were analysed.

XBeach simulations were done using an idealized profile of Katwijk. The simulation we used was a 10-hour storm, with constant boundaries of 8-meter wave height, 13.9 seconds wave period, and 6-meter water setup. Median grain size was set to  $2 \cdot 10^{-4}$  meters, and the simulation was done in Surfbeat mode. The rest of the XBeach parameters were set to standard values.

We set the CS-model mimicking as much as possible the setup used in the XBeach simulation. We create a profile that resembles most of the characteristics while maintaining the discretization adopted in the CS-Model, which differs considerably from the XBeach discretization (Figure 18). Boundary values and sediment size remained the same.

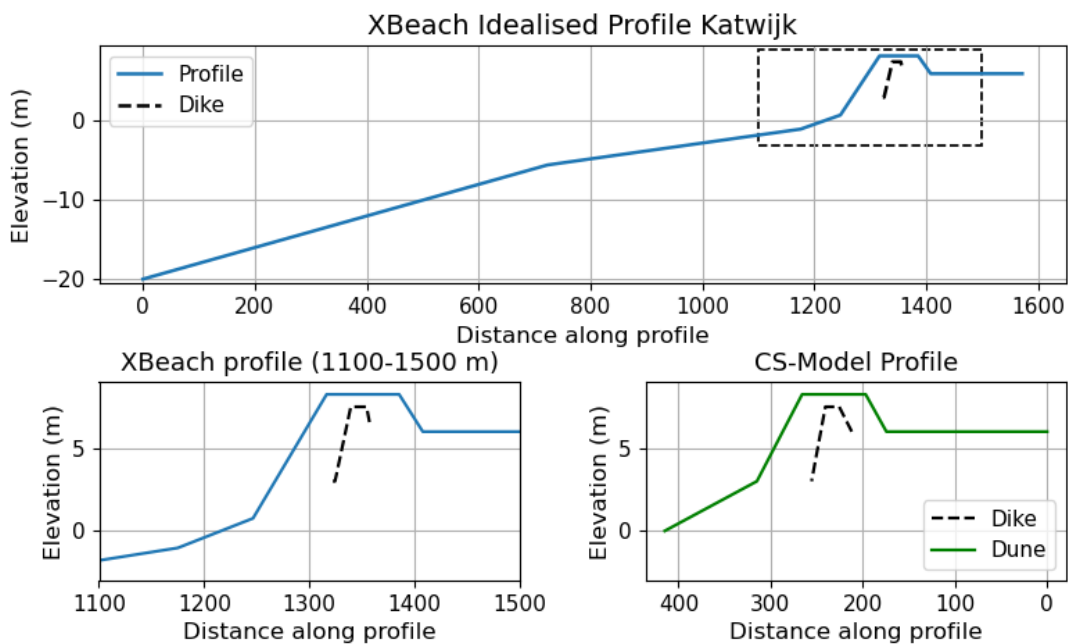


Figure 18: Domain composition used in the XBeach simulations and adapted to the CS model.

Results show that several processes were sufficiently simulated, such as the front erosion of the dune and overwash processes leading to landward sediment transport, deceleration of the erosion due to increased fetch due to seaward sediment transport, and consequent increased wave dissipation, and exposure of

the dike (Figure 19). The main differences were in the patterns of dike exposure. In the XBeach simulation, the dike is exposed early in the simulation, starting from the top after one hour of the simulation, with increased exposure. In our model, the dike starts being exposed from the bottom and much later in the simulation (after 4 hours). This has to do with the rules used in our model and the discretization differences. While XBeach has a grid-based discretization, where changes in neighboring cells can propagate gradually from one point to the next (thus representing the morphology development at a finer scale), our model represents the dune as a single morphological unit, which has to be schematized. This means that XBeach can resolve smaller-scale morphological adjustments and the progressive lowering of the dune profile, exposing the dike early in the process. Nonetheless, both models show a highly exposed front dike by the end of the simulation.

Another difference is the top exposure of the dike, which only occurs in the XBeach simulation and not in the CS model. Although overwash processes are represented in the CS-model and landward transport occurs like in the XBeach simulation, the rate of erosion in XBeach is higher than in the CS-model. One hypothesis is the underrepresentation of the infragravity waves in the CS-model. Further tuning of the overwash parameters will be evaluated with WP12 after their experiments.

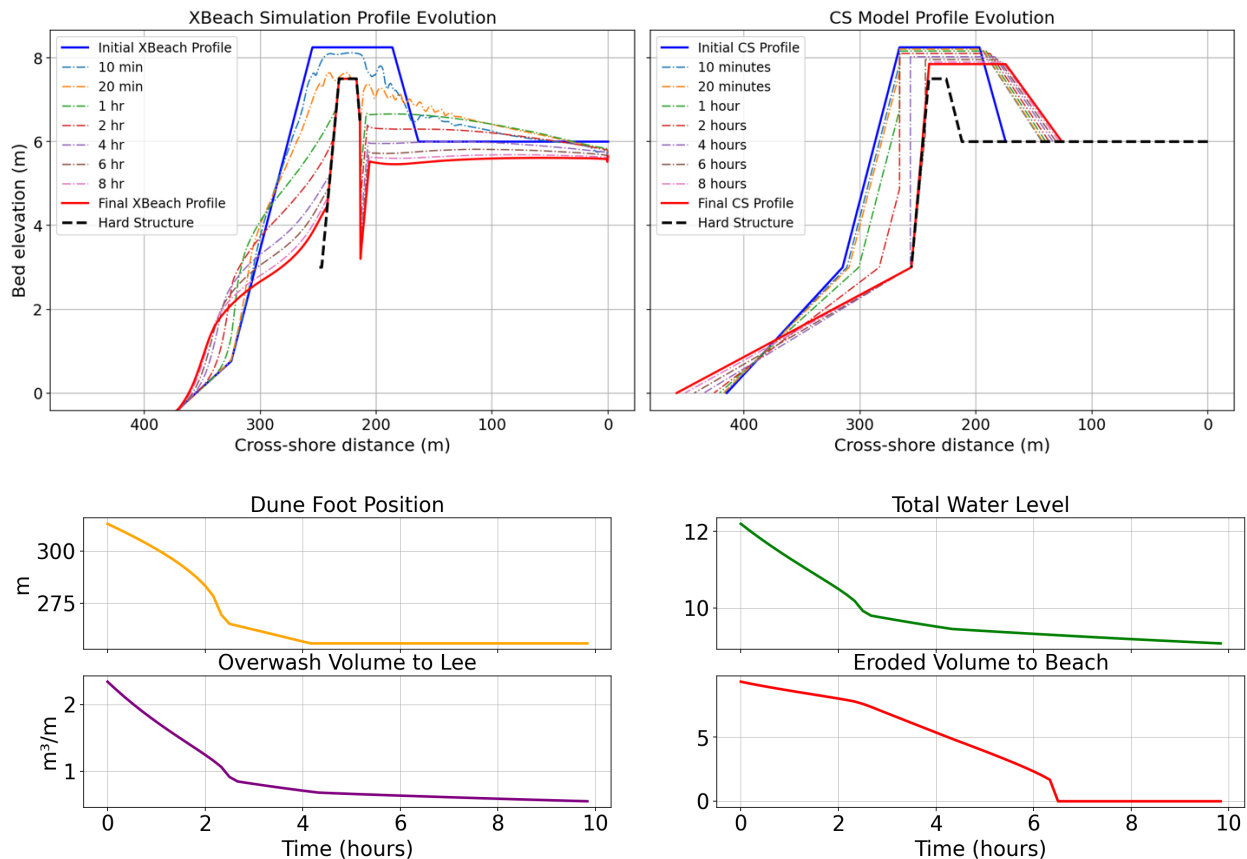


Figure 19: (a) Profile evolution in the XBeach simulation. Initial profile mimics a schematized profile of Katwijk, with the dike (dashed line) within the dune profile (blue line). (b) Profile evolution in the CS-model, highlighting the dike exposure, the overwash patterns, and the increase in beach width as sediment is eroded from the dune to the beach. Initial schematized profile

*as identical as possible to the XBeach initial profile (c) Evolution of parameters for the CS simulation, highlighting the reduction of eroded sediment to the beach as it reaches the dike and the reduction in total water level as beach width increases.*

#### 2.3.4 Hondsbossche Duinen (NL) – Coupling method and 2D

To test the 2D implementation and the coupling strategies chosen, we apply the coupled CS model - ShorelineS to the Hondsbossche Duinen demonstrator (NL). The Hondsbossche Duinen hybrid system is approximately 8 kilometers long and was constructed in 2015 as part of a coastal reinforcement project, following an assessment that the local dike did not meet safety criteria. The project involved the placement of approximately 35 million cubic meters of sand to build dunes up to 5 meters high and beach widths that vary between 100-500 meters. The project also included planting of vegetation for dune stabilization and growth stimulation.

We test the coupled model by simulating the period of 2020-2021 in the area. Initial shoreline and dunefoot positions are based on 0-m and 3-m contours, extracted and smoothed from LiDAR data provided by the Dutch authorities (Rijkswaterstaat). Wave and wind data are openly available through open repositories from the Dutch authorities Rijkswaterstaat and KNMI. The closest points available were extracted and used as boundary conditions for the model, assuming low intraboundary variability. Other parameters, such as grain size, were gathered from Kroon et al. (2022).

All three coupling methods described in Section 2.2.3 were tested, and the best results for this demonstrator came from the strategy where shoreline positions are calculated in the shoreline model, and changes are passed through to the CS model by a new position itself, instead of passing through the alongshore gradients.

Results show that the coupled model satisfactorily handles the general behavior related to the dune growth and beach volume change (Figure 20). For dune development, the model reproduced most of the general spatial gradients with larger growth on the sides bordering the area, where median differences were in the order of 15 m<sup>3</sup>/m. Magnitudes were slightly off in certain areas, like the stretch between 8-10 km and 1-2 km alongshore. For beach volume, the overall trend was also captured, with general erosion in the Hondsbossche area, with larger erosion in the central portion, likely due to its bulbous shape that induces alongshore spreading of sediment. As of shoreline position, the model reproduced the displacement between kilometers 0 to 6 and 10 to 14 relatively well. However, the model did not reproduce the stretch between the alongshore distances of 6-10 well, where it predicted an erosion in the order of 10 meters, while the data shows an accretion that ranges from 10-20 meters.

One hypothesis is the difference between the cross-shore sediment redistribution along the profile in the measured data, which may have caused a flattening effect, a phenomenon that is not included in our simplified model. The match between beach volumes gives strong support that the mismatch may be related to differences in cross-shore sediment redistribution. Considering the scope of our modelling approach, where long-term trends are the main goal, flattening effects would have a much lesser influence in longer periods than the beach and subtidal volume. Another potential reason is alongshore grain size variability, which is also not included in the model and could also be relevant for other Demonstrator sites. Another potential reason is a shoreface nourishment of about 280 m<sup>3</sup>/m that was conducted in 2019 and

hence was not included in our simulation, which could change the local shoreline signal. Nonetheless, general patterns of sediment alongshore redistribution and the overall effects on the dunes were generally reproduced by the model, especially regarding volumes.

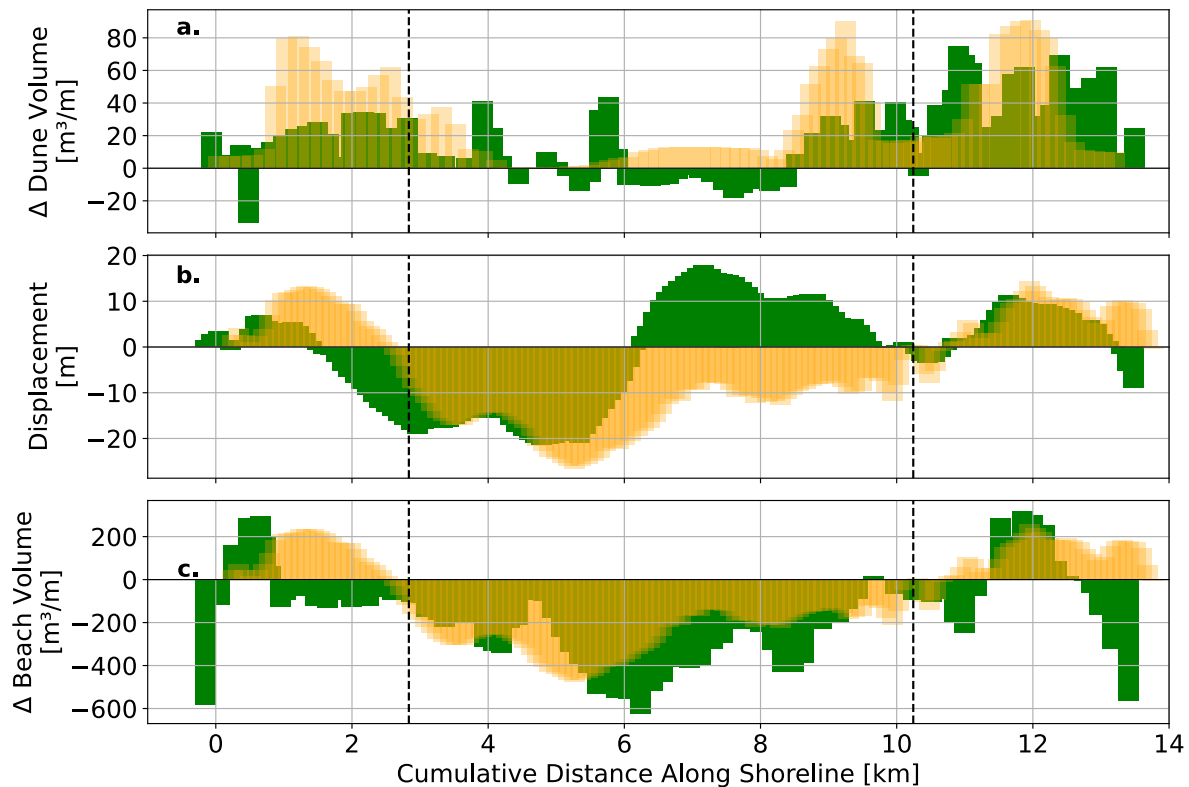


Figure 20: Comparison between measured (green) and modelled (yellow) evolution of the Hondsbossche area after a one-year simulation. Aspects compared are dune volume change (a.), shoreline displacement (b.), and beach volume change (c.). North to the right of the Figure.

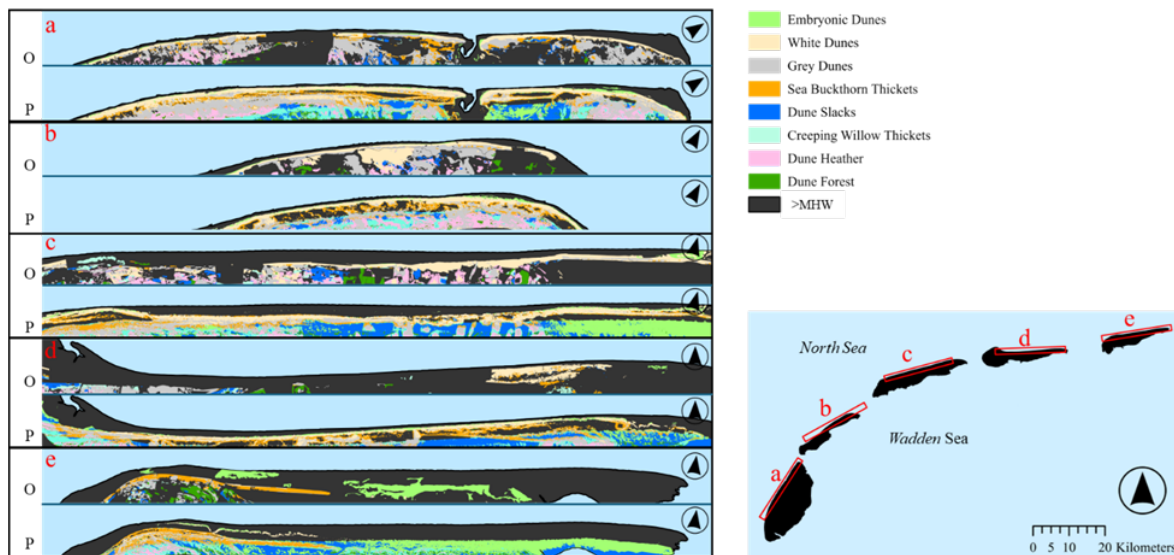
### 2.3.5 Wadden Islands (NL) – Ecotope definition

The goal of this work is to translate the PDT outputs (e.g., varying beach-dune morphology) into Natura 2000 habitat types, enabling the PDT to report on key performance indicators (KPIs) for biodiversity that are aligned to the reporting and assessment frameworks of the Habitats and Birds Directives, the EU Nature Restoration Law, and the EU Biodiversity Strategy for 2030. We trained the framework using the Dutch Wadden Sea barrier islands; locations where natural coastal dynamics dominate. It is planned that the resulting model will be tested on one of the demonstrator sites at a later stage. Conceptually, parameters used in the PDT would predict which Natura 2000 type is present in the area and, subsequently, how the habitat types change over time as a function of the PDT forecasts on space and time.

Natura 2000 dune habitats are legally recognised under the EU Habitats Directive and reflect different combinations of sediment dynamics and groundwater regimes. Embryonic and white dunes form where sand mobility is high, grey dunes develop with reduced aeolian activity and soil formation, and moist dune slacks occur where groundwater reaches the surface.

To link morphological model output to ecological habitat responses, we related the presence of Natura 2000 dune habitat to five abiotic drivers that the PDT can simulate or approximate: groundwater depth, distance to mean high water (MHW), relative elevation, slope, and decadal elevation change. Habitat probabilities were predicted using logistic Generalized Additive Models, allowing non-linear responses. Each grid cell is classified as the habitat with the highest predicted probability. Groundwater depth was estimated using a simplified Ghyben–Herzberg (Badon-Ghyben, 1888, Herzberg, 1901) method, providing a fast, island-scale approximation suitable for integration with PDT workflows.

A single global model successfully reproduced the dominant habitat–environment relationships across the Wadden islands (Figure 21). Groundwater depth and distance to mean high water emerged as the strongest predictors, while slope and long-term elevation trends acted as secondary modifiers. Model predictions showed qualitative agreement with observed patterns in seaward zones—embryonic, white, and grey dunes—and became less certain inland where fine-scale hydrology, vegetation feedbacks, and successional processes dominate. First results show potential, as the simplified groundwater approach provided a first-order representation of freshwater-lens geometry for robust landscape-scale prediction, with deviations mainly at local hydrological boundaries. Further improvements are planned alongside the ongoing PDT development and application at different sites, including exploring the implementation of a quantitative validation framework.



	Island-specific									Global								
	Beach	Embryonic Dunes	White Dunes	Grey Dunes	Creeping Willow Thickets	Dune Slacks	Sea Buckthorn Thickets	Dune Heather	Dune Forest	Beach	Embryonic Dunes	White Dunes	Grey Dunes	Creeping Willow Thickets	Dune Slacks	Sea Buckthorn Thickets	Dune Heather	Dune Forest
Beach	90.4	1.5	2.1	1.4	0.3	0.8	1.4	0.2	1.9	91.5	1.4	0.7	1.6	0.6	0.4	3.6	0	0.1
Embryonic Dunes	21.6	67.6	5.8	0.8	0.2	1.1	0.6	0.3	2.1	32.6	43.8	12.5	0.7	1.6	6.5	1	0.1	1.2
White Dunes	8.2	5.1	54.3	16	1	2.1	6	4.4	3	10.6	3.9	49.1	14	4.1	0.8	12.9	3.6	0.9
Grey Dunes	6.4	0.6	11.6	41	3.8	2.7	11.1	17.2	5.6	6.7	1.2	13.5	34.1	8.1	1.6	13.7	19.1	1.9
Creeping Willow Thickets	12.7	2	1.3	9.2	31.1	19.9	3.6	7.7	12.6	17.5	3.3	1.5	2.1	30.6	27.2	4.1	8.3	5.4
Dune Slacks	12.1	0.8	0.3	1.4	7.4	59.9	2.3	3.2	12.5	19.6	9.2	0.3	0.3	15.5	47.2	1.4	1.4	5.1
Sea Buckthorn Thickets	10.7	0.9	9.1	18.1	3.9	3.9	44.3	4.9	4.3	13.1	3.4	12.3	19.3	9.3	4	31.2	5.1	2.3
Dune Heather	3.1	0.1	0.9	19.6	6.3	6.4	1	49.8	12.9	3.1	1.2	0.9	21.7	20.5	9	4	32	7.6
Dune Forest	4.5	1.5	1.8	6.6	2.7	13.3	2.6	10.7	56.3	6.6	3.9	1.2	7.4	18.5	29.2	6	11.9	15.3
	Observed									Observed								

Figure 21: Observed (O) and predicted (P) habitats based on the global GAMs for the five Dutch Wadden Sea islands: Texel (a), Vlieland (b), Terschelling (c), Ameland (d) and Schiermonnikoog (e). Normalized confusion matrices of ecotope predictions for the island-specific models (f), and the global model (g). Each row shows the proportion of true ecotope samples assigned to each predicted class (row-normalized). Values on the diagonal indicate correct classification rates (recall), while off-diagonal cells indicate misclassifications. Darker (green) colours represent higher proportions

### 3. Code access instructions

The current PDT prototype datasets are deposited in the 4TU Research Data repository under the following DOI: <https://doi.org/10.4121/e333cbe4-531a-4216-bdee-ee875dd3bee0>. Structure and usage information are available in the repository. The repository contains an evolving alpha-level prototype rather than a fully operational tool. Public access is therefore restricted during the review and

development phase (embargo until 2027). A final public release is planned within the DuneFront project timeframe. In the meantime, access can be provided upon request.

## 4. Conclusions

This report brings together the work carried out under the first three tasks of WP13 (Predictive Digital Twin). These tasks focused on designing the initial PDT architecture and on calibrating and validating a first functional PDT modelling framework. The base architecture of the PDT framework was designed based on technical and user needs, ensuring a functional development and use. At the current stage, the functional modelling framework emphasizes the different connections between code blocks needed for the functioning of the PDT, ensuring data needed for the simulations are properly gathered, prepared, processed, and returned to the user. Technical work on preparing the different layers and connections, as well as translating models to a common programming language, was done in this phase. The basic structure of the PDT is in place and reflects the original plan for the design phase (T.13.1).

Based on the chosen core of the model, we used process understanding available in literature and through different WPs to parametrize reduced-order elements into the PDT. This included adding rules and simplified physical descriptions to account for the influence of vegetation on deposition patterns and erosion volumes, as well as the presence of hard structures, on beach-dune development on hybrid dune-dike systems. Sensitivity analysis showed that general patterns expected from the literature were successfully described with the reduced-order parametrizations, reflecting the plan for the calibration phase (T13.2)

The prototype PDT was tested in different demonstrators sites. We checked whether the reduced-order modelling approach sufficiently reproduced the main patterns of beach-dune evolution in hybrid conditions. General patterns were simulated, although local differences were also spotted, which are mostly due to the generalization and reduced-order form of the models chosen. Although local differences were expected given the generalization of the modelling approach, the impact of these on the PDT applicability will need to be re-evaluated with the users in the coming period. Comparing the model with data from the demonstrators was important to highlight strengths and weaknesses of the current prototype, and was in line with the validation plan (T13.3).

Overall, this phase focused on establishing and testing the core PDT framework, highlighting the main patterns captured while identifying areas that will be further improved in the next phase. All validation and sensitivity tests showed that the prototype captures the expected large-scale patterns as expected within reduced-order modelling, although the assessment was primarily qualitative (i.e., visual inspection of modelled parameters and comparison with measured data rather than formal statistics metrics). Hard structure influences were evaluated for a single hybrid configuration (dune-in-dike), selected as one of the most complex cases at this stage. Evaluation on how the PDT performs for different hybrid systems, including different hybrid designs and boundary conditions beyond the North Sea, is expected as the PDT is broadly applied to the different demonstrators in the project. The current PDT is therefore a functioning

prototype that remains under active development. Further refinements, including the introduction of quantitative validation and uncertainty assessment where feasible, are planned for the next phase.

In summary, we provide a first prototype of the PDT that can move to the next phase, where Performance Indicators needed for the Blueprints from WP14 are defined, setting up different demonstrators is done, and development toward a final alpha version is foreseen. By openly applying the prototype on different demonstrators, we expect the model to be further tuned and applied by different WPs in the coming period.

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