multiclimact

D10.4 - DIGITAL SOLUTION FOR MONITORING AND EARLY-WARNING OF FLOOD DEFENCE SYSTEMS

Development for the Application to a Real Demo Case

March 2026 |DELFT UNIVERSITY OF TECHNOLOGY

MULTICLIMACT
D10.4 - DIGITAL SOLUTION FOR MONITORING AND EARLY-WARNING OF FLOOD DEFENCE SYSTEMS

Project Title	MULTI-faceted CLIMate adaptation ACTions to improve resilience, preparedness and responsiveness of the built environment against multiple hazards at multiple scales
Project Acronym	MULTICLIMACT
Contract Number	101123538
Project Coordinator	Rina Consulting S.p.A.
WP Leader:	Antonio Di Pietro

Deliverable	D10.4 - DIGITAL SOLUTION FOR MONITORING AND EARLY-WARNING OF FLOOD DEFENCE SYSTEMS
DoA	T10.4 -Digital solution for monitoring and early-warning of flood defence systems during flood and drought episodes
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Due date	30.03.2026
Report date	25.03.2026
Version	V1.4

Document classification	PU Public

Revision Table

Version	Date	What
V1.0	01/01/2026	Table of Contents
V1.1	09/02/2026	First Draft
V1.2	16/02/2026	Draft after internal quality check
V1.3	01/03/2026	Document ready for quality control
V1.4	23/03/2026	Final version ready for submission

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Abbreviations and Acronyms

ACRONYM	DESCRIPTION
API	Application Programming Interface
BOFDR	Brillouin Optical Frequency Domain Reflectometry
CSV	Comma-Separated Values
D10.4	Deliverable 10.4
DAS	Distributed Acoustic Sensing
DFOS	Distributed Fiber Optic Sensing
DTS	Distributed Temperature Sensing
DTSS	Distributed Temperature and Strain Sensing
DoA	Description of Action
EWS	Early Warning System
FOS	Fiber Optic Sensing
FPH	Flood Proof Holland
GPS	Global Positioning System
GSM	Global Systems for Mobile Communications
HTTP	Hyper Text Protocol
JSON	JavaScript Object Notation
PC	Personal Computer
TU Delft	Technical University of Delft
VPN	Virtual Private Network
WP	Work Package

Co-funded by
the European Union

Executive Summary

Deliverable D10.4 – Digital Solution for Monitoring and Early-Warning of Flood Defence Systems presents the development, integration, and demonstration of an innovative digital early warning system (EWS) designed to enhance the resilience, preparedness, and response capacity of dikes and movable flood barriers under flood and drought conditions. The work forms a key component of the MULTICLIMACT project's mission to provide practical, scalable solutions that strengthen climate adaptation across the built environment.

The solution developed in this deliverable integrates advanced distributed fiber optic sensing, temperature and strain measurements, machine-learning-based surrogate models, and predictive simulation tools into a unified monitoring and decision-support platform. A three-layer architecture; sensor layer, integration layer, and presentation layer ensures robust data collection, reliable processing, and clear, actionable visualization for end users. The system continuously measures temperature variations along fiber optic cables embedded in the dike, enabling the inference of moisture content, phreatic line elevation, seepage patterns, and anomalies that may indicate internal erosion or structural weakening. Complementary ground-based moisture sensors, pressure divers, and local rainfall data strengthen system accuracy and redundancy.

A key output of the deliverable is the Dashboard, which translates complex sensor data into intuitive, multi-level visualizations tailored to diverse users. Engineers gain access to detailed raw and processed time series, cross-sections, anomaly detection tools, and sensor health indicators. Decision-makers receive simplified risk overviews, color-coded alerts, and predictive insights on emerging hazards. Field inspectors benefit from georeferenced maps that highlight problematic sections for targeted on-site evaluations.

The system incorporates forecasting capabilities by combining real-time data with rainfall predictions and physics-based models to estimate moisture infiltration dynamics, rate of phreatic line rise, and potential exceedance of critical thresholds. Scenario-based simulations (e.g., heavy rainfall events or drought conditions) support proactive planning, while potential breach of propagation and flood mapping enhance emergency preparedness.

The monitoring infrastructure and dashboard were implemented and demonstrated in a real dike case in Leischendam (South Holland), Flood Proof Holland and Limburg where a single-mode fiber optic line and multiple moisture and pressure divers were installed. Performance evaluation shows high-resolution, reliable data acquisition, and the ability to detect both seasonal variations and localized anomalies.

The deliverable was primarily developed by TU Delft, with contributions from RINA-C on methodology and framework integration, and Fibristerre providing hardware, cloud services, and data transmission components. The resulting EWS directly contributes to MULTICLIMACT's broader toolkit of design practices, materials, and digital solutions, supporting municipalities, infrastructure managers, and emergency agencies in improving the resilience of vulnerable assets.

As a general conclusion, D10.4 demonstrates a robust, scalable digital early warning solution that significantly enhances monitoring, diagnosis, and anticipatory management of flood defence systems. It lays the foundation for wider deployment across varied European contexts, supporting climate adaptation strategies and reducing risks to communities and critical infrastructure.

1. INTRODUCTION

Deliverable D10.4 – Digital Solution for Monitoring and Early-Warning of Flood Defence Systems focuses on developing a digital solution for monitoring and early warning of flood defence systems during flood and drought episodes, particularly targeting dike system and movable flood barriers.

After the description of pursued objectives and applied methodologies (Chapters 2 and 3), in Chapter 4 an extensive description of the developed software dashboard is reported. Such dashboard is based on two different digital tools, already designed in task T4.3 of the project, aimed to realize an Early Warning System (EWS) for Dike and Movable barriers monitoring systems. Thus, the data collection, storage and transmission process toward the dashboard is described in Chapter 5. Deviation from the initial plan, output for the future development of the project and conclusions are reported respectively in Chapter 6, 7 and.8.

The early warning system leverages advanced technology systems such as fiber optic sensing, machine learning based on surrogate models and an integration of state-of-the-art prediction systems to enable timely intervention and mitigate the impacts of disasters Monitoring and early warning is an integral part of MULTICLIMACT project's goal of enhancing preparedness and enhancing responsiveness to climatic hazards.

1.1. PURPOSE AND TARGET GROUP

This deliverable aims at developing a monitoring and early warning system for dikes and movable barriers able to translate processed outputs from the sensor and integration layers into actionable and understandable information, with the help of visualizations, alerts and reports. The target group includes public authorities, city planners, infrastructure managers, and other stakeholders involved in disaster risk management and urban planning. It aims to provide them with a high-level risk overview by issuing alerts and warnings when defined thresholds have been reached. The target group will benefit from the insights and tools provided, enabling them to enhance the resilience of their respective regions against flood-related hazards.

1.2. CONTRIBUTIONS OF PARTNERS

The following Table 1 depicts the main contributions from project partners in the development of this deliverable.

Table 1. Contributions of Partners

PARTNER SHORT NAME	CONTRIBUTIONS
TUDELFT	Definition of the dashboard layout, development, and calibration of the EWS. Report writing of Chapters 4, 5, 6, 7, 8, 9, 10.
FIBRISTERRE	Setting the parameters of the hardware for data transmission. Report writing of section 5.3.
RINA-C	Support in an experimental campaign. Report writing of Chapters 1, 2, 3.

2. OBJECTIVES AND EXPECTED IMPACT

The MULTICLIMACT project aims to develop a mainstream framework and a tool for supporting public stakeholders and citizens to assess the resilience of the built environment and its people at multiple scales (buildings – including cultural heritage, urban areas, infrastructures) against locally relevant natural and climatic hazards and supply-chains, as well as to support them to enhance their preparedness and responsiveness across their life cycle. MULTICLIMACT will support natural and climate adaptation actions by implementing a toolkit of Design Practices, Materials, and Digital Solutions.

2.1. OBJECTIVES

One of the project's aims is Developing the MULTICLIMACT toolkit. This work package consists of developing and advancing interoperable Digital Solutions for their demonstration in different real contexts. In particular, the main objective of Task T10.4 is the development, integration, and demonstration of an innovative digital early warning system (EWS) designed to enhance the resilience, preparedness, and response capacity of dikes and movable flood barriers under flood and drought conditions. The work forms a key component of the MULTICLIMACT project's mission to provide practical, scalable solutions that strengthen climate adaptation across the built environment and, thus, improve the protecting role of the built environment for people's safety and quality of living.

2.2. EXPECTED IMPACT

This document describes the development of a digital solution designed to strengthen the resilience of the built environment. By supplying decision-makers, as well as water and flood-defence asset managers, with reliable and timely information, the solution supports a better understanding of potential natural hazards and their effects on critical infrastructure, including flood barriers and protection systems.

The proposed digital system aims to support disaster risk management through real-time monitoring and early warning functionalities. These features allow for prompt action, helping to avoid severe failures, safeguard human lives, and reduce economic damage. Moreover, the solution contributes to increasing the robustness of critical infrastructures by enabling preventive maintenance strategies and faster responses to emerging risks. Overall, the project seeks to foster safer communities and enhance the resilience of urban areas as they face growing natural and climate-related challenges.

3. OVERALL APPROACH

The work is carried out following a structured and interdisciplinary methodology that combines advanced sensing technologies, data-driven modeling, and decision-support tools. The approach began with the definition of system requirements based on the needs of infrastructure managers, engineers, and decision-makers involved in flood-risk management. These requirements guided the selection and integration of distributed fiber optic sensing technologies, complementary in-situ sensors, and external data sources, such as rainfall observations and forecasts.

A layered system architecture was then adopted to ensure reliability, scalability, and clarity throughout the data workflow. The sensor layer focuses on continuous data acquisition from fiber optic cables and ground-based instruments embedded within the dike structure. These data are transmitted to the integration layer, where quality control, data fusion, and machine-learning-based surrogate models are applied to extract meaningfully.

4. SOFTWARE DASHBOARD

4.1. STRUCTURAL HEALTH MONITORING (DIKE DASHBOARD)

4.1.1. DASHBOARD INTERFACE VISUAL DESIGN

The aim of this dashboard is to translate processed outputs from the sensor and integration layers into actionable and understandable information, with the help of visualizations, alerts, and reports. To achieve this ultimate goal, the architecture of the EWS was split into three sections to clearly outline the processes: the sensor layer, integration layer, and the presentation layer. The sensor layer comprises the data collection system, transmission, and storage of the raw data. The integration layer tackles the processing of the data.

The Presentation Layer is what engineers, decision makers, field staff and other relevant authorities under MULTICLIMACT see. For engineers, relevant data included detailed time series, the raw data, moisture profiles, phreatic line data, soil properties, the specific fiber segments over the dike, both in time and space and to also see the details of the calibration readings so that any anomalies in the dike can be easily noted during inspections and perhaps compare these with ground truth.

For decision-makers, the idea was to provide them with a high-level risk overview by issuing alerts and warnings when defined thresholds have been reached. Even though thresholds have not been exceeded, it is significant to show changes over time and keep historical records, which helps to give an indication over damaged/high-risk sections along the dike length. Just like engineers, it is also useful for decision makers to know the predicted phreatic line behavior and propose what actions are needed. For instance, if the dike is getting too dry and cracked, it is important to indicate when they should start watering the dike and at which sections they should first prioritize. It is also useful to use the EWS data to develop flood maps of potentially affected areas in the case of a dike breach. Unlike engineers, the raw data files may not be useful for decision makers as they do not tell anything interpretable about the dike's structural health status.

For field inspectors and maintenance staff, the dashboard was designed to be useful for localization of problem areas along the dike, identification of dike segments that are problematic as fiber cables are prone to breaking when excessive force is applied either during excavations or otherwise. It is also a powerful tool to guide where to inspect and give them the ability to see recent temperature or moisture fluctuations within sections of extensive dikes.

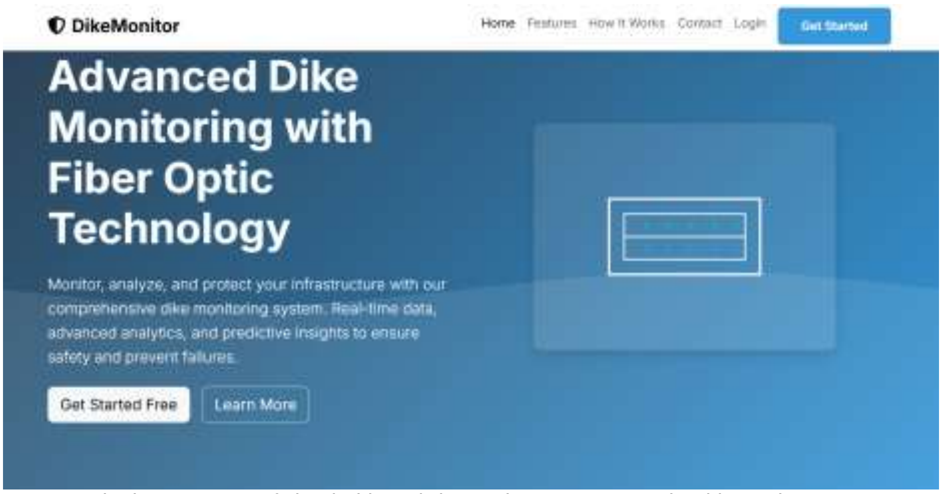

Figure 1: The home screen of the dashboard that welcomes users to the dike early warning system

The early warning system was designed to assess multiple dikes and movable barrier locations. For that reason, a user can then sign up and input details of their system, as shown in Figure 1 above, based on the location of the dike or movable barrier, and other features that are unique to each distinguished site.

In addition to that, historical monitoring and performance over time can be used to build further confidence of the public when compared to the compliance of dike safety standards, which can be used as a powerful tool for public awareness. Providing access to both raw and processed data can also help other researchers and data modelers to run “what if” scenarios and perform comparisons with past events or use this data to validate other models.

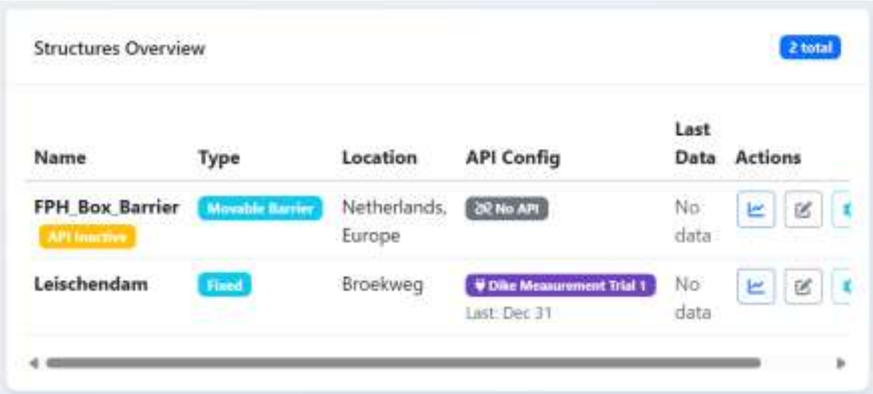

Figure 2: An overview of the active monitoring sites, one for the dike in Leischendam and one for the movable barrier

Figure 2presents the Structures Overview interface of Early Warning System (EWS) for dikes and movable barriers. The screen provides a centralized operational overview of monitored structures, listing each asset by name, structural type, geographic location, API configuration status, and data availability. It also highlights the differences in monitoring configuration and data connectivity. The interface clearly indicates whether automated data ingestion via API is active and reports the timestamp of the most recent measurements, enabling rapid assessment of system status. Action icons allow users to directly access data visualization, configuration, or management functions, supporting efficient supervision of multiple assets within a distributed fiber optic monitoring network.

4.1.1.1. SITUATION MAP

The dashboard has a GIS based map (Streetview) showing the dike section under study within the project, the nearby water channel, the fiber cable layout, and its precise coordinates. It also shows the precise location of the 12 volumetric moisture sensors spread along the dike length, used for validation of the moisture inferred from the fiber optic measurements. It shows the location of pressure divers which were used to monitor the fluctuation of the water table on the crest and the toe of the dike.

Figure 3: A map describing the precise location of the single mode fiber optic cable installed in the dike under study in Leischendam, South Holland, represented with a green continuous line.

Figure 3 shows the precise location of the cable which is buried at an average depth of 40 cm can be seen with the green line. The dashboard also has an overlay of the risk status per section of the dike. This was done by providing different color codes to entail the moisture content of the dike both in time and in space. The color codes entail safe dike status, caution, warning level and critical levels that need intervention or evacuation. It also has a phreatic line projection overlayed on a cross-section of the dike, clearly indicating the location of the phreatic line over the crest, slope, and toe of the dike. The cross-section considered the average dimension of the crest, the slope, and the toe of the dike and indicated the known saturated zones.

Since the water level in the channel is always maintained constant by controlling the pump, the external influencing factor of the change in moisture in the dike is rainfall, unlike for primary dikes that are affected by river water level changes or river surge.

4.1.1.2. PRINCIPLES FOLLOWED IN DASHBOARD DESIGN

To ensure optimal use and effectiveness of the EWS, the design followed a clear hierarchy of disseminating information. For critical alerts were designed to be immediately visible, while the more detailed data, including the raw data can be accessed in layers to avoid overcrowding the dashboard with data, thereby keeping the interface focused during on priority of notable events (Men et al.).

In addition to that, the system alerts were color coded based on the severity of events. The colors green, yellow, and red were assigned constantly to represent the status of the dike, with green being good, orange requiring close monitoring and red meaning severe. These colors were used on a white background to avoid color blindness and to visual overload. All data was also labeled with the corresponding units i.e. temperature in ^{0}C, distance in (m) and time in days (Tan et al.).

It also shows the last update timestamp per measurement for easy data analysis and comparison to past events. To offer interactive navigation, one can use click-through from maps to sensor views. Currently, there is no mobile version of the application, but that will be considered as part of the future developments for the EWS to ensure easy access in the field (Tan et al.).

4.1.1.3. DASHBOARD INDICATORS

The early warning system leverages distributed fiber optic temperature sensing to continuously monitor moisture content and saturation levels in different sections of the dike (crest, slope, and toe). The system identifies changes within the section with elevated water ingress by detecting changes in temperature, induced by a change in thermal properties correlated with increased moisture. These readings are benchmarked against threshold values to highlight locations or times at which there is alarming changes in moisture. Current temperature data collected so far indicates the inferred volumetric moisture levels within monitored segments, thereby providing operators with a real-time view of potential failure points over time (Tan et al.).

A key stability parameter tracked is the phreatic line elevation, which is compared against predefined safe limits. The system also calculates the rate of phreatic line rise (in mm/hour). This is an important indicator of potential seepage acceleration or the effect of rainfall (Fargier et al.). Persistent or rapid elevation increases can suggest abnormal pore pressure buildup, warranting further investigation as only rainfall is assumed to be the most significant factor influencing change. These insights will allow engineers to assess not just current conditions in the dike but also the speed at which conditions may deteriorate.

To support predictive assessments for decision-makers, the system integrated both **short and medium-term rainfall forecasts** to estimate their likely impact on subsurface moisture and phreatic line movement. This forecasting capability improves preparedness during seldom storm events by correlating anticipated precipitation with modeled seepage responses (Zeng et al.). Finally, the system includes deliberate locations where the cable is exposed to atmospheric conditions to ensure data reliability and robustness of the system by comparing the atmospheric temperature measured using the FOS to temperature data from the nearby weather station, allowing engineers to act with confidence based on the information presented(Y. Dong et al.).

4.1.1.4. TIME SERIES

The system provides a detailed temperature-time series for the entire fiber length. It offers both raw temperature measurement profiles and processed profiles with minimized noise to highlight trends. The time series is essential for identifying subsurface anomalies such as zones elevated phreatic surfaces or zones of seepage especially in the toe of the dike. By analyzing these time series over time, engineers can detect gradual shifts in behavior that may precede failure mechanisms, such as saturation-driven deformation (‘DOMINO PROJECT REP3 V.1.1 - Monitoring’).

In addition to thermal data, the system visualizes moisture content and phreatic line elevation over time, enabling clear tracking of how internal water dynamics evolve under changing environmental or loading conditions. These trends can be compared across multiple depths and locations, such as base against crest elevations, providing spatial context to temporal changes. This depth-resolved perspective is used for distinguishing between surface infiltration and deeper seepage, helping engineers pinpoint the origin and direction of water movement within the structure (‘DOMINO PROJECT REP5 V.1.0 - Models Technical Description’).

To aid interpretation and decision-making, the time series panel incorporated **threshold** overlays, visually marking transitions across safe, caution, and critical levels. This allows for immediate recognition of changes beyond design tolerances. Additionally, environmental parameters such as rainfall and ambient air temperature are plotted alongside internal temperature measurements, providing context for observed changes. Correlating external drivers with internal responses enhanced the diagnostic accuracy and gave basis to support proactive risk assessment, especially during extreme weather events.

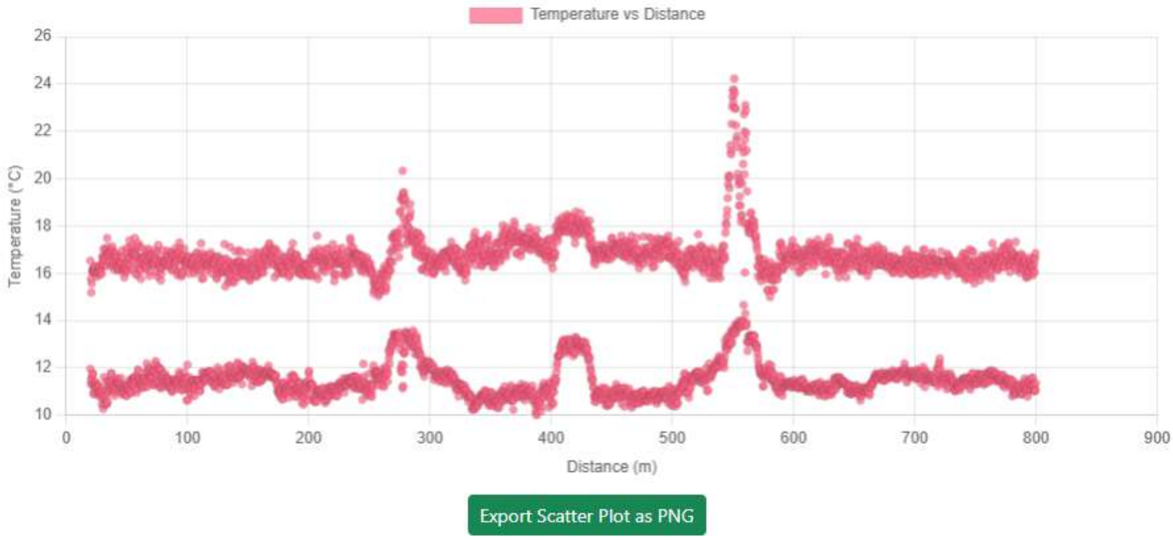

Figure 4: A scatter plot of the distribution of temperature along the dike length. This was a selected comparison of temperatures between two distinct days of 08 July 2025 and 13 November 2025

From Figure 4 above, it can be observed that the temperature comparison that summer temperatures were significantly higher in the dike as compared to the winter temperature, with a notable decrease in the magnitude of the peak between the two different times. In terms of data formats, the dashboard also has an option of exporting the scatter plots as .png files which can then be easily referenced for further processing, external communication, or for record-keeping.

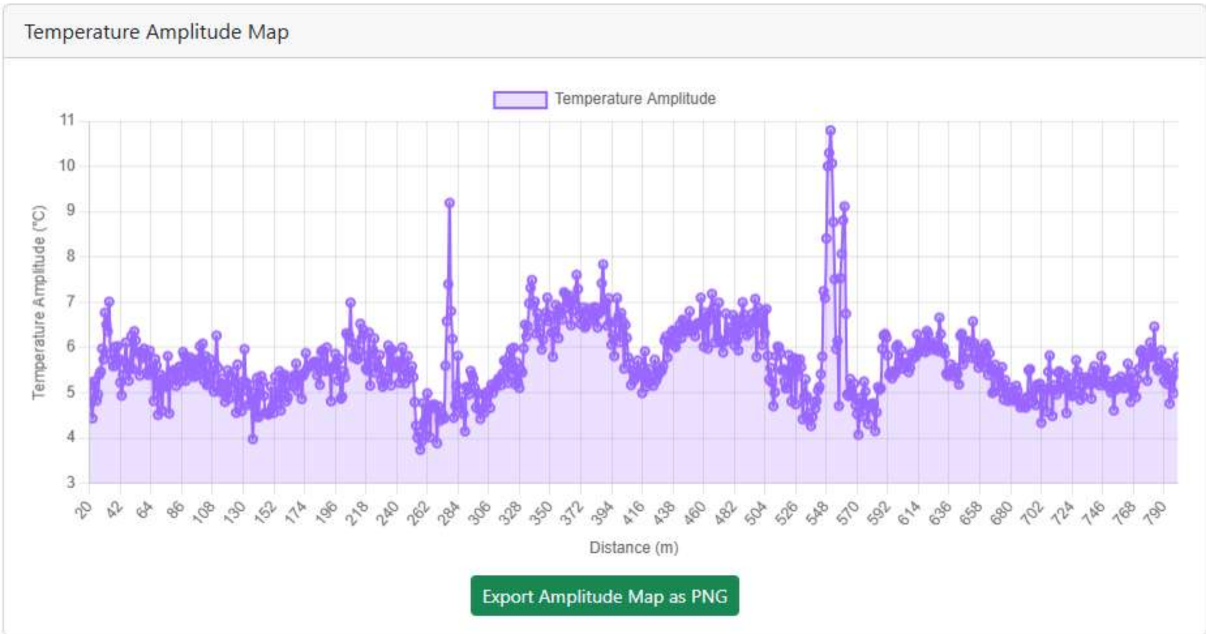

Figure 5: The temperature amplitude over the entire length of the fiber cable

The temperature amplitude over the dike can also be plotted and presented as shown in Figure 5above. Data from the high-resolution sensor, taken every 20 cm as averaged per meter to provide a smooth waveform that indicates a natural thermal variation along the dike, while the notable spikes around 284 m and 570 m indicate localized anomalies (a point where the fiber cable was damaged and buried at a different Depth of 10cm below ground level after repair). The shaded region under the curve highlights the amplitude of magnitude for easier visual interpretation, which comes in handy when scanning anomalies as illustrated on 284 m and 570 m.

It can be clearly seen that the EWS is handling large datasets efficiently, rendering over 4,000 points without clutter, maintaining interaction, and preserving the visual clarity of the data. Just like for the scatter plot, the amplitude map can be exported as a .png for readability and anomaly identification, among other functions.

4.1.1.5. TEMPERATURE-TIME SERIES FOR DIKES

To understand better the temperature variations over a period of 24 hours, Figure 6 below is a time series that captures a repetitive pattern of temperature behavior over the dike with respect to time. It can be noted from the chart that throughout the afternoon and evening hours, the peaks gradually become higher, indicating a warming trend as the day progresses, indicating a delayed response time from when the sun heat the surface of the soil to the time the heat is transmitted in time and space.

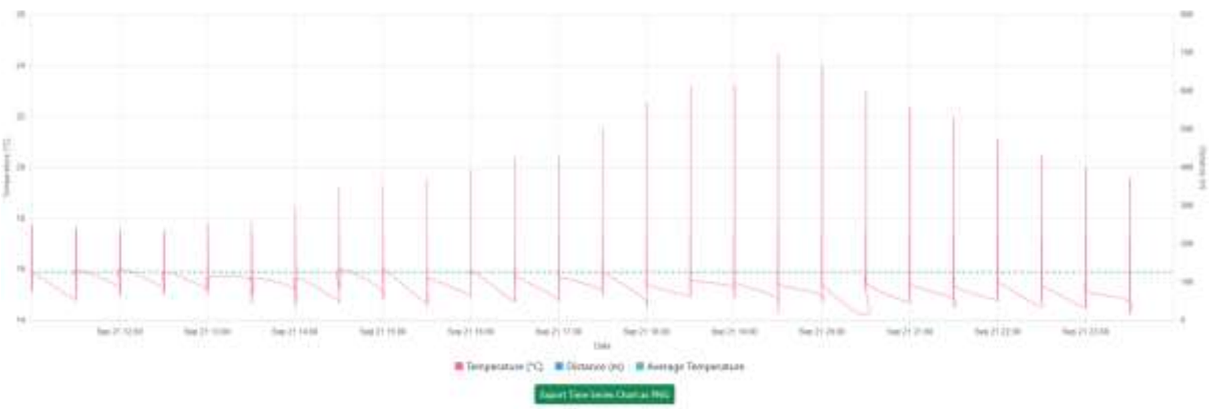

Figure 6: A time series over a period of 24 hours, showing how the temperature varied in the dike between day and night

Due to the variations of record low temperature from day to day (see Figure 6), it can also benoted from the dashboard that the cooling cycle consistently returns to a lower baseline, although the lowest points are different at different days, which underscores the underlying temperature increases.

In summary, the chart shows the thermal variation of the dike with respect to time. The regularity of the temperature rise, almost occurring in a perfect cycle, is representative of the patterns of temperature changes between day and night as a product of heat from the sun or other environmental factors. Due to the high-resolution measurements, the system can be seen to function reliably and capturing fine changes and minimal temperature changes of the lowest degree.

4.1.1.6. SPATIAL CROSS-SECTION

During the system installation, the FOS sensors were placed at a relatively uniform depth of 40 cm below the surface. With this depth, the system generates detailed cross-sectional visualizations of the dike, displaying temperature, moisture content, and the phreatic level, among other parameters. By plotting these variables across the crest, slope, and dike toe, engineers and decision makers can assess the gradient of moisture, which is a key factor in seepage-driven failures. It was important to indicate the profile to critically understand how water moves vertically through the dike structure. With cross-section analysis, combined with detailed soil profiles, it is easier to identify and visualize zones with elevated moisture content that may compromise the entire dike stability.

Improvements are being made to display multiple vertical profiles side by side along the length of the dike to form a longitudinal cross-section as well. This spatial distribution will allow for the identification of trends along the alignment, such as zones with consistently higher saturation near the toe or anomalous wetting patterns in localized areas which may indicate internal erosion pathways. Comparing multiple profiles over time will enhance the system's ability to detect emerging weak zones before they manifest at the surface or in structural deformation.

In addition to real-time data, these visualizations include overlays of the phreatic line position and can be configured to show safe, caution, and critical thresholds for volumetric moisture content. This enables immediate interpretation of whether subsurface conditions remain within design tolerances or require intervention. By integrating multiple vertical datasets into a cohesive spatial panel, the system will then provide a powerful diagnostic tool to assess internal dike health across both depth and distance with improved accuracy.

4.1.1.7. ANOMALY AND EVENT DETECTION COMPONENT

This feature provides a focused view of recent deviations from expected thresholds, using automated algorithms to flag zones where conditions have changed significantly over short timeframes. Key triggers include rapid increases in moisture content over minimal rainfall, sharp rises in phreatic line elevation, or patterns consistent with inferred leakage especially in the toe of the dike. These anomalies are identified by comparing real-time data against historical baseline, which was regarded as the first measurement by the FOS system, fine-tuned with FEM expectations and predefined thresholds.

Each detected event is presented with clear indicators of spatial location and depth, the magnitude of temperature change, with the corresponding moisture content and its effect on the change of location of the phreatic level. The panel also indicates where and how severely the system has deviated from considered optimal operating conditions.

4.1.1.8. ALERTS, WARNING AND NOTIFICATIONS PANEL

The system provides a centralized overview of all active and historical alerts, enabling real-time operational awareness of developing conditions within the dike structure. Each alert is categorized by severity (informational level, caution level or critical level), with associated metadata such as timestamp, spatial location over the dike length and details of the moisture content and phreatic level. The system also has a pre-defined corresponding action for every level of alert, whether to just observe and be alert while monitoring the situation, to water the dike, or to evacuate the nearby population.

The panel maintains a full alert history, supporting traceability and post-event analysis. Users can filter alerts by type (e.g., phreatic line rise, moisture increase, sensor fault), or time window. This history is essential for understanding recurring issues and their precise locations along the dike length, validating system behavior over time, and supporting audit or regulatory reporting requirements. Escalation protocols can also be visualized, indicating whether an alert has been acknowledged, assigned to a responsible party, and whether corrective or mitigation actions have been initiated.

4.1.1.9. MODEL OUTPUT AND PREDICTION

The Model Visualization and Forecast Panel serve as a core component of the Early Warning System, combining real-time monitoring data with predictive modeling to forecast insights into dike performance under changing environmental conditions. By integrating continuous field measurements with advanced computational models, the panel allows operators to anticipate how the dike might respond to variables such as rainfall, rising water levels, and soil moisture changes (Tan et al.).

The system's capabilities are particularly focused on predicting phreatic line elevations and moisture infiltration dynamics, which are critical indicators of internal dike stability. These predictions are generated from a combination of physics-based simulations, which use hydrological and geotechnical principles to model subsurface behavior and data-driven models trained on historical and real-time sensor data. Through continuous calibration with live field measurements, the system ensures that forecasts remain both accurate and site-specific, accounting for variations in soil type, hydraulic conductivity, and environmental conditions.

Beyond continuous forecasting, the system enables scenario-based simulations to support proactive risk assessment and operational planning. These simulations allow users to test "what-if" conditions to explore potential outcomes under specific environmental scenarios. For example; "If X mm of rainfall occurs over the next T hours, the phreatic line is expected to reach elevation Z m. Therefore, given current soil moisture trends, critical thresholds could be exceeded in N hours without intervention."

Such dynamic, data-informed forecasts give managers and engineers the ability to visualize how the dike system might behave under future stresses. This helps them anticipate possible instabilities, prioritize inspections, and implement timely preventive measures, transforming reactive management into proactive decision-making.

The system's analytical outputs can also be used to generate flood and breach propagation maps, modeling how potential failure scenarios may unfold downstream. By integrating existing hydrodynamic or GIS-based flood mapping tools, the platform simulates variables such as time-to-peak flooding, inundation extent, and exposure of critical infrastructure. These visualizations play a vital role in emergency preparedness and response coordination, providing agencies with actionable information to plan evacuations, deploy resources, and mitigate damage.

Ultimately, by merging real-time sensor data, environmental forecasts, and predictive analytics, the Forecast Panel converts raw monitoring information into actionable intelligence. This integrated approach enables engineers and decision-makers to anticipate risk conditions before they become critical, ensuring the flood defense system remains resilient and responsive in the face of evolving environmental challenges.

4.1.1.10. SENSOR HEALTH, ACCURACY AND DATA QUALITY

The performance of the fiber optic sensing system is continuously monitored throughout its operation to ensure the accuracy and reliability of the collected data. Prior to deployment, the system was first calibrated using both warm and cold baths, establishing a reference baseline for temperature measurements. During operation, any deviation from these calibrated parameters can be easily identified by observing the system's dashboard interface. Such deviations are typically visible as shifts in the Brillouin frequency signals, which serve as key indicators of potential anomalies. In addition to signal shifts, the system allows operators to detect other irregularities, including signal breaks or disruptions, unusually high attenuation, or gradual calibration drift. By providing this data in real time, the system enables prompt detection and correction of potential faults, ensuring consistent monitoring performance.

Apart from the fiber optic sensors, the EWS integrates multiple layers of data redundancy to safeguard against data loss or sensor failure. One of these layers includes Sensoterra's in-situ moisture content sensors that continuously record soil moisture data alongside the FOS measurements. This parallel data collection serves as a valuable backup in the event of fiber cable damage or temporary communication issues. Complementing these ground-based sensors, a rain gauge installed on top of the pump house collects real-time precipitation data. This information is especially useful for compensating for any missing or compromised readings in the temperature or moisture datasets, allowing for a more complete and reliable interpretation of site conditions.

When analyzed collectively, these datasets of temperature, moisture, and rainfall provide a comprehensive view of environmental behavior at the monitored site. Coupled with finite element modeling tools, the data can be further processed to simulate subsurface conditions and assess potential structural or geotechnical risks. This integrated approach not only enhances the accuracy of data interpretation but also supports decision-making based on evidence, ensuring a swift and effective response to emerging conditions.

4.1.1.11. REPORTS AND LOGS

The Early Warning System (EWS) features a well-structured historical reporting tool that tracks and visualizes temperature fluctuations at 30-minute intervals. By compiling this data into clear visual representations, the system enables users to easily observe and analyze changes over time. This functionality is particularly valuable for post-event assessments, as it allows engineers and analysts to identify and interpret patterns related to temperature, soil moisture levels, phreatic line behavior, and alert histories. Such insights are essential for understanding the conditions leading up to an event and for improving predictive models or mitigation strategies in the future (see Figure 7).

Figure 7: A analysis of the temperature fluctuation over a randomly selected point (at 350 m), indicating in summary, the highest, lowest recorded temperatures and the temperature gap within a period of 24 hours over that point

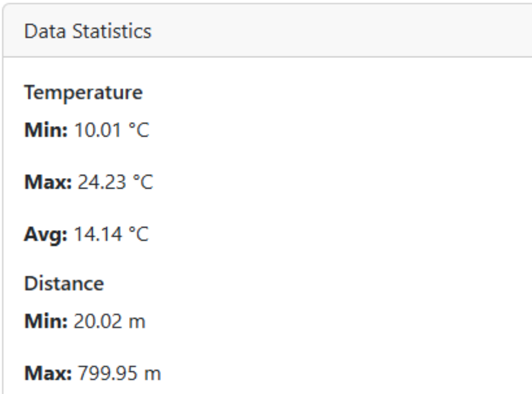

Figure 8: A data statistics panel which shows the summary of notable temperatures of interest

The data statistics panel in Figure 8shows aggregated key matrices such as max, min, and mean temperatures which gives a quick insight without the need to analyze the full graph. This function was added as part of quality assurance and validation of the dataset before visualization. With this, the engineers can easily verify if the dataset falls within expected data ranges or if there are any potential outliers and it can also be used for informed decision-making during analysis of the dike's thermal behavior in time and space.

In addition to environmental data, the EWS keeps a comprehensive record of all system activities through detailed action logs. These logs document every action taken—specifying who performed it, when it occurred, and what was done. This includes maintenance operations, sensor calibration details, inspection reports, and responses triggered by threshold exceedances or alert notifications. Maintaining this level of traceability ensures that every operational decision and intervention can be verified, audited, and reviewed over time, which is critical for accountability and continuous improvement of the monitoring process.

To further enhance the system's usefulness, the platform provides robust data export capabilities. Users can easily download time-series, spatial information, and event logs in widely supported formats such as CSV. This flexibility allows external researchers, engineers, and analysts to integrate the EWS data into third-party modeling tools, analytical software, or reporting systems. As a result, the system not only serves as a monitoring and alerting platform but also as a valuable data source for deeper analysis, predictive modeling, and decision-making in broader risk management and environmental studies.

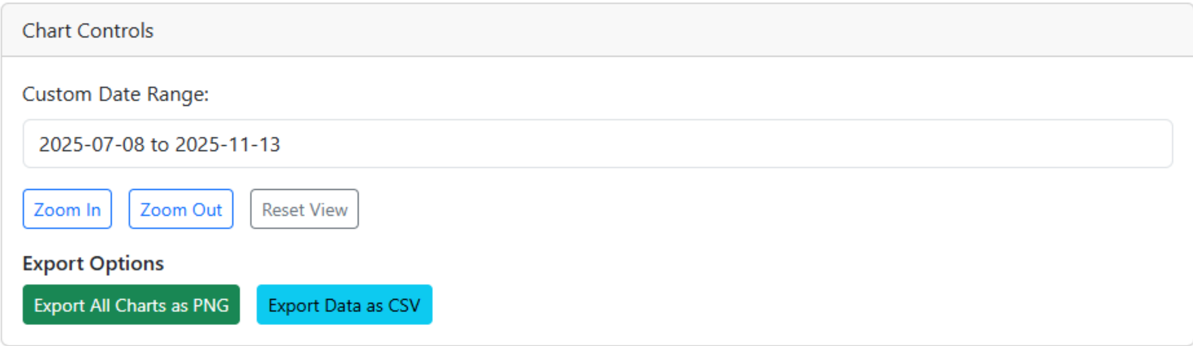

Figure 9: Chart controls and the system's ability to to show custom range of data and export it in other workable format such as .csv file format.

The chart control panel (see Figure 9) gives the user an option to view a custom range of data in case there is a specific date or time of data that is of interest to the user.

4.1.1.12. GEO-REFERENCING

The Distributed Fiber Optic Sensing (DFOS) system provides data in terms of fiber distance, which represents the position along the optical fiber where a signal response is recorded. However, for hydrological interpretation and structural assessment of the dike, it was essential to correlate these fiber-based distances with real-world spatial coordinates (Men et al.; Tan et al.). This spatial mapping enables the identification of exact locations within the dike where temperature and strain changes occur, allowing for accurate localization of potential seepage, deformation, or other structural changes.

To achieve a precise mapping between fiber distances and the physical layout of the dike, we employed the Distributed Acoustic Sensing technique in combination with a high-accuracy Global Positioning System. The DAS system provided accurate location of the fiber cable by interpreting the change in signals as frequencies changed when a weight was brought closer to the cable while conducting continuous measurements along the fiber. The GPS data was used to geo-reference the cable route. When the cable location was established, the exact path of the fiber optic cable was recorded as GPS points at regular intervals and at every notable change in direction or elevation. This process allowed for the creation of a detailed geospatial profile of the fiber position relative to the dike geometry. The integration of these datasets ensured that each measurement from the DFOS could be directly linked to a specific coordinate on the dike surface, providing a clear spatial context for hydrological analyses and event localization. It was also verified that the cable was installed at an average depth of 40 cm below the ground level, except for the beginning of the cable, which is exposed to the atmosphere, thereby acting as a control by measuring the surface temperature as well.

In the FOS system, the entire length of the dike is represented as a one continuous straight line, while in reality, there is a part of the cable that is in the crest of the dike, another part in the slope and the last part of the cable measures the temperature in the toe of the dike, as shown in Figure 10 below(‘fTB 5020 Technical Documentation’). The dashboard was then hard coded with reference to the GPS locations of the cable to easily relate the fiber length to the positions at which measurements are being taken. The three lines towards the end of the dike are then represented below over a single measurement.

Figure 10: Isolates the temperature in the crest, slope and toe of the dike for easier understanding of the cable location in relation to the fiber distance.

With reference to Figure 10above, the red line is the temperature from the crest of the dike, which is between chainage 118 – 178 m of the dike length. The blue line represents the temperature in the slop, which is between 190 – 250 m of the fiber's length, and the green part is the temperature in the toe of the dike. With this graphical presentation, it is therefore easier to visualize the temperature change within sections of the dike, and a cross-section can easily be selected and analyzed.

Figure 11: An analysis of the temperature variation in the crest, slope and toe of the dike to aid a quick analysis of the temperature changes in the three parts over a defined period of time.

From Figure 11above, the temperature variations in the different parts of the dike can be easily compared. For instance, the maximum, minimum, and average temperatures in the crest, slope, and in the toe of the dike have been isolated, and a temperature variation in the three parts has also been given. For engineers, it will be very important to observe the temperature variations within the dike as this affects the thermal properties of the dike structure. From the sets of data collected so far, it has shown that the dike absorbs heat from direct sunlight during the day, and it tends to release that heat when temperatures get lower, especially during the night hours. The magnitude of this change is greater in the summer compared to the winter, where changes of 1^0C can be observed. The above analysis underscores the accuracy of the FOS monitoring system as changes of even less than 1^0C can be observed and reported.

Additional mapping information was obtained from splice positions within the fiber. Because the Early Warning System (EWS) employed double-ended measurements, a distinct reference point exists where the fiber was spliced to itself at chainage 400 m to create a loop. This splice location introduces a measurable discontinuity in the backscatter signal, characterized by a notable change in amplitude and frequency response. The coordinates of the splice were precisely recorded and incorporated into the project's geospatial database. This splice not only serves as a permanent optical marker but also as a calibration point for aligning and validating fiber distance measurements. In the backscatter profile, the splice manifests as a distinct signal loss feature, easily recognizable in both single-ended and double-ended acquisitions. Anchoring the fiber distance scale to this known reference improved the accuracy and consistency of the entire mapping process, ensuring that any detected anomalies can be rapidly and confidently located on the dike.

Furthermore, the moisture sensors installed at various points along the dike provide an additional layer of spatial reference. Each sensor was deployed with known GPS coordinates and positioned in close proximity to the fiber optic cable, ensuring that the two measurement systems are spatially correlated. These moisture sensors not only contribute valuable environmental data (temperature and moisture content) but also serve as geospatial checkpoints for verifying the position of the optical fiber. When cross-referenced with the DFOS data, the moisture sensor coordinates enable precise correlation between hydrological readings and fiber-based measurements. This integrated referencing system, combining GPS-tracked fiber routing, identifiable spliced points, and co-located sensor coordinates created a robust and highly accurate spatial framework for the interpretation of temperature data within the dike structure.

4.1.2. SENSOR PRE-PROCESSING

The stability of earthen dikes is closely related to the behavior of water within their bodies. Moisture infiltration and the position of the phreatic surface directly affect pore pressures and thus influence the likelihood of failure by seepage, piping, or slope instability. For this project, slope instability is considered. Traditional methods of monitoring phreatic levels such as piezometers and observation wells provide valuable but sparse information, often limited to discrete points. Distributed fiber optic sensing (DFOS), particularly systems based on the Brillouin scattering principle in single-mode fibers, offers a powerful alternative as they have emerged to be transformative tools for structural health monitoring and geotechnical assessment. However, the raw data generated by these systems is rarely in a state suitable for immediate interpretation or decision-making. Raw signals are often contaminated by noise, environmental effects, sensor drift, or other impurities.

To transform this raw data into meaningful, actionable information, a preprocessing module is required. This module serves as the front-end stage of the overall data analysis pipeline, ensuring that subsequent algorithms such as predictive modeling operate on high-quality input. The preprocessing stage for the early warning system comprised of the following explained stages and components.

4.1.2.1. NOISE FILTERING

In Brillouin Optical Frequency Domain Reflectometry (BOFDR), the Brillouin frequency shift is measured along the fiber length, which is highly sensitive to both **temperature and strain**. For the setup in the dike, the Brillouin shift predominantly reflects temperature variations. By analyzing thermal responses, one can infer the spatial distribution of soil moisture, and from there, determine the phreatic level within the dike.

However, the raw data acquired from DFOS contains noise, systematic drift, and influences from other external environmental forces besides temperature. Additionally, the measurements are reported in terms of fiber distance, which must be accurately mapped to physical positions along the dike structure. This necessitated a robust preprocessing module to ensure that subsequent analyses such as translating fiber distances to interpretable cable locations, translating thermal signals into moisture content which was checked against existing moisture sensors installed in strategic points next to the fiber cable.

To begin with, the beginning and the end of the double ended measurement signal were trimmed to only focus on the fiber optic length that was buried in the ground. This was necessary to filter out the noise and variations from the part of the cable that was exposed to the atmosphere and the coil installed in the interrogator, whose operating conditions were different from the soil properties of the dike. The picture below shows the before and after initial processing of the signal.

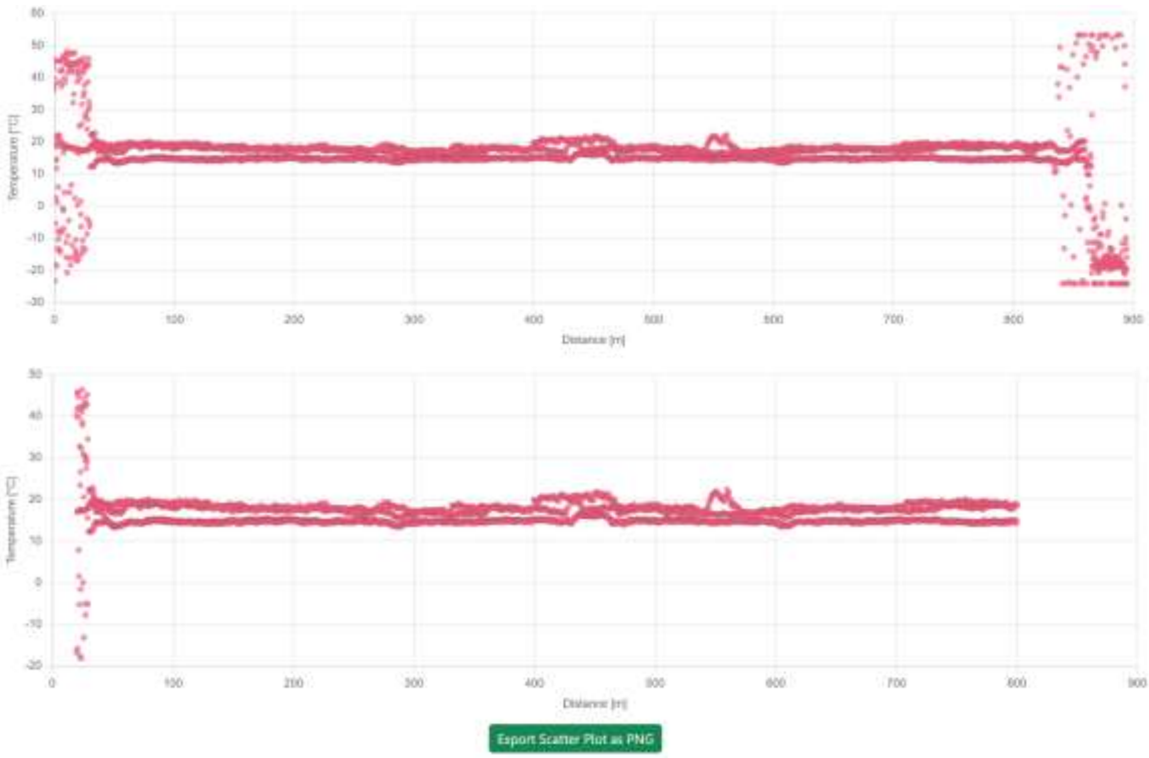

Figure 12: The two signals, one that has a lot of noise at both ends of the cable and one has a filtered signal that focuses on the temperature readings in the dike

From the Figure 12showed above, it can be seen that the noise from the beginning and end of the cable (seen from the top part of the figure) was cut out to focus only on the temperature readings from the dike as seen in the bottom part of the figure. The noise is not part of the cable installed in the dike, but rather the cable coiled inside the interrogator which has slightly different properties from the one in the dike. Since part of the cable is exposed to the atmosphere for the first 3 meters, that part was left out to be analyzed during the post processing of the data to compare the temperature readings of the cable to measurements observed from the other sensors on site.

4.1.2.2. OUTLIER REMOVAL

Since the fiber optic system operates at high spatial resolution (20 cm) over a total fiber length of 800 m, the cumulative impact of noise was substantial. Other factors such as double-ended measurements introduce points of energy loss that need to be considered during data analysis. In addition to that, during data collection, there was an unfortunate incident where the fiber optic cable was accidentally cut during the installation of pressure divers as independent sources of data. Because of the splice made during the repair, there was a significant amount of notable loss in energy that needed to be removed and the temperature change in the dike proved to be homogeneous except for one point at 560 m chainage that deviated excessively as shown on the image below. It was then removed by an algorithm that averaged the signals and removed the outlier from the signal as part of preprocessing.

Figure 13: The outlier signal highlighted in the red circle. It was later filtered out and the signal was stabilized

It can be noticed from Figure 13 above that there is an abnormal rise in temperature around 660 m of fiber length. This outlier is important to note because during the installation of pressure divers in the dike, the cable was punctured and the fiber broke. As a result, the repaired section was cotted with a pvc pipe, 20 mm diameter, and it was buried much close to the atmosphere as compared to the rest of the length that is buried at 40cm below ground level. PVC exhibits different properties that the soil covers where it absorbs heat at a different rate which is reflected in the peak recorded in the fiber. This also acts as a mapping tool for the team to know exactly which points were repaired in the system.

Since the spatial resolution is 20 cm, the observed peak can further be analyzed close and in further detail to show the changes over a single point in time. To achieve this, the dashboard allows a dynamic analysis over a selected point to analyze closely and it also has a feature to further deepen the analysis to 5 m on both sides of the cable at one go to clearly show how the temperature changes both in space and in time. The user can input the distance of interest that should be analyzed. For example, a detailed analysis at 559.2 m was selected to show the temperature changes around that point.

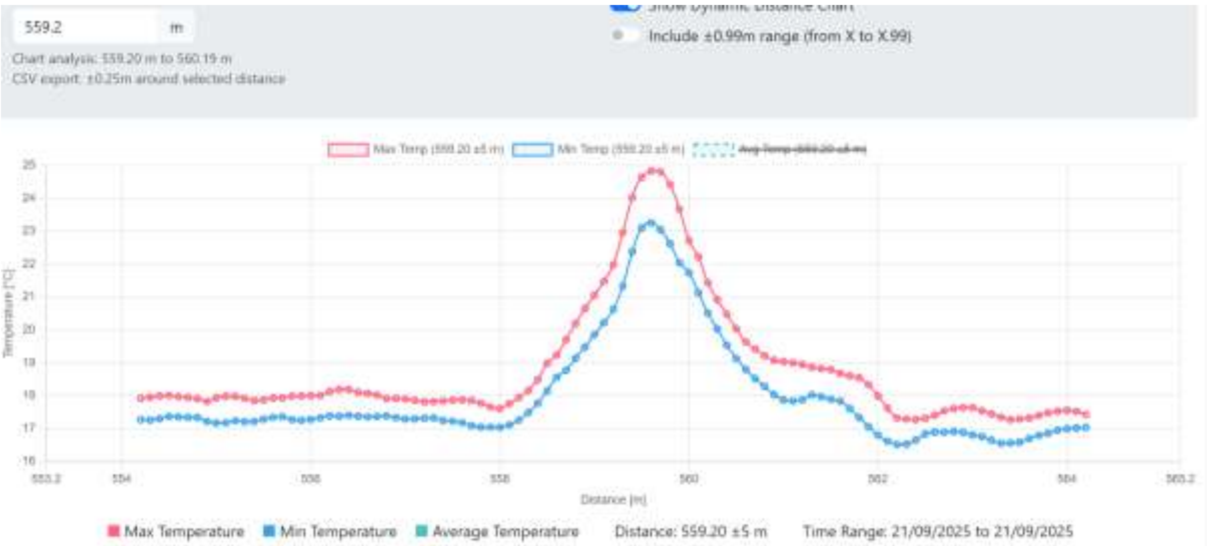

Figure 14: The peak temperaures recorded over th spliced point which has a PVC covering, burie closer to the surface, that exhibits different properties than that of the surrounding soil

Isolating the peak and analyzing the temperature changes during the day (see Figure 14), the temperature variation at around 559.2 m is very huge compared to the rest of the dike (with a gap of about 9^0C). This strange signal is also attributed to the change in properties of the fiber materials during the splicing/soldering as this introduced an impedance to the flow of light through the fiber, thereby giving this point a permanent deformation which is different from the rest of the fiber length. This can also be shown as the rest of the section recorded lower temperatures, but the highest temperature is only observed at around 660 m.

4.1.2.3. CORRECTION FOR EXTERNAL FACTORS

The thermal properties of the dike are influenced by more than just soil moisture; it is also strongly influenced by external environmental factors (M. Zhang et al.). One of the most significant of these is the fluctuation of ambient air temperature, which directly impacts the surface and upper layers of the dike. As temperatures rise and fall throughout the day and across seasons, the soil within the dike responds, often creating temperature variations that may not be directly linked to actual changes in moisture levels (Sayde et al.).

In the MULTICLIMACT Project, **rainfall** was considered to play a major role in altering the thermal state of the dike as the water levels in the channel are maintained at constant levels. When rainwater infiltrates the soil, it causes a temporary cooling effect and changes the soil's thermal conductivity. In addition, the timing and intensity of rainfall events introduce variability that must be accounted for when monitoring dike stability, hence the basis of the idea to monitor dike structural health using moisture content (T. Zhang et al.).

Another important factor is **solar radiation**, which drives daily heating cycles near the dike's surface. During the daytime, the sun warms the outer layers, while cooler conditions return at night, creating a repeating pattern of thermal changes. This diurnal cycle can mask the natural thermal signals generated by soil moisture and make it more difficult to isolate the true influence of water content within the dike (Hilgersom et al.).

Finally, factors such as wind and humidity affect the boundary conditions of the dike and contribute to changes in heat transfer processes. Wind can accelerate cooling or evaporation at the surface, while humidity influences how quickly the soil exchanges heat with the atmosphere. Together, these external factors can alter the thermal signatures associated with soil moisture, making it crucial when analyzing the thermal behavior of dikes (Dong).

4.1.3. SENSOR POST-PROCESSING

The temperature data obtained from the interrogator was further processed under the Integration Layer (‘D4.4_Design of Digital Solution Early Warning SYSTEM - TU DELFT[1] (1)’). This is the calculation engine for the EWS where the moisture content of the dike was estimated from temperature measurements. It should be noted that due to the challenging nature of working with clay soils, whose moisture content is harder to predict based on the methods developed by Ciocca et al, research is still going on under MULTILIMACT to test different methods and identify which model is best suited for the prediction of moisture content in clay.

4.1.3.1. ESTIMATION OF SOIL MOISTURE VIA THERMAL CONDUCTIVITY

Soil moisture content can be estimated from thermal conductivity, which can also be estimated from temperature measurements (Ciocca et al.), based on the methods presented by (Ciocca et al.; J. Dong et al.) with active heating where a heat source was identified and a specific amount of heat was applied. For this project, passive heating was rather considered where the heat source was the diurnal pattern of the sun and other environmental factors.

When the surrounding soil is heated, the heat propagates radially into the cable (Ciocca et al.). The resulting temperature evolution depends on the soil’s thermal conductivity (λ) and thermal diffusivity (K), both of which are strongly influenced by soil water content. The physical interpretation relies on the classical line heat-source (probe) method, which provides analytical solutions for heat conduction from a cylindrical source embedded in a homogeneous medium. For the case of MULTICLIMACT, the heat source was direct sunlight.

At sufficiently long times after heating begins or ends (diurnal pattern), the temperature increase becomes a logarithmic function of time. In this asymptotic regime, the slope of temperature versus logarithmic time depends on the applied heat per unit length and the soil's thermal conductivity of the soil. This property makes it possible to estimate λ without detailed knowledge of the cable geometry or insulation effects, which were not considered in this project (J. Dong et al.; Dong).

Equation [10] from Ciocca therefore estimates the thermal conductivity by superimposing two heat sources; one for heating the soil and a cooling phase for cooling the soil when heating stops.

$$\Delta T(t) = \frac{Q}{4\pi\lambda} ln\left[\frac{t}{t-\Delta t_h}\right]$$

Where;

ΔT(t) is the temperature increment relative to pre-heating conditions,

Q is the heat input per unit cable length,

λ is the soil thermal conductivity,

t is time since heating started,

Δt_h is the heating duration (Ciocca et al.).

The estimation of soil water content is a two-step process which is best described below with the following equation:

$$\lambda = (\lambda_{sat} - \lambda_{dry})\kappa_e + \lambda_{dry}$$

where λ_{dry} and λ_{sat} are the thermal conductivities of the dry and saturated soil, respectively.

i. Thermal Conductivity Estimation

Using the two equations explained above, the thermal conductivity λ is estimated from the slope of the temperature–logarithmic-time relationship during the cooling phase. This step relies purely on heat transfer physics and DTS temperature measurements.

ii. Conversion from Thermal Conductivity to Water Content

Thermal conductivity is then related to volumetric water content (θ) using an empirical–physical constitutive model. The study employs the model of Lu et al. (2007), which expresses λ as a function of θ through a Kersten number formulation (Ciocca et al.; M. Zhang et al.):

λ increases strongly with increasing θ, reflecting enhanced heat transfer through water-filled pores. Soil-specific parameters (dry and saturated thermal conductivity, texture-dependent coefficients) are calibrated independently. By inverting the λ–θ relationship, the measured thermal conductivity profile along the fiber is converted into a spatially distributed soil moisture profile.

However, the above procedure has some limitations and implications, some of which are explained below:

i. Sensitivity decreases at high water contents where λ varies slowly with θ, leading to larger uncertainty
ii. In dry soil, longer times are required to reach the asymptotic regime, otherwise λ (and thus θ) may be underestimated
iii. The time-corrected cooling analysis substantially improves accuracy, particularly in wetter soils.

4.2. BOX BARRIER DASHBOARD

The EWS has two main parts of the dashboards, one for the dike, and another component that analyses the movable barriers. The principle of operation is similar, but the difference is that the movable barrier dashboard was developed based on strains while the dike dashboard was developed based on temperature measurements.

4.2.1. DASHBOARD INTERFACE VISUAL DESIGN

The dashboard of the proposed early warning system is the central decision-support interface for monitoring the structural performance of movable flood barriers during deployment and loading. Its primary objective is to translate high-frequency fiber optic sensing (FOS) data into actionable information that allows operators to rapidly assess the barrier integrity, detect early signs of displacement or failure, and inform on the preventive measures before loss of functionality occurs (Men et al.).

Given the transient nature of flood events and the rapid deployment philosophy of the Box Barrier system, where it must be erected within a few hours before flooding occurs, the dashboard must emphasize **real-time responsiveness**, clarity and robustness, rather than detailed post-processing analytics. The design is therefore informed by the MULTICLIMACT experimental setup done in Flood Proof Holland where strain and water levels are monitored simultaneously under controlled loading conditions.

Besides the fiber optic cables, there were two additional data streams where we had the thermal camera monitor leakage, and pressure divers monitored the change in ground water levels during water loading. However, for the visualization layer of this dashboard, the fiber optic data was considered to be the main indicator and the backbone of the dashboard.

The dashboard displays a longitudinal strain profile along the interconnected barriers, mapped to box numbers and clamp positions. From this setup, the real-time strain values are updated at the rate of the interrogator's sampling frequency, which was around every 40 seconds per iteration on average. To aid the interpretation of the data, the strain levels were color-coded to immediately highlight abnormal strained areas.

Under normal operating conditions (Explained under experiment 1), the dashboard showed low, gradually increasing strain levels corresponding to the hydrostatic loading and minor settling of the boxes. In contrast, under failure prone conditions (Experiment 2), localized strain anomalies emerged earlier and with higher magnitude, particularly near the partially filled box. With this early detection during the monitoring, it proved to be possible that the strains can be monitored in real-time and that signals of places that are prone to failure can be sent to managers for the next course of action.

Therefore, the dashboard can track explicitly the time first strain anomaly within the boxes, the rate at which the strain increases as loading of water continues. This function acts as a proxy for displacement acceleration. The dashboard can also show the strain of asymmetry between adjacent boxes, which is a result of the differential movement. These metrics allow the system to not only monitor but also offer early failure prognosis.

4.2.2. EVENT DETECTION AND THRESHOLDS

To function as an early warning system, the dashboard incorporated a multi-phase alert system. It has an advisory level, which is triggered by strain exceeding 1000 με over normal loading rates. It also has the warning level which is triggered by a rapid strain increase beyond 1500 με. Lastly, it also has the critical level which is triggered by strain patterns that are consistent with loss of stability of the boxes or when uplifting is about to start. Based on the FPH experiments, this was reached around 3,000με.

In as much as the thresholds were set on fixed values based on the type of coupling of the fiber cable used, they can also be set to be dynamic based on the loading speed or the filling rate of water on one side, the water level difference within the boxes and the thresholds can also be set based on the comparison of two adjacent boxes. for instance, in Experiment 2, the dashboard identified the partially filled box as an outlier, which had earlier warnings as compared to the filled boxes. This capability demonstrates the suitability of the system for real-world warning applications.

In as much as it is important to plot time-series of the rising water levels, the height of water on the loading side cannot be predicted by the strain measurements alone, hence there was a need for other measurement techniques such as simply having a leveling staff that indicated the height/depth of water as the barrier system was being loaded. The results from the hydraulic loading can then be correlated to the strain measurements for detailed interpretation.

4.2.3. SENSOR PRE-PROCESSING

Preprocessing of the data signal involved frequencies sweep which was a function embedded by FibrisTerre. It also involves storage of the measurement files in formats that can be easily accessed and analyzed even on other platforms. Just like the dike data, the files were stored as .txt files. Unlike the dike data where the focus was on the temperature files, here the focus was on the strain files but to allow uniformity, the data format remained the same.

4.2.4. SENSOR POST-PROCESSING

Processing the strain data for the movable barriers was more straightforward as compared to the temperature data for dikes because the strain between boxes directly indicated the displacement between boxes. Hence, the post processing of the data involved the analysis of the changes in magnitude of the strain signals observed in real time. Before any measurements were carried out in the field, the fiber parameters had to be calibrated to match the specifications of the EWS; the system strain coefficient and temperature coefficient had to be determined in the process. The process is explained in MULTICLIMACT Report D9.1 and here the values were applied. The process also involved the determination of thresholds for issuing warnings when certain levels of strains were reached. This is elaborated below.

Three levels of warnings were established based on the magnitudes observed before total failure of the boxes. The first warning of displacement was issued when a force equivalent to a strain of1800 με was observed. At this point, there was no shift of the boxes yet with reference to the ground, but the cable was getting more strained. This alert was important to identify the possible failure points of the barrier. The second threshold was at 2,350με when the water level kept on rising. At this point, the cable was under tension, and this meant that any further rise in the water level would lead to a breach between the barriers. At this point, if there could be any people and valuable items in the dry land in real life, evacuation at this point would be the best thing to do to prevent damage and loss of life. The final warning was issued at 3,380 με which symbolized which was recorded as the maximum amount of force from the rising water that the boxes would withstand before failure.

It should be clearly noted that these forces are hard to reach in the event of an actual flood as was the case in this controlled environment where the loading was deliberately pushed beyond the limits just to test how far the system can respond. It was a great success and satisfactory to observe that the measurements observed in real time could be observed and interpreted every 42 seconds on average, which gave a chance to managers and engineers to observe and make decisions as events unfold. All files were made available and accessible in the cloud service for future references.

The same experiment was then repeated in Limburg in a real case scenario, and the details of the findings were explained in MULTICLIMACT report D11.3.

4.2.5. DASHBOARD TESTING FOR FPH EXPERIMENTS

Below are some of the key features of the EWS dashboard deployed for the movable barrier experiments.

Co-funded by the European Union

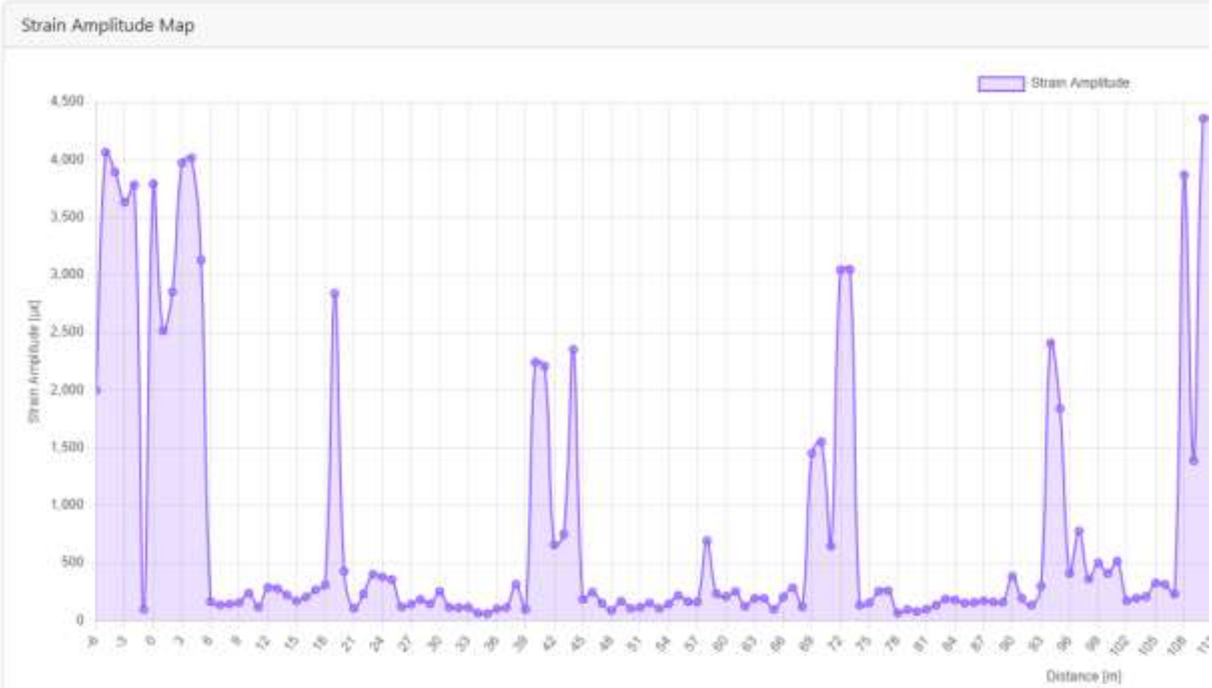

Figure 15: Temperature amplitude map, showing strains with reference to a zero point

The strain amplitude map (see Figure 15) illustrates the measured structural response of the movable barrier system as the water level was progressively raised on one side. The horizontal axis represents distance along the barrier alignment, while the vertical axis shows strain amplitude in micro strains. Distinct peaks are visible at specific locations, corresponding to the movement in the joints between individual barrier boxes. These high points indicate where strain concentrations developed as differential hydrostatic pressure increased, demonstrating how the barrier deformed at the connections rather than being uniformly distributed along the entire length of the barrier.

Over time, as the water level continued to rise, the data revealed fluctuations in strain magnitude between boxes, reflecting the dynamic interaction of the system under loading. Lower strain values between peaks suggest relatively stable behavior within individual boxes, whereas the repeated high-amplitude spikes highlight critical joints experiencing greater deformation. This pattern is consistent with expected structural behavior for movable barriers, where joints act as primary load paths. Overall, the strain measurements provide clear insight into how induced loads evolved spatially and temporally, identifying potential fatigue locations, and informing future design or reinforcement strategies.

In addition, because this monitoring approach is based on fiber optic sensing technology, the strain amplitude map can function as an effective early warning system for the movable barrier structure. Fiber optic systems provide continuous, real-time strain measurements with high spatial resolution, allowing abnormal strain development at joints to be detected as it occurs. Sudden increases in strain amplitudes or changes in established strain patterns can therefore be identified early, well before visible damage or functional failure develops. This capability supports proactive decision-making during barrier operation, enabling timely intervention, load adjustment, or inspection, and ultimately enhances the safety, reliability, and long-term durability of the barrier system under variable water level conditions.

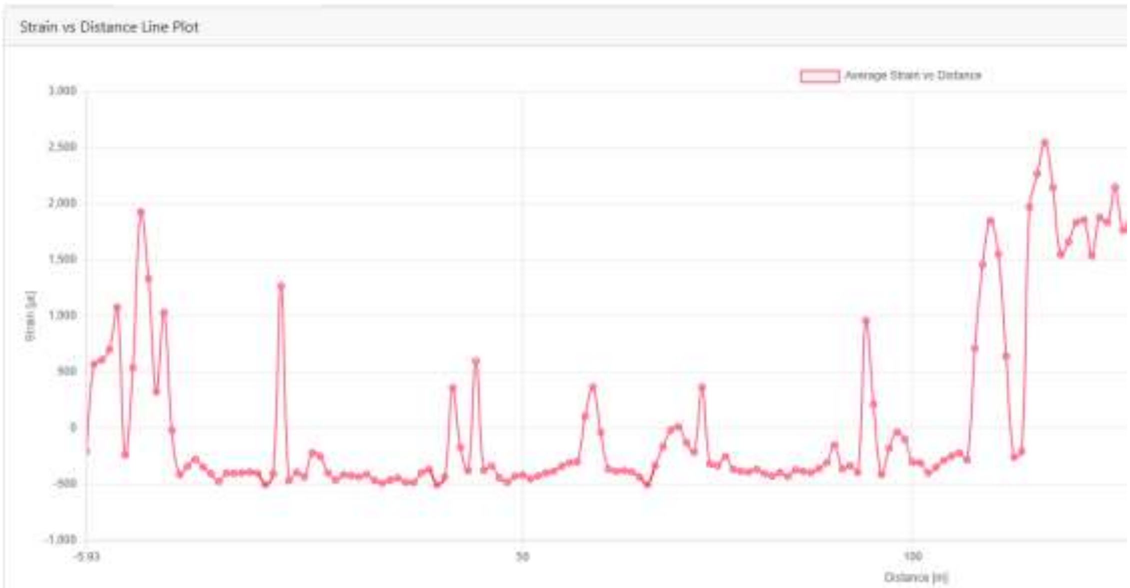

Figure 16: Shows the strain measured along hte barrier with respect to the entire length of the defence system

This strain-versus-distance plot (see Figure 16) highlights how the fiber-optic monitoring system can serve as an effective early-warning tool for a movable barrier. The smaller fluctuations represent normal operational movements, while the sharp peaks show areas where the structure experiences unusual or elevated strain. By continuously tracking these changes, the system can detect early signs of mechanical instability before they escalate into failures.

Peaks occurring between boxes are especially important, as these joints are typically the first to show abnormal movement or wear. When the system identifies strain levels that exceed expected patterns, operators can be alerted immediately, allowing for timely inspection or intervention. This early-warning capability enhances safety, reduces downtime, and supports proactive maintenance of the movable barrier.

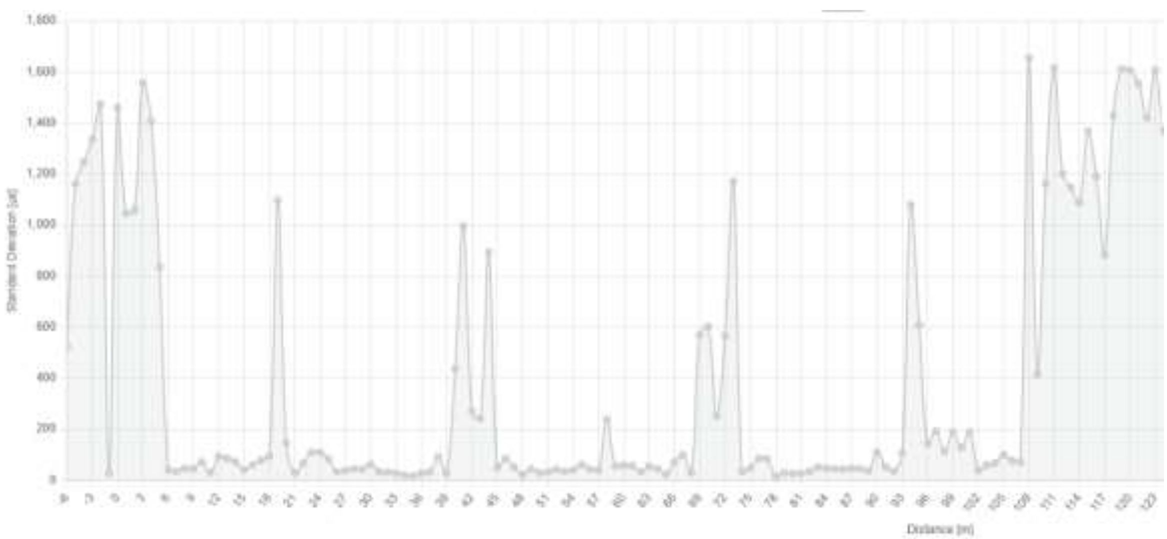

Figure 17: The standard deviation of strain along the movable barrier

Figure 17above shows the standard deviation of strain along the length of the fiber-optic movable barrier monitoring system. Most of the barriers display low variability, indicating stable and consistent behavior during operation. However, several sections exhibit sharp increases in standard deviation, highlighting areas where strain fluctuates significantly over time.

High standard-deviation regions indicate rapidly changing strain, serving as an important early-warning indicator. Areas showing persistence or increasing variability may signal loose connections, developing misalignments, or components approaching failure. Monitoring these fluctuations enables operators to detect emerging issues before they escalate, providing valuable time to intervene, inspect, or perform maintenance to ensure the movable barrier continues to operate safely and reliably.

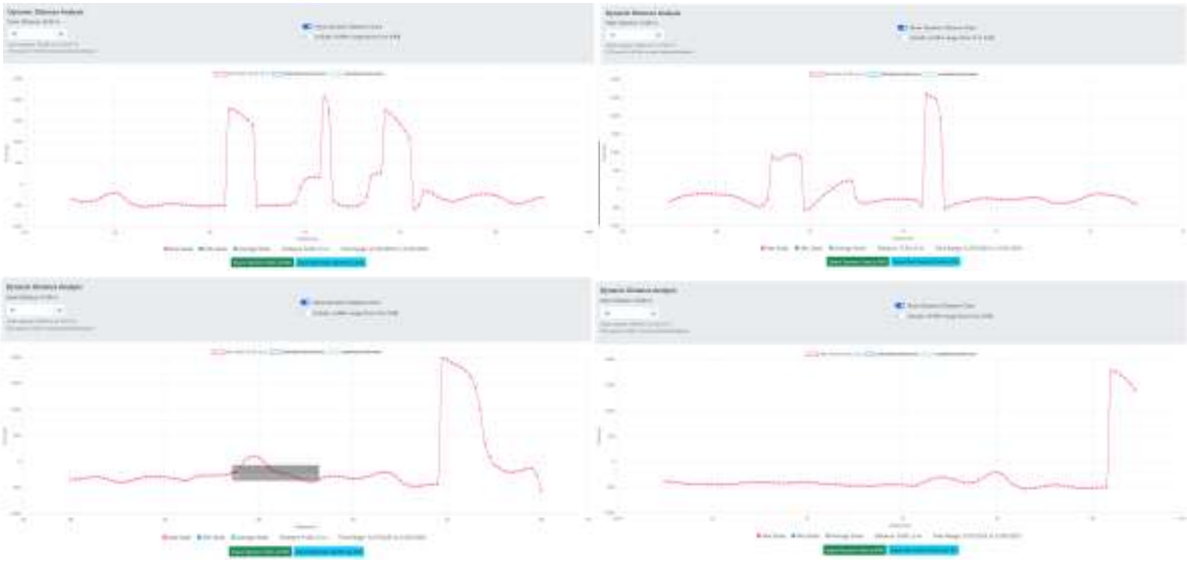

Figure 18: Shows the focused dynamic distance monitoring of the strains to isolate the critical points of attention in the system

These focused strain profiles (see Figure 18) illustrate how a distributed fiber-optic sensing system can isolate and analyze localized mechanical behavior along the movable barrier. By evaluating maximum, minimum, and average strain within a narrow window around specific distances, the system highlights subtle variations in structural response that may not be evident in broader, whole-system plots. The repeated appearance of sharp, high-magnitude strain peaks at certain distances indicates zones of concentrated mechanical loading, often corresponding to joints, hinge points, or interfaces between barrier sections. Conversely, flatter regions with consistent low-level strain represent stable structural segments experiencing uniform loading.

Because this analysis is performed along the same continuous fiber, the system provides a direct comparison of how different barrier locations behave under similar conditions. Progressive increases in peak strain amplitude, widening strain envelopes, or rising local variability can signal the early development of mechanical fatigue, loosening components, or misalignment long before cracks or deformation become visible. By repeatedly sampling these focused regions over time, the fiber-optic early warning system enables predictive maintenance: identifying emerging failure points, validating repair effectiveness, and ensuring that intervention occurs before structural performance degrades or safety is compromised.

5. DATA COLLECTION AND TRANSMISSION

5.1. IN-SITU MEASUREMENTS (DATA COLLECTION AND STORAGE)

For the collection of temperature data in the dike, the early warning system uses the fTB 5020 interrogator unit from FibrisTerre. The fTB 5020 is the latest generation of fibrisTerre distributed fiber-optic monitoring systems, engineered to deliver precise and dependable measurements of strain and temperature along an optical fiber. It can cover loop lengths of up to 50 kilometers with spatial resolution as fine as **20 centimeters**.

It uses Brillouin optical frequency domain analysis (BOFDA) technology, which provides an unmatched level of accuracy, resolution and usability, with a repeatability of the Brillouin measurements at 100kHz. When the sensing fiber are calibrated, one can achieve measurement accuracy of better than 0.1 ^{0}C for temperature and 2 με for strain. For the spatial resolution, since the measurement length is 800 m (< 2km), the system utilized the optional enhanced spatial resolution of 20 cm for both the dike measurements and box barriers.

For the temperature measurements in the dike, the system has a local PC stationed in the pump house that is connected to the internet. With this setup, it also allowed remote-controlled access to the operations. The local PC is connected to FibrisTerre's cloud service that has cloud storage for keeping the raw files in .msr format. With this format, one can easily export data in .txt file format, which was the preferred format, to work with when it comes to post processing of the data.

For the fiber optic cable used in the strain measurements, it uses single mode cables s9/125, 1.9 x 3.1 m, blue outer coating (fiber color: orange, blue, fiber type: Corning CLearCurve LBL)

Figure 19: The type of cable used for the strain measurements

Figure 19 shows the details of the cable that was used for the strain measurements in the lab, FPH and Limburg experiments. The cable was anchored to the box barriers with a special design of clamp developed by TU Delft under T9.1 of MULTICLIMACT (See details in D9.1)

5.2. HARDWARE

The hardware component of the setup was installed in the dike and in the pump house located at the dike in Leischendam whose details of location were explained in D9.1. There is a fiber cable that was installed at an average depth of 40 cm into the ground, except for the first few meters that are exposed to the atmosphere to help monitor the surface temperature and atmospheric temperatures. Inside the pump house, there is an interrogator developed by FibrisTerre, connected to the fiber cable that is used to shoot a laser into the fiber and measure the temperature over the entire length.

Figure 20: The interrogator (issues a laser pulse to the fiber cable for the measurement of temperature and strain) installed in the pump house for measuring temperature

This interrogator (see Figure 20) is connected to a computer on site which has the interface to command the operations. This computer is also connected to a WiFi network that helps to upload the collected data into the cloud service and to also act as a physical storage for measurements.

There are moisture sensors from Sensoterra that are spread over the dike to monitor the in-situ moisture content in the dike. They basically have two types of sensors; single depth sensors that collect the moisture content at a single depth, while the multi-depth sensors collect measurements at various depths from 10 cm to 90 cm (see Figure 21). in addition to the moisture content, they also have the capability of measuring the surface temperatures on the dike, which is a reference point for the temperature measurements obtained from the fiber cables.

Figure 21: The single depth sensors (left) with different measurement depths and the multi depth sensor (right)

The sensors' data can be accessed remotely as well. These sensors are self-powered with a battery that is designed to last at least 8 years. They also have a GSM model that gives the sensor an ability to upload the data into the cloud hence the moisture data can be accessed remotely and in real-time.

For the movable barriers, the collection of data was similar, except in this case, the cable was attached to the box barriers and not buried in the ground as was the case with the dike.

5.3. FIBER OPTIC SENSOR SYSTEM (FIBRISTERRE CLOUD SERVICE AND API)

FibrisTerre's DTSS system in the configuration used for the Tedingerbroek dike demonstrator has the following components in the data flow:

- fTB 5020 interrogator unit connected to the fiber-optic cable used as a sensor
- Local PC running fTView (local application to configure, perform, analyze and store DTSS measurements on the fTB 5020)
- 4G wireless modem and router for connectivity of the local PC to the internet
- fTScope: fibrisTerre's proprietary cloud database platform

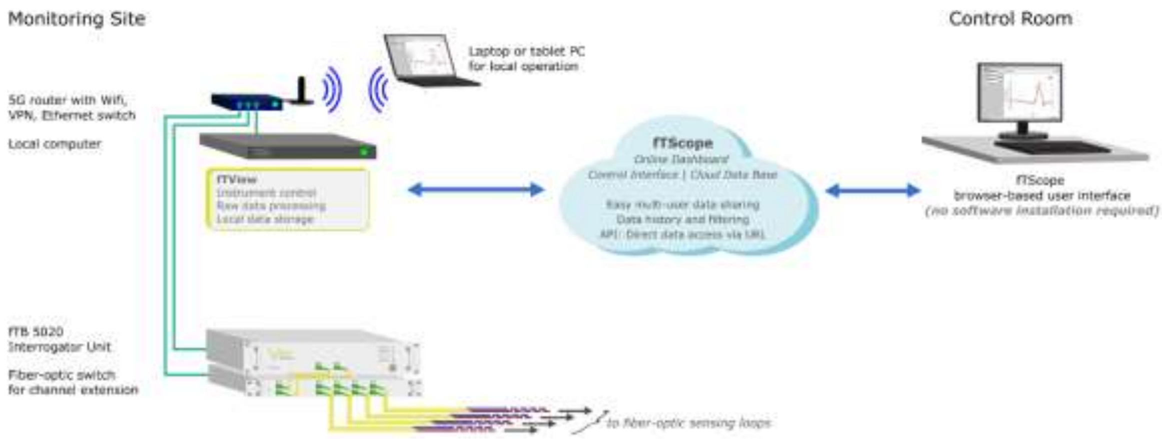

Figure 22: The configuration of the full DTSS system set-up with the fTB 5020 interrogator unit and data connectivity to the cloud database platform fTScope

fTScope has been set up to become the central hub of control and data flow throughout the experiment and demonstrator phaseFigure 22. It is a service deliberately developed for 24/7 monitoring and maintenance of geotechnical measurements and has been prototyped and beta-tested throughout the MULITCLIMACT activities.

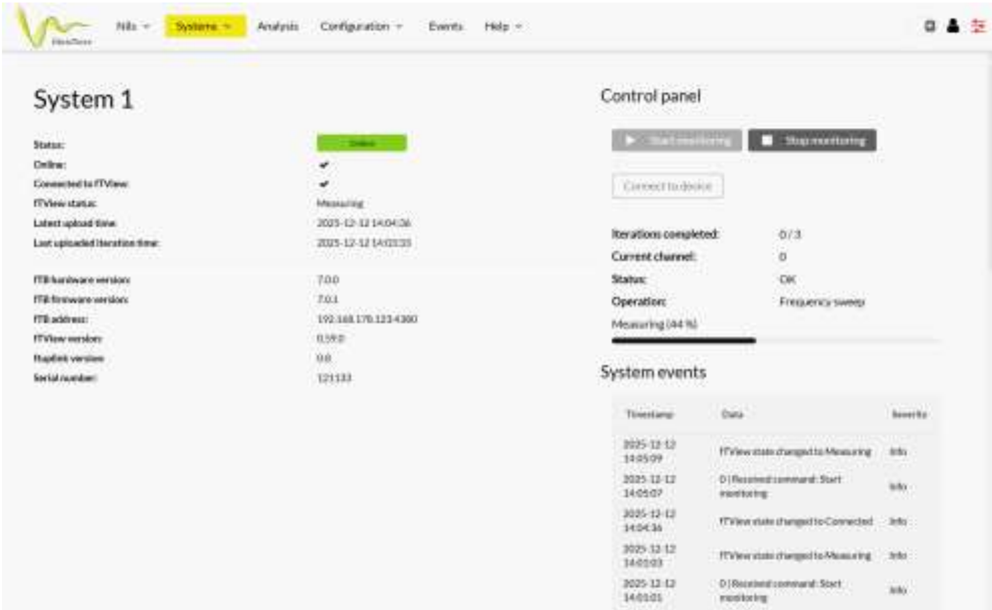

Figure 23: Screenshot of fTScope with the remote control interface to the fTB 5020 interrogator unit

fTScope is capable of

- Sorting and managing all data ever recorded in a database, categorized by project, system, channel, date, etc.
- Access to data and visualization tools from a web browser (that means, from any computer anywhere with internet connection)
- Remote control of the measurement through the web browser
- Data and remote system access with no need for software installation or dedicated VPN connections
- Sharing data and visualization (like a specific view on a selected data set) with authorized users (partners, colleagues, us, ...)
- Access to multiple systems (possibly on different project sites) from only one user interface
- An easy-to-use API to directly access data fields in the database and remote control the measurements from the user's own software application

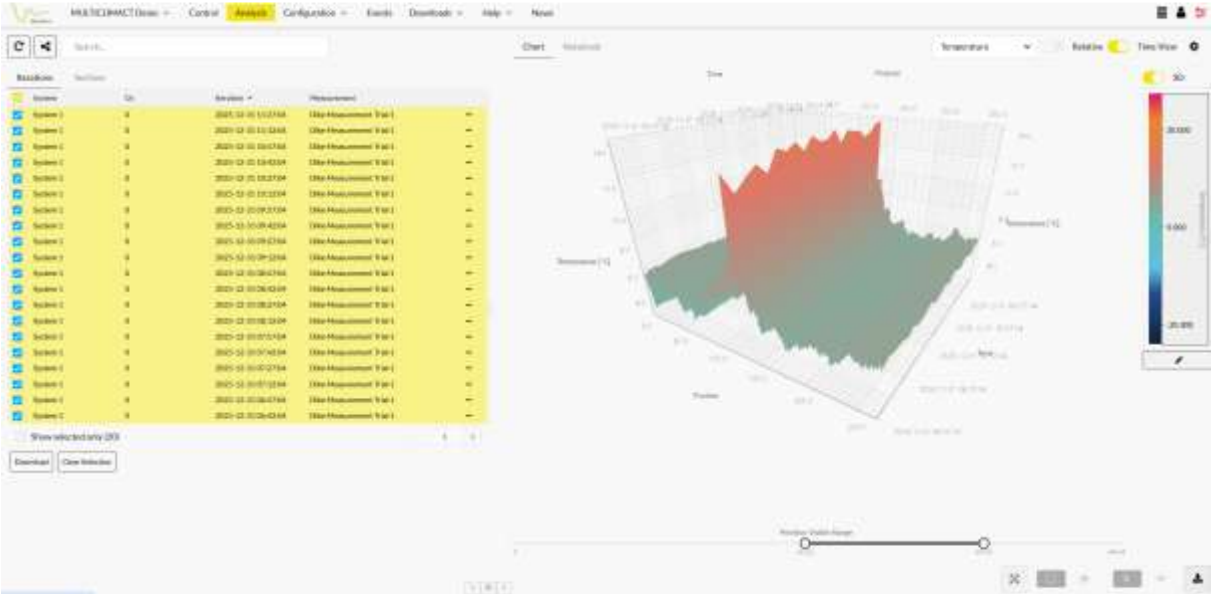

Figure 24: Screenshot of fTScope with a 3D visualization of the data from the test dike at Tedingerbroek

5.4. DASHBOARD POST-PROCESSING

The system collects temperature and strain data from DFOS interrogators through the fTScope API. Each monitored structure is registered on the platform as a dedicated project and linked to secure API credentials. Data retrieval is handled automatically by a scheduled ingestion process that continuously synchronizes new measurements from the cloud, ensuring that the monitoring workflow runs without manual intervention.

To maintain data integrity and efficiency, the ingestion engine tracks the timestamp of the last successfully retrieved dataset and only requests new information from that point onward. This approach prevents duplicate data from being stored, automatically fills in any missing measurements if connectivity is temporarily lost, and reduces unnecessary network and API traffic. Each DFOS acquisition includes thousands of spatial measurement points distributed along the fiber optic cable and is stored in the system as a time-stamped JSON record, providing a high-resolution and traceable dataset for analysis and early warning assessments. From the storage of the DTSS data in the cloud database, further processing of distributed strain and temperature values can be performed. Ultimately, the data flow leads to a top-level dashboard indicating early failure mechanisms for use in flood resilience enhancement.

When a user requests a function from the dashboard interface, the API primarily performs three stages of computation; temporal aggregation, spatial aggregation, and segment-based structural analysis.

5.4.1. TEMPORAL AGGREGATION

Since the interrogator's spatial resolution is 20 cm, the system does the following for each processing iteration: the system calculates the minimum, average, and maximum values of the measured parameters. These statistical measures provide a concise representation of temporal behavior to the highest resolution. This is essential for time-series trend analysis and for the support of anomaly detection by highlighting deviations from normal patterns and enabling timely alerting when thresholds are exceeded.

5.4.2. SPATIAL AGGREGATION

For spatial analysis, measurement values are grouped according to fiber distance in the cable, and it is aggregated over defined time windows. This approach allows the system to compute temperature amplitude and standard deviation while identifying persistent hot and cold spots. The aim of this aggregation is to reveal localized thermal behaviors that may indicate structural changes.

5.4.3. SEGMENT-BASED STRUCTURAL ANALYSIS

The dike set-up divides the dike into three engineering zones: the crest (118–178 m), the slope (190-250 m), and the toe (258–318 m). Each segment is analyzed independently rather than relying on global averages. This segmentation ensures that localized effects are not masked by broader trends.

By analyzing each segment separately, the system can detect localized instability, seepage, or thermal anomalies specific to a given zone. This targeted analysis enhances diagnostic accuracy and supports early intervention by focusing attention on the most vulnerable parts of the structure.

5.4.4. PERFORMANCE OPTIMIZATION

To guarantee scalability, the EWS employs a set of performance-oriented data management strategies, including time-range indexed queries instead of costly date extraction, keyset pagination to prevent database slowdowns, compressed daily caching to reduce storage and retrieval overhead, and ETag-based HTTP cache validation to minimize redundant data transfers. Together, these optimizations enable system dashboards to load and visualize tens of thousands of spatial measurement points within milliseconds, while fully preserving analytical accuracy and responsiveness.

5.4.5. SCIENTIFIC INTEGRITY

Raw sensor data is never overwritten, altered, or downsampled. Instead, all analytical outputs are generated directly from these immutable measurements. This approach ensures complete end-to-end traceability while also preserving long-term reproducibility, allowing every analytic result to be reliably traced back to its original source data (see Figure 25).

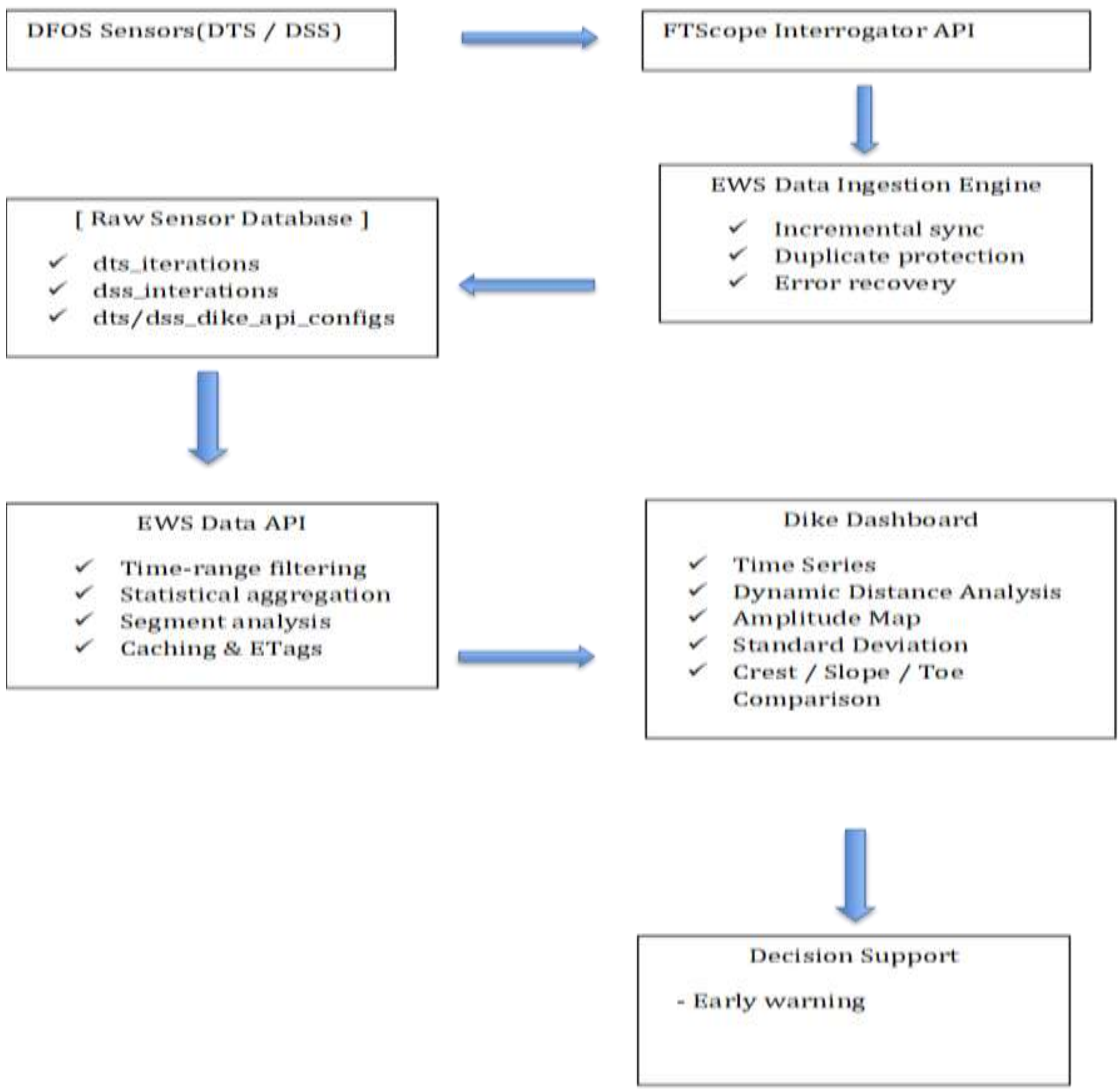

Figure 25: The system architecture for the EWS, to make sure that the scientific integrity of the system is maintained

The system collects temperature and strain data from distributed fiber-optic sensors (DTS and DSS) installed along the dike and in the Box Barrier. This data is pulled from the FTScope interrogator through an API and handled by the EWS data ingestion engine, which ensures the data is transferred reliably by syncing incrementally, avoiding duplicates, and recovering errors. All raw measurements and configuration details are stored in a central sensor database, creating a reliable base for further analysis.

The data is then made available through the EWS Data API, allowing efficient querying, aggregation, and segment-based analysis. These results are visualized in the dike dashboard, where users can explore time series, amplitude maps, variability, dynamic distance analysis, and crest, slope, and toe comparisons.

5.5. STAKEHOLDER ENGAGEMENT

Although Deliverable D10.4 focuses on the technical development and demonstration of the Early Warning System, there were continuous consultations among the stakeholders of the project. This engagement enabled user-centered validation which was essential to ensure operational relevance, acceptance and long-term adaptation. The dashboard has been designed using a user-oriented approach, differentiating between engineers, decision-makers, and field inspectors through tailored access levels, visualization depth, and alert interpretation layers. Its layered architecture (sensor, integration, and presentation layers) and modular presentation components enable iterative refinement based on user feedback without altering the underlying sensing infrastructure.

Other activities within MULTICLIMACT, such as Task 11.3 of the Dutch Demo helped to formalize stakeholder validation through the pilot demonstrations and structured feedback processes involving infrastructure managers and water authorities. These activities focused on validating usability, alert clarity, forecast interpretability, and the translation of technical indicators into meaningful warning categories aligned with emergency and maintenance procedures. Going forward, further stakeholder engagements, the cross-work package collaboration will further embed the EWS within broader resilience and governance frameworks, ensuring scalability and effective deployment across diverse European flood defence contexts.

6. DEVIATIONS TO THE PLAN

Initially, Deliverable D10.4 was scheduled for submission in month 24 but was later postponed to month 30. This delay was mainly due to procurement challenges, as the interrogator and related equipment were custom-built for the project and required additional improvements and adjustments. Implementing these changes took longer than expected which in turn delayed the measurement campaign. The project team also needed to collect data that was representative of both drought and flood conditions, requiring extended field monitoring and resulting in a justified deviation from the original plan outlined in the Grant Agreement.

In addition, the installation of a fish passage by project partner Delfland, temporarily disrupted continuous monitoring and data collection (to avoid repetition of text; details of activities are described in D9.1). As a result, more time was needed to obtain a complete and representative dataset for developing the early warning system.

This issue, as well as the postponement of D10.4, were communicated to the Project Leadership and the PO and were approved as minor adjustments. The delays also had knock-on effects on Deliverable D9.1, which was dependent on the outcomes of D10.4.

The extended field monitoring campaign ultimately improved the quality and value of the collected data as it captured compete cycles of summer and winter which represented flooding and drought conditions. Because the main monitoring period coincided with a significantly dry summer, the project captured rare and scientifically valuable observations of soil conditions under extreme drought. The stable weather also enhanced data quality by reducing interruptions and ensuring consistent measurement conditions.In addition to that, the extended monitoring window provided stronger temporal coverage, enabling clearer assessment of seasonal dynamics and long-term trends. These conditions provided adequate data for model validation, particularly for climate-stress scenarios, and enhanced the relevance of the dataset for future climate-impact analysis.

7. OUTPUTS FOR OTHER WPS

7.1. LINKS TO OTHER WPS

The output of this deliverable, which is the early warning system will be used as an input in WP 11 (Demonstration of the MULTICLIMACT framework at the territorial scale, especially Task 11.3 of the Dutch Demo). The outputs of this package also complemented Task 9.1 (Fiber optic-based monitoring systems for flood defense – development for the application to a real demo).

7.2. EFFECTS ON OTHER WPS

This deliverable depends on the output of T9.1. It also used the outputs of WP 3 and WP 4 (Tasks 3.1 and 4.4) as this deliverable was a continuation of these tasks.

Co-funded by the European Union

8. CONCLUSION

The task T10.4 demonstrates that distributed fiber-optic sensing provides a reliable and high-resolution framework for monitoring the structural behavior of movable barrier systems, enabling early detection of deformation long before conventional inspection methods would identify visible symptoms. Through the analysis of strain profiles along the continuous fiber cable, the system successfully highlights localized loading patterns, repeated stress concentrations, and abnormal strain signatures, each of which serves as an indicator for potential failure. The ability to focus analytical windows around known or notable structural points, such as joints between boxes, further enhances diagnostic precision by allowing operators to compare temporal changes in strain magnitude, frequency, and variability under identical operational conditions.

From a policy perspective, these findings support the integration of fiber-optic early-warning systems as a standard component of safety-critical movable infrastructure. Traditional maintenance practices, which are largely reactive and dependent on periodic manual inspections, are insufficient for systems that experience continuous dynamic loading and where early micro-failures can rapidly propagate into structural hazards. In contrast, fiber-optic sensing enables a proactive maintenance regime aligned with modern asset-management principles: continuous condition assessment, predictive failure modeling, and targeted intervention based on quantifiable risk indicators. Policies governing the operation of movable barriers should therefore mandate the implementation of distributed sensing as a core monitoring technology, along with clear protocols for threshold-based alerts, automated reporting, and integration with existing control systems.

Technically, the results confirm that high-resolution strain data not only enhances situational awareness but provides the analytical foundation for predictive modeling, allowing operators to identify trending behavior indicative of material degradation. The combination of spatially resolved strain maps and time-based comparative analysis establishes a robust platform for quantifying structural health in real time. This capability offers measurable improvements to system reliability, operational safety, and lifecycle performance. Moving forward, institutional adoption of this technology should be accompanied by investment in data analytics, automated diagnostics, and standardized calibration procedures to ensure consistency and interoperability across deployments.

In summary, the integration of fiber-optic sensing into movable barrier monitoring represents a significant advancement in both policy and practice. By transitioning from reactive maintenance to predictive, data-driven asset management, infrastructure operators can mitigate risk, extend system longevity, and ensure safer, more resilient barrier operations in line with contemporary engineering and safety standards.

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