



The HuT

The HuT innovative nexus monitoring activities – lessons learned

Deliverable D4.4

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AUTHORS

Guido Rianna (CMCC); Eisharc Jaquet (ARANTEC)

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Project Coordinator	Michele Calvello UNIVERSITA DEGLI STUDI DI SALERNO mcalvello@unisa.it
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3. Introduction

This Deliverable provides a comprehensive overview of the monitoring activities carried out across the ten Demonstrators (DEMs) of The HuT project within the framework of Task 4.2. For the purposes of this document, monitoring is understood in a broad sense, encompassing instrumental approaches based on in-situ sensors, the exploitation of freely available data sources such as Earth Observation products and atmospheric reanalyses, and community-based monitoring initiatives aimed at characterising vulnerability or documenting the spatial and temporal extent of hazard impacts. Regardless of the specific approach adopted, monitoring activities are always conceived as instrumental to broader Disaster Risk Reduction (DRR) objectives and are systematically linked to the goals for which they are conducted, whether supporting the development of predictive tools, feeding early warning systems, or informing decision-making processes at local and regional level.

This perspective is deeply rooted in the Nexus framework that constitutes the conceptual backbone of The HuT project. Monitoring does not represent an end in itself, but rather a means of connecting environmental observations with the scientific, technological, and governance dimensions that together define resilience to climate extremes. In this sense, the value of a monitoring activity is assessed not only in terms of data quality or spatial coverage, but in terms of its capacity to feed into the integrated understanding of hazard precursors, exposure, and vulnerability that the project seeks to advance.

The Deliverable is organised according to the structure of the ten Demonstrators. For each DEM, a brief introduction to the case study is provided, followed by a description of the monitoring activities conducted within the Task. The flagship activity is then identified and discussed in terms of its relevance within the Nexus framework, its innovative character, and its potential for amplification, understood as the possibility of replicating, scaling, or transferring the approach to other contexts. The section concludes with the lessons learned and a concise summary of the main outcomes.

It should be noted that not all DEMs have conducted activities that fall directly within the scope of monitoring as defined here. This is not a limitation of the project, but rather a reflection of the deliberate and context-sensitive approach that characterises The HuT philosophy. The selection of activities for each Demonstrator has been shaped by the specific vulnerability profile of the area, the maturity of solutions already in place, and the real socioeconomic context in which the project operates. The resulting portfolio is therefore by design not uniform: it represents an intentionally diverse and locally calibrated set of innovations. Moreover, in the spirit of the Nexus approach, several activities developed within other work packages have been valorised here where they contribute, directly or indirectly, to the monitoring objectives of the Task, further enriching the scope and coherence of this Deliverable.

4. Lessons learned from DEMs

4.1. DEM1 Valencia [Spain]

4.1.1. Introduction on the activities carried out on monitoring

The activities carried out within the DEM1 focused on understanding and modelling extreme events in the city and region of Valencia, particularly heatwaves, droughts, and the Urban Heat Island (UHI) effect. These activities combined climate modelling, satellite data analysis, and environmental forecasting tool to provide a comprehensive assessment of climate risks and their impacts on urban environments and vulnerable populations

Beyond the specific modelling activities reported in D4.5-6-7, in DEM1, a surface temperature map of the city was produced using Landsat 9 satellite imagery provided by NASA/USGS (data source: <https://earthexplorer.usgs.gov/>). The images are post-processed by using Google Earth Engine. The map features a spatial resolution of 30 meters and an acquisition frequency of less than one month, making it particularly suitable for monitoring the evolution of urban heat islands [Figure 1]. Land Surface Temperature (LST) was derived and combined with land use, land cover, and socio-demographic data (e.g., census sections, vulnerable populations, and sensitive urban spaces). This enabled the identification of spatial patterns of heat exposure, hot and cold spots, and their relationship with urban morphology and land cover. Statistical analyses (e.g., ANCOVA) were applied to quantify the influence of land cover on temperature.

Additional exploratory work included the study of tropical nights, heat mortality thresholds, and Local Climate Zones (LCZ), although these were set aside so that could focus on the previous topics.

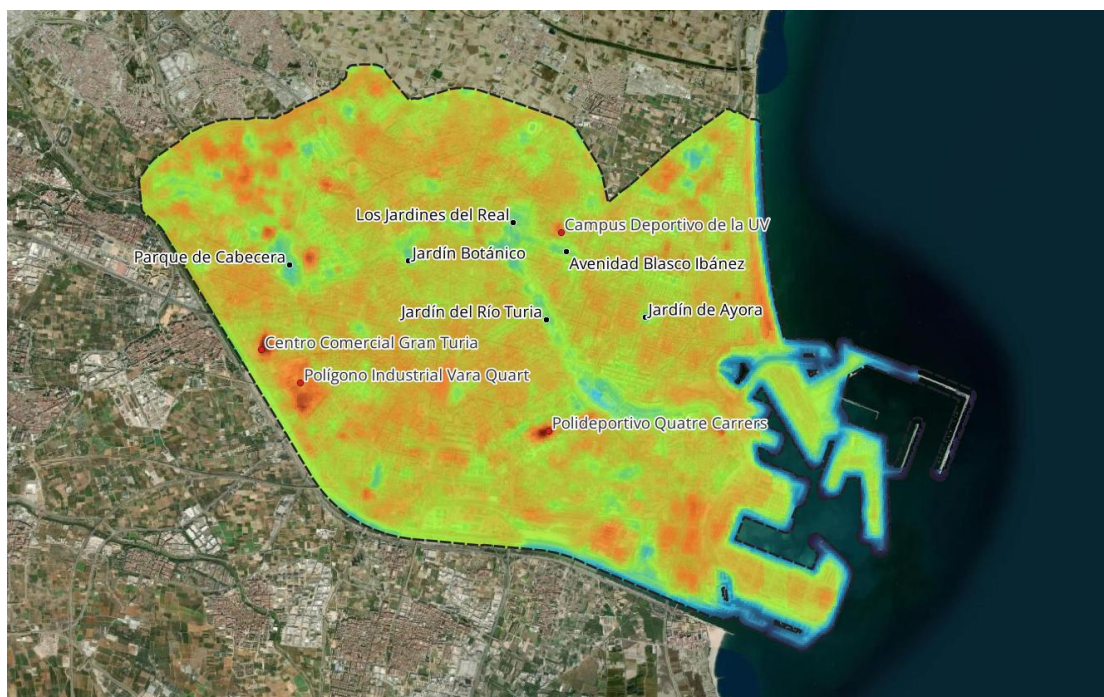


Figure 1: Surface temperature map for Heatwave affecting the municipality of Valencia (30/7/2022-14/8/2022); anomaly was about 3.5°C, Tmax about equal to 37 °C

4.1.2. Main features and the link with the Nexus

Understanding urban heat is highly relevant because heatwaves are one of the most critical climate hazards affecting urban populations, particularly in Mediterranean cities such as Valencia. Their impacts are not uniformly distributed across the urban fabric: the UHI effect amplifies thermal stress in dense and poorly vegetated areas, while socioeconomic vulnerability determines which population groups are most exposed to health risks. The ability to characterise heatwave dynamics at multiple scales, from large-scale climate projections down to the fine-grained spatial variability of land surface temperature within the city, is therefore essential for moving beyond aggregate risk assessments and identifying where and for whom heat constitutes a genuine threat. The innovation of this activity resides in the integration of satellite-derived land surface temperature data at 30 m resolution with land use, land cover, and sociodemographic information, enabling a spatially explicit and socially grounded analysis of urban heat exposure. By combining multi-model climate projections with high-resolution remote sensing, the approach bridges the gap between large-scale climate signals and the fine-scale thermal patterns that determine actual exposure at the neighbourhood level. The application of statistical methods to quantify the influence of land cover on surface temperature adds a layer of analytical rigour that goes beyond descriptive mapping, allowing the relative contribution of different urban elements to be disentangled and assessed. Crucially, this is not a retrospective exercise: the framework is designed to support forward-looking analysis by feeding climate projection outputs into the same spatial monitoring infrastructure, enabling an assessment of how heatwave dynamics may evolve under different emission scenarios.

This activity strengthens the Nexus by establishing a direct and operational link between environmental monitoring, urban systems, and social vulnerability. Surface temperature data derived from satellite imagery are not treated as an end product but as an input into a broader analytical chain that connects physical hazard characterisation with urban planning, adaptation strategy design, and the identification of priority intervention areas. The explicit attention to Sensitive Urban Spaces and their differential thermal exposure ensures that the monitoring outputs are relevant not only to technical users but also to local administrators and civil protection agencies responsible for protecting the most vulnerable segments of the population. In this sense, the activity exemplifies the Nexus vision of The HuT: monitoring is instrumental to DRR and acquires its full value only when embedded in a system that connects observations to decisions.

The implementation followed a sequential and integrated workflow. The analysis drew on a combination of ERA5 and ERA5-Land reanalysis data, Landsat 9 satellite imagery at 30 m resolution, land cover information from the COSCV (Cartografía de Ocupación del Suelo de la Comunitat Valenciana) dataset, and sociodemographic data at census section level. Heatwaves were characterised using percentile-based threshold definitions aligned with the criteria adopted by the Conselleria de Sanitat of the Generalitat Valenciana, and key indicators including duration, intensity, frequency, and risk level were computed across multiple climate models and emission scenarios. Land Surface Temperature was then retrieved from the satellite imagery and integrated with land cover and vulnerability data to produce spatially explicit maps of urban heat exposure. The influence of land cover on surface temperature was quantified through ANCOVA, allowing a statistically grounded interpretation of the spatial patterns observed across the urban fabric, including the identification of hot and cold spots associated with specific urban elements and green spaces.

4.1.3. The HuT amplification and how to improve the approach

The approach developed in DEM1 carries significant transferability potential. The satellite-based urban heat monitoring framework is applicable to any city for which Landsat imagery and basic



sociodemographic data are available, and the methodology can in principle be extended to other climate hazards beyond heatwaves, including tropical nights and minimum temperature extremes.

At the same time, several limitations constrain the transferability of the approach in its current form. The mismatch between the spatial resolution of the thermal data (30 to 100 metres) and the coarser scale of available sociodemographic information introduces uncertainty in the characterisation of population exposure at the finest scales. The limited density of ground-based weather stations makes validation of surface temperature retrievals across different Local Climate Zones difficult, requiring assumptions that reduce the precision of the analysis.

Several lines of work initiated during the project remained not fully developed. The analysis of tropical nights and minimum temperature extremes needs reaching an higher level of maturity as the heatwave and UHI components, and the integration of Local Climate Zones into the urban classification framework was not fully achieved. The inclusion of heat mortality thresholds at neighbourhood scale and the modelling of air temperature at fine spatial resolution using differential approaches such as UrbClim represent clear directions for future development.

4.1.4. Take-home messages

The activities conducted in DEM1 demonstrate that understanding urban heat requires simultaneous consideration of multiple scales, from the large-scale climate signal that determines the frequency and intensity of heatwave episodes to the fine-grained spatial variability within the city that determines who is actually exposed and to what degree. By combining climate projections, satellite-derived surface temperature data, and sociodemographic information, the DEM has shown that heatwaves are not a future threat but a present reality, already increasing in frequency, intensity, and duration, and that their impacts are shaped far more by land use, urban morphology, and vegetation cover than by simple proximity to the city centre. Vulnerable populations are systematically exposed to higher temperatures, a finding with direct implications for the design of targeted adaptation interventions.

4.2. DEM2 Val d'Aran Region [Spain]

4.2.1. Introduction on the activities carried out on monitoring

The monitoring activities in DEM2 focused on expanding and strengthening the environmental sensor network in the Val d'Aran region to improve spatial data coverage, test communication technologies in remote areas, and incorporate new variables into the modelling framework. A dual deployment strategy was followed. Type 1 devices were installed near existing stations to enable data comparison and validation, improving measurement reliability. Type 2 devices were deployed in previously unmonitored areas to extend spatial coverage and capture environmental variability across different elevations. The monitoring stations measure key variables including soil moisture, air temperature, relative humidity, and rainfall. Soil moisture is particularly relevant, as it provides critical insight into hydrological processes such as snowmelt, accumulated precipitation, and their influence on runoff generation and slope stability. Six stations were installed across a wide altitudinal range, allowing improved representation of mountain processes. The deployment involved full installation procedures, including site preparation, sensor placement, and integration with data acquisition nodes. Existing infrastructures were reused, when possible, to optimize costs and efficiency. The system uses LoRaWAN communication technology, enabling reliable data transmission in remote areas without conventional coverage. Stations are powered by photovoltaic systems and transmit data hourly.



These activities aim to generate a more comprehensive dataset to support future model calibration, validation, and improvement. In particular, the inclusion of soil moisture allows analysis of its correlation with snowmelt and rainfall, enhancing model performance once sufficient long-term data is available.

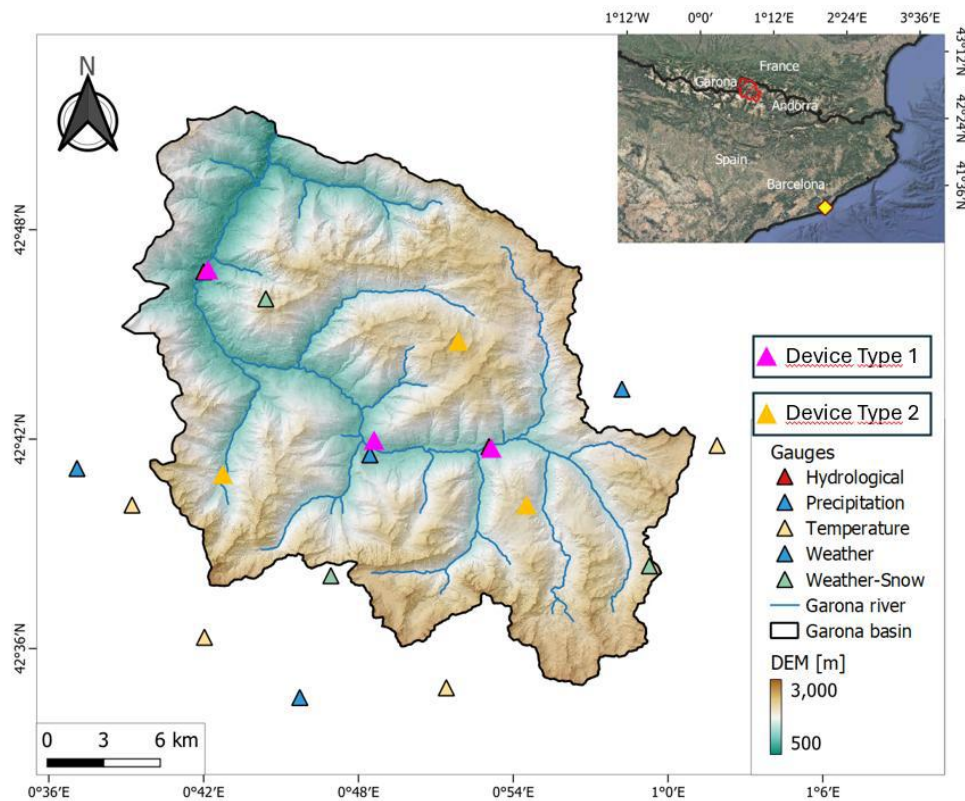


Figure 2: Location of monitoring stations from the regional official networks and installed within the framework of The HuT Project (big triangles); pink: volumetric water content, temperature and relative humidity, yellow: rainfall, volumetric water content



Figure 3: Installation of new monitoring stations within the DEM2 (from left to right: excavation for sensor installation, installed weather station, researchers engaged in sensor installation, volumetric water content sensors installed horizontally on the excavation face).

4.2.2. Main features and the link with the Nexus

The flagship monitoring activity of DEM2 is the design, installation, and operation of an expanded environmental sensor network in the Val d'Aran region, conceived to address critical gaps in spatial coverage and variable representation that constrained the capacity of existing systems to adequately characterise the hydrometeorological conditions driving flood and landslide hazards in this complex alpine environment. In a region where heavy precipitation events and snowmelt dynamics can simultaneously trigger flooding in valleys and destabilise slopes, the availability of reliable and spatially distributed observations of rainfall, soil moisture, air temperature, and relative humidity across a wide altitudinal range is a prerequisite for any credible early warning capability.

The innovation of the monitoring activity resides in its dual deployment strategy, combining stations installed near existing reference points to enable data comparison and validation with stations placed in previously unmonitored remote areas to extend spatial coverage into elevation zones not reached by the official regional network. The use of LoRaWAN communication technology for data transmission in areas without conventional mobile coverage, paired with solar-powered autonomous operation, represents a practical and replicable solution for instrumentation in high-mountain environments where access and connectivity are structurally limited. Soil moisture, a variable entirely absent from the pre-existing monitoring framework, was introduced as a key observable, reflecting its recognised role as a predisposing factor for both runoff generation and slope instability. The monitoring network was not designed in isolation but as an integral component of the broader early warning system, with station locations and variable selection driven by the data needs of the hydrological and slope stability models it is intended to feed.

The monitoring network contributes to the Nexus by providing the observational foundation upon which the predictive and decision-support components of the DEM rest. Without spatially representative and temporally continuous measurements of the key hydrometeorological variables driving hazard dynamics in the Val d'Aran, the modelling framework would lack the ground truth necessary for calibration, validation, and operational reliability. In this sense, the monitoring activity is not ancillary to the early warning system but constitutive of it: it transforms the system from a modelling exercise into an operationally grounded tool capable of generating forecasts that emergency managers and local authorities can trust and act upon. The integration of monitoring data into the Portal (WP1) further ensures that observations are not only used internally for model development but are made accessible in a format that supports situational awareness and informed decision-making at the local level.

4.2.3. The HuT amplification and how to improve the approach

The monitoring network was deployed following a systematic approach that prioritised both technical robustness and spatial representativeness. Installation procedures included full site preparation, sensor placement, and integration with data acquisition nodes, with existing infrastructure reused where possible to optimise costs and efficiency. Six stations were instrumented across a wide altitudinal range, ensuring that the monitoring network captures the variability of hydrometeorological conditions characteristic of mountain catchments where elevation-dependent processes, including snowmelt and orographic precipitation, play a dominant role. Data are transmitted hourly via LoRaWAN to a centralised system, enabling continuous availability of observations for both operational and research purposes. The progressive expansion of the network was accompanied by iterative engagement with the Conselh Generau d'Aran and local emergency management authorities, ensuring that station locations and monitored variables remained aligned with the operational needs of the early warning system under development.



The monitoring approach demonstrates meaningful potential for replication in other mountain regions facing similar challenges of sparse network coverage, remote accessibility, and the need to observe soil moisture alongside conventional meteorological variables. The reliance on LoRaWAN communication, solar power, and commercially available low-cost sensors reduces the barriers to adoption in resource-constrained contexts and makes the configuration transferable without requiring bespoke infrastructure. Scaling up to larger regions would demand a proportional increase in station density to maintain spatial representativeness, while scaling down to smaller catchments may require careful reconsideration of variable selection and sensor placement to capture the dominant processes at finer scales. The main constraint on replication is not technological but institutional: sustained operation of the network beyond the project timeline requires local ownership, maintenance capacity, and a clear integration pathway into existing regional monitoring frameworks.

Earlier engagement with national meteorological services and regional civil protection agencies would have facilitated smoother integration of the newly installed stations into existing operational monitoring infrastructures, increasing data accessibility and institutional legitimacy from the outset. Greater attention to connectivity assessment and power supply dimensioning during site selection would have reduced the risk of data gaps, particularly during winter periods when solar irradiance is limited and transmission reliability is most critical. In retrospect, a more systematic effort to document and share the practical lessons learned during installation, including sensor intercomparison and calibration procedures, would have generated a more transferable methodological output for other DEMs and future projects operating in comparable environments.

4.2.4. Take-home messages

The monitoring activities conducted in DEM2 demonstrate that expanding observational coverage in data-sparse mountain environments is not only technically feasible but operationally essential for any credible multi-hazard early warning capability. The installation of six autonomous sensor stations across a wide altitudinal range in the Val d'Aran region, measuring soil moisture alongside conventional meteorological variables and transmitting data continuously via LoRaWAN, has provided the observational foundation that the hydrological and slope stability models underpinning the early warning system require to move from research prototype to operational tool. The deliberate inclusion of soil moisture as a monitored variable reflects a broader lesson that applies well beyond this specific case: predisposing conditions matter as much as triggering forcings, and early warning systems that ignore antecedent wetness state will systematically underperform in environments where saturation dynamics govern hazard initiation.

The experience also highlights that the technical dimension of monitoring, however important, is only part of the challenge. Sustained operation beyond the project timeline depends on institutional buy-in, local maintenance capacity, and a clear integration pathway into existing regional frameworks, none of which can be established at short notice. The Val d'Aran case offers a replicable template for low-cost, autonomous, and spatially distributed monitoring in alpine catchments, but its most transferable lesson may be that monitoring networks are most valuable when they are designed from the outset around the decisions they are meant to inform.

4.3. DEM3 Lattari Mountains [Italy]

4.3.1. Introduction on the activities carried out on monitoring

The DEM3 pilot case focuses on the Monti Lattari area, located in the southern part of the Campania Region, southern Italy. The area encompasses territories of outstanding naturalistic and



historical-architectural value, including Sorrento and Amalfi, which attract large numbers of tourists from around the world. At the same time, the area is widely recognized as highly vulnerable to hydrogeological hazards of meteorological origin, primarily due to its distinctive geomorphological characteristics. A large portion of the hillslopes in the area are mantled by pyroclastic deposits resulting from past eruptions of the Somma-Vesuvius and Campi Flegrei volcanic complexes. The actual stratigraphy is therefore a function of successive eruptive events, which produced layers of ash and pumice of varying thickness. These materials, owing to their high water retention capacity and mineralogical composition, have made the area exceptionally fertile; however, they are also widely susceptible to shallow landslide initiation and debris flow triggering. In recent decades, such phenomena have caused substantial damage and loss of life. Among the most catastrophic events in Italy's recent history, the May 1998 disaster in Sarno involved geologically analogous terrains and stands as a benchmark reference for this type of hazard. Similarly, the geographical setting and the presence of small mountain catchments make the area prone to flash flooding and convective rainfall events. Multiple hazard catalogues —ISPRA web platform on landslides and floods (<https://idrogeo.isprambiente.it/app/>), FranelItalia (<https://zenodo.org/records/15144334>), ITALICA (<https://zenodo.org/records/8009366>)—consistently document the occurrence of these phenomena across different seasons and across different parts of the area. Despite this well-documented hazard profile, significant monitoring gaps remain. The spatial extent of the area and the difficulty of access make it challenging for official networks to adequately capture both the driving forces and the system response. Rainfall, which exhibits strong spatial variability across the territory, is not adequately represented by the official rain gauge network. Volumetric water content, on the other hand, is not currently part of the monitoring system operated by the Campania Region, despite its widely recognized role as a proxy for antecedent conditions and a predisposing factor for landslide initiation. Compounding these gaps are technology-specific challenges related to sensor selection, data transmission, storage, and post-processing. Open questions include: which variables should be monitored and at which transects; how reliable is the official sensor calibration; and how can data be used when independent recalibration is not feasible? A further critical need is the development of an impact catalogue that is continuous in both time and space, capable of capturing damage to infrastructure and associated disruptions to mobility that are systematically underrepresented in national databases.

In light of these challenges, identified and discussed with local actors through multiple rounds of stakeholder consultation, two main lines of action were pursued: complementing the existing monitoring network by testing the robustness of different commercial solutions across a range of price points, and adopting community monitoring approaches to improve impact data coverage. With respect to monitoring, activities focused on the installation of field monitoring stations designed to measure volumetric water content and soil suction, thereby characterizing both the quantity and the energy state of water in the soil, together with rainfall as the primary forcing variable and streamflow in small torrential watercourses that drain from the inland valleys toward the inhabited coastal zones. The study areas selected are those of Sorrento and Amalfi. This choice reflects several considerations: the two municipalities are arguably the most representative and internationally recognized localities within the DEM3 area; both have a documented history of geohydrological events; and local stakeholders have demonstrated a proactive attitude, granting access to monitoring sites, providing logistical support, and offering ongoing feedback on the activities carried out.

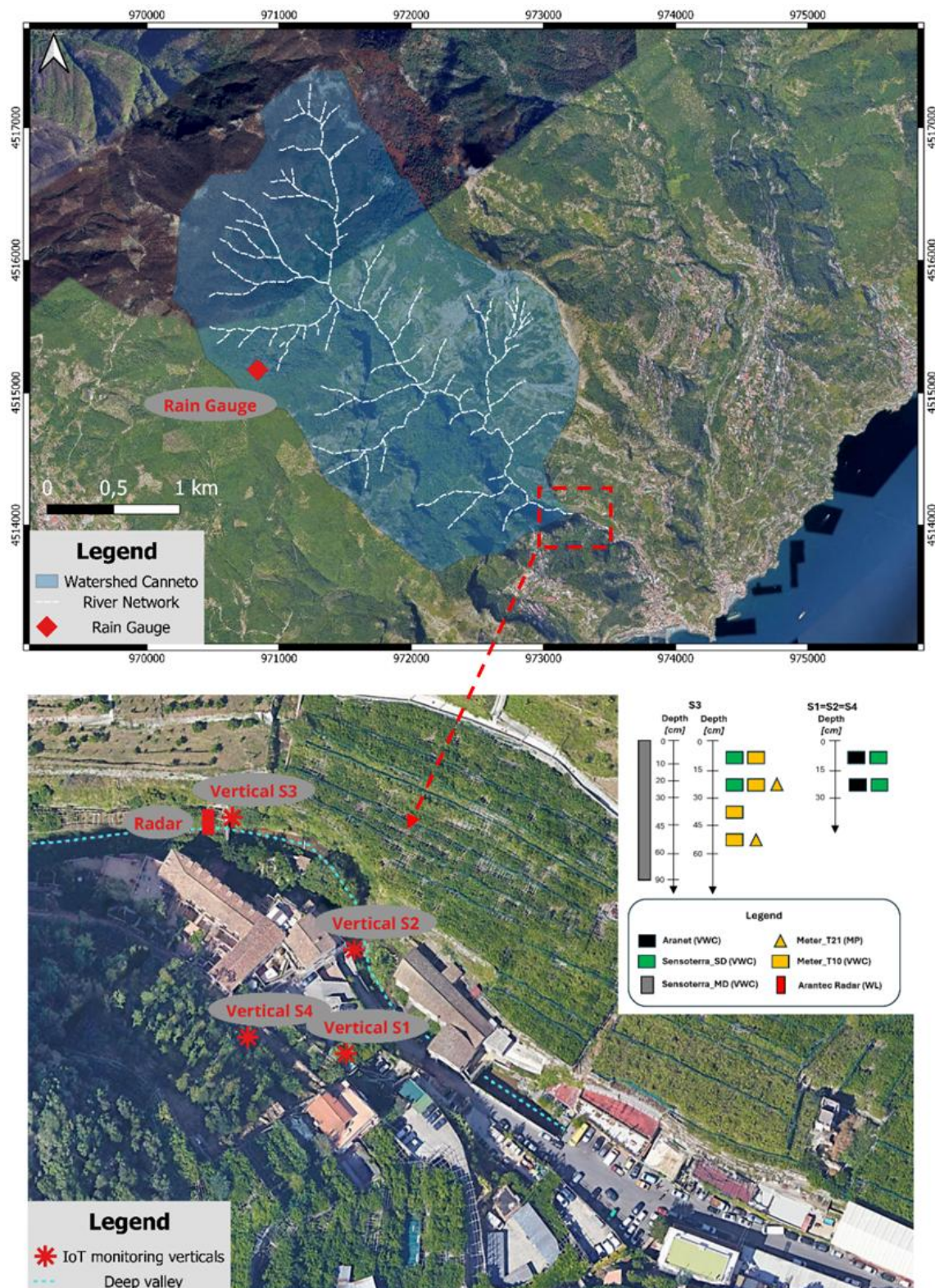


Figure 4: Layout of the IoT monitoring network installed in the Canneto catchment (Amalfi).
Legend: VWC: volumetric water content; MP: matric potential; WL: water level.

The community monitoring activity is based on a dedicated application developed within the KoBoToolbox collaborative development environment. The KoBoToolbox app enables the collection of georeferenced reports, photographs, and additional descriptive information related to hydrogeological events and their impacts. Once the KoBoToolbox app has been downloaded — available for both iOS and Android — users can access the specific project form directly within the platform. Registration on the KoBoToolbox platform is required to submit reports, though no dedicated registration for the project itself is necessary. A tutorial, provided in both video and slide formats, was developed and shared with local stakeholders. The dissemination was carried out deliberately through local associations rather than directly through the municipal civil protection authority, in order to avoid any overlap or ambiguity between institutional roles and citizen reporting activities. A new data collection campaign will be conducted across the Sorrento and Amalfi pilot areas during the summer of 2026, with the aim of expanding the impact dataset and further engaging the local community in systematic hazard reporting.

4.3.2. Main features and the link with the Nexus

The flagship monitoring activity of DEM3 consists of the installation and operation of an integrated field measurement network across the Sorrento and Amalfi study areas, targeting three key variables: rainfall, volumetric water content, and streamflow. A rain gauge installed in the upstream portion of the Amalfi catchment fills a spatial gap in the official regional network and provides antecedent precipitation information relevant to nowcasting activities in the downstream municipal area. Soil moisture monitoring profiles have been deployed in the Vallone delle Ferriere area immediately upstream of Amalfi, where the concentration of multiple measurement verticals within a spatially limited and geologically homogeneous site creates an open-air laboratory enabling direct inter-sensor comparison under nearly identical conditions. Streamflow is monitored on small torrential watercourses that flow through the historic centres of both municipalities before reaching the sea through culverted sections, a configuration that makes rapid discharge increases particularly hazardous for the urban areas downstream. An analogous setup has been replicated in the Sorrento area, where rainfall, soil moisture, and streamflow are monitored in the upstream catchment and at the Vallone dei Mulini immediately adjacent to Piazza Tasso.

The monitoring approach is characterised by two elements of innovation that distinguish it from conventional instrumentation campaigns. The first concerns the use of volumetric water content measurements: rather than seeking absolute soil moisture values in a strict metrological sense, the network is designed to detect deviations from climatological conditions that can serve as switching criteria between warning phases, for instance from pre-alert to full alert, or as a binary threshold indicator. This pragmatic reframing of measurement objectives is particularly appropriate given the calibration uncertainties inherent in FDR sensors deployed in volcanic soils, for which manufacturer calibration functions derived from broader soil datasets carry non-negligible uncertainty. The second element of innovation concerns the role attributed to streamflow, which is exploited not only as a hydraulic indicator of potential criticality in the monitored watercourses but also as an integrative proxy for the overall wetness state of the catchment and therefore for its predisposition to geo-hydrological hazard initiation, consistent with recent literature formalising this dual function (Mirus et al., 2025).

The monitoring network was designed in close and iterative dialogue with local stakeholders in both municipalities, who contributed to the identification of measurement locations, recognised streamflow monitoring as a locally critical need given the torrential character of the watercourses, and provided logistical support for power supply and data transmission. This co-design process ensures that the monitoring outputs are directly relevant to the decision-making responsibilities that municipalities bear under Italian civil protection legislation, where mayors hold direct



accountability for local risk management yet currently receive hazard information almost exclusively from regional and national sources. By providing locally grounded, high-resolution observations of the variables most relevant to geo-hydrological hazard initiation, the network bridges the gap between large-scale alert systems and the specific conditions of individual catchments. Data are made accessible to local decision-makers through the WP1 desktop and smartphone application, embedding the monitoring outputs directly into the operational tools available to those who need them most.

Variable selection and station placement were defined jointly with local stakeholders, whose involvement was essential both for identifying representative monitoring cross-sections and for securing the logistical support that made installation possible. The implementation was nonetheless affected by significant delays attributable to bureaucratic procurement procedures and protracted negotiations with suppliers, compounded by the absence of dedicated field teams: all installation activities were carried out by UNISA and CMCC staff alongside their regular institutional commitments. These structural constraints, while reflecting the genuine commitment of the teams involved, represent a limitation that should be explicitly factored into the planning of analogous activities in future projects.

4.3.3. The HuT amplification and how to improve the approach

The monitoring configuration developed and tested in the Sorrento and Amalfi pilot sites was conceived from the outset with replication in mind. The geomorphological homogeneity of the Monti Lattari territory across large portions of the area means that the approach can in principle be transferred to additional sites without fundamental redesign, making horizontal scaling within the DEM area a realistic near-term prospect. At the same time, the activity embodies a form of downward scaling that is perhaps its most distinctive feature: rather than adding a new layer of observation to an already instrumented landscape, the network is designed to provide the sub-catchment scale information that regional and national systems are structurally unable to deliver, embedding locally grounded observations directly into the predictive tools and decision processes of the existing early warning framework. The monitoring is therefore not conceived as an alternative to institutional systems but as a targeted complement to them, filling the spatial and variable gaps that those systems leave unaddressed.

The deliberate choice to test sensors from multiple manufacturers across a range of price points has generated comparative insight into the relative performance of different solutions under the specific conditions of volcanic soils, representing in itself a transferable output for future deployments in analogous environments. The experience has also surfaced a set of practical lessons that should systematically inform the design of similar networks: connectivity conditions must be assessed carefully during site selection, with explicit attention to the reliability of mobile network coverage at each location, and power supply dimensioning must account for seasonal variability in solar irradiance and for extended periods of reduced insolation during winter. The most significant unresolved challenge, however, is institutional rather than technical. Despite repeated attempts throughout the project, engagement with regional and national level authorities did not yield the outcomes sought. Broadening institutional buy-in beyond the municipal scale remains an open priority: without it, the pathway from a well-functioning local monitoring network to a formally integrated component of the regional early warning system will remain incomplete.

4.3.4. Take-home messages

The monitoring activities conducted in the DEM3 Monti Lattari pilot case addressed two well-documented structural gaps in the existing hazard observation framework: insufficient spatial coverage of rainfall forcing and the complete absence of soil moisture monitoring from the official



regional network. Field stations measuring volumetric water content using Frequency Domain Reflectometry (FDR) technology, rainfall, and streamflow were installed in the Sorrento and Amalfi areas, complemented by a community monitoring application developed in KoBoToolbox for georeferenced impact reporting. The design of the monitoring network was shaped from the outset by iterative stakeholder engagement: variable selection, site identification, and logistical arrangements were all co-defined with local actors, who also secured power supply and data transmission support. Two elements distinguish this approach as innovative. First, measurements are not intended to provide absolute soil moisture values but to detect anomalies with respect to climatological baselines, enabling their use as switching criteria between warning phases — a practical and robust application given the inherent calibration uncertainties of commercial FDR sensors in volcanic soils. Second, streamflow is exploited not only as a hydraulic indicator but as a catchment-scale proxy for predisposing wetness conditions, consistent with recent literature. Key lessons learned include the importance of assessing connectivity and solar irradiance conditions during site selection, the significant overhead introduced by procurement bureaucracy and the absence of dedicated field teams, and the persistent difficulty of engaging authorities beyond the municipal scale despite repeated attempts. The monitoring configuration is replicable across the Monti Lattari area given its geomorphological homogeneity, and the data feed directly into the WP1 operational platform, embedding local observational capacity into the broader project decision support infrastructure.

4.4. DEM4 Vilnius [Lithuania]

4.4.1. Introduction on the activities carried out on monitoring

The monitoring activity conducted in DEM4 departs from the sensor-based approaches adopted in most other Demonstrators and is instead grounded in the systematic reconstruction of a pluvial flood impact catalogue for the city of Vilnius, covering the period from 2013 to 2024.

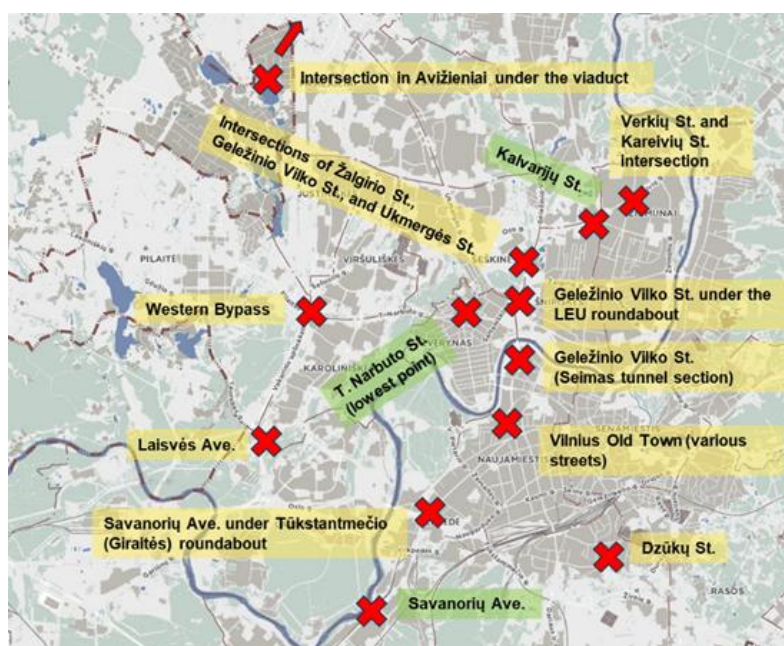


Figure 5: Identification of hot-spots, areas affected by pluvial flooding events in the city center of Vilnius.

In the absence of officially collected and structured impact data, publicly available information sources, including media reports, municipal communications, and other open channels, served as the primary means of documenting historical flooding events. Each record was structured according to time of occurrence, affected streets, and type of reported damage, and cross-checked against meteorological precipitation data from Vilnius stations to establish the link between observed impacts and intense rainfall episodes. The compiled dataset encompasses 48 heavy rainfall events, of which 38 are associated with detailed location information and 21 met the criteria for hazardous or severe precipitation intensity. The result is a spatially referenced impact record that, despite its inherent limitations, provides the most comprehensive overview of pluvial flood dynamics in the urban area currently available.

4.4.2. Main features and the link with the Nexus

The relevance of this activity lies in the recognition that impact data are themselves a form of monitoring output, and that their systematic collection and analysis can yield information on hazard hotspots, temporal trends, and the effectiveness of infrastructure interventions that no sensor network alone could provide. The approach is innovative in treating publicly available, unstructured information as a legitimate and analytically rigorous data source, integrating heterogeneous records into a coherent long-term database rather than analysing individual events in isolation. The identification of recurrent flooding hotspots and the documented reduction in impacts following stormwater infrastructure upgrades on specific streets demonstrate that the catalogue is capable of supporting evidence-based assessment of both risk concentration and intervention effectiveness, two outputs of direct operational relevance for urban planners and municipal decision-makers.

The impact catalogue strengthens the Nexus by connecting hydrometeorological observations with the urban infrastructure and governance dimensions of pluvial flood risk. By mapping where flooding occurs repeatedly and linking those locations to precipitation records and infrastructure conditions, the activity provides decision-makers with the kind of locally specific, historically grounded evidence needed to prioritise investments, evaluate the effectiveness of past measures, and design more resilient urban drainage systems. The results were presented at the Vilnius DRR Forum in March 2025, bringing together national and municipal decision-makers, infrastructure managers, scientists, urban planners, and local communities, an event that exemplifies the Nexus aspiration of connecting scientific outputs directly to governance and planning processes.

4.4.3. The HuT amplification and how to improve the approach

The activity was carried out in several stages, beginning with systematic data collection from publicly available sources and progressing through structured analysis of time, location, and impact type for each identified event. Cross-referencing with meteorological station data enabled verification of the rainfall-impact relationship, while trend analysis assessed how impacts have evolved over time in relation to infrastructure developments. The methodology was refined iteratively in response to the limitations of the available data, including fragmented records, potential media coverage bias, duplication of reports, and the limited spatial representativeness of the meteorological station network for capturing localised intense rainfall events.

The primary strength of this approach from a replication standpoint is its low barrier to entry: it requires no dedicated instrumentation, relies entirely on data that are increasingly available in most urban contexts, and can be implemented even where formal monitoring systems are absent or inaccessible. The methodology is transferable to other cities facing similar challenges of data scarcity and is particularly valuable as a first-order diagnostic tool for identifying priority areas before more resource-intensive monitoring or modelling investments are made. Its main limitation

for scaling is the time and effort required for manual data collection and verification, and the potential inconsistency of media coverage across different periods and contexts, which introduces biases that are difficult to fully correct without additional data sources.

The application of text analysis or artificial intelligence tools to automate the identification and extraction of relevant reports from large volumes of unstructured data would substantially reduce the manual effort involved and improve the reproducibility and scalability of the approach. Integration of radar-based precipitation data or observations from additional meteorological stations, including private networks, would improve the spatial resolution of the rainfall characterisation and reduce the risk of missing localised events not captured by the official gauge network. More structured collaboration with municipalities, infrastructure operators, and insurance companies from the outset would have improved data quality and provided access to records that remain outside the public domain, addressing one of the most persistent limitations of the approach.

4.4.4. Take home messages

This activity demonstrated that even when using non-traditional data sources, valuable insights into urban resilience to extreme rainfall can be obtained. The compiled dataset enabled the identification of recurrent pluvial flood “hotspots” in Vilnius and supported the assessment of the impacts of infrastructure changes. Although the method has limitations related to data accuracy and the complexity of data collection, it provides a flexible and easily adaptable tool for urban risk analysis. This approach can be further developed through the integration of automation solutions and additional data sources, thereby strengthening decision-making and urban resilience planning.

It also highlighted the need to improve the exchange of impact-related data between different institutions (e.g. municipality, university, insurance, NGOs) Considering the projected increase in extreme precipitation due to climate change, such approaches are becoming increasingly important for future urban resilience planning.

4.5. DEM5 Schleswig-Holstein State [Germany]

The Schleswig-Holstein State Demonstrator (DEM5) did not commit to monitoring activities. However, leveraging the Nexus approach, a “Buddy System” citizen science initiative was designed, and some preliminary tests were conducted in Glückstadt, a relatively small town of 14,000 people with well-connected neighborhoods. The initiative was primarily aimed at the most vulnerable segments of the population, including immigrants, the elderly, and people with disabilities, as these groups may struggle to access messages shared via social media or other technologies. The system, if implemented operationally, is expected to ensure that well-informed and/or physically capable citizens take on the responsibility of properly alerting vulnerable individuals and making sure they have the necessary resources to cope with the emergency.

4.6. DEM6 East fjords [Iceland]

4.6.1. Introduction on the activities carried out on monitoring

The flagship activity of DEM6 focuses on the analysis and operational integration of the extensive monitoring network already in place in Seyðisfjörður, where a comprehensive array of



instruments, including automatic weather stations, weather radar, snow sensors, borehole water-level gauges, soil moisture sensors, inclinometers, GNSS stations, ground-based InSAR radar, and extensimeters, provides a continuous and spatially distributed record of the hydrometeorological and ground-deformation conditions governing landslide dynamics. The core contribution of The HuT project in this DEM has been not the deployment of new sensors but the development of a rigorous analytical framework to extract operational meaning from the data these instruments generate, translating heterogeneous and complex monitoring signals into coherent, actionable indicators for early warning purposes. This work was carried out in close collaboration with the Norwegian Geotechnical Institute, which contributed substantially to the methodological design and calibration approaches adopted. The modelling components that build on this monitoring foundation are discussed in the companion Deliverable D4.7.



Figure 6: Monitoring stations in Seyðisfjörður; it represents a clear example of diffuse monitoring including, among the others, extensimeters, sensors for soil volumetric water content and temperature, discharge levels, weather stations (DEM6)

4.6.2. Main features and the link with the Nexus

The innovation of this activity resides in the integration and normalisation of fundamentally different types of monitoring data within a single operational framework. Precipitation records from three rainfall stations, groundwater-level time series from twelve borehole monitoring points, and antecedent rainfall indices with effective memory over a decadal horizon are brought together within an integrated threshold framework that addresses both shallow rainfall-induced landslides and deep-seated slope instability processes driven by prolonged hydrological loading. A conceptual tank model was developed to translate borehole water-level observations into a dimensionless proxy for slope saturation, enabling direct cross-sensor comparison across elevation zones and providing an intuitive, physically interpretable indicator of hydrological loading that supports duty staff in routine monitoring. Antecedent precipitation calculations were implemented directly within the live monitoring system, updating continuously from sub-hourly gauge observations rather than relying on the daily precipitation totals used by the previous, separately maintained analytical system. This represents an operational advance over previous approaches applied in Iceland. All threshold methods and hydrological indicators were operationalised within a Grafana-based environment, enabling near-real-time visualisation of

threshold exceedance, automatic classification into warning levels, and continuous tracking of sustained critical conditions.

The activity strengthens the Nexus by establishing a direct and transparent link between environmental monitoring data and operational decision-making within the institutional framework of the Icelandic Meteorological Office, which bears statutory responsibility for issuing hazard warnings in Iceland. By transforming raw and heterogeneous monitoring signals into coherent, continuously updated indicators that are accessible through a structured visualisation platform, the activity reduces the interpretive burden on duty forecasters and supports more consistent and timely communication with emergency services and local authorities. The monitoring framework is instrumental to the broader DRR objectives of the DEM precisely because it does not operate in isolation: it is embedded within the institutional processes through which IMO issues hazard warnings, which in turn inform the protective measures, including evacuations, decided upon by civil protection authorities and local police.

4.6.3. The HuT amplification and how to improve the approach

The approach shows potential for transferability, as it is largely sensor-agnostic and relies on commonly available datasets, primarily precipitation and groundwater-level observations. This makes the methodology applicable in regions where basic hydro-meteorological monitoring is in place. In terms of scalability, the conceptual tank model and associated threshold framework are applicable only in areas with sufficient sensor coverage and long data series, particularly multiple groundwater-level observations, as the reliability of the approach depends strongly on the availability and spatial density of monitoring data.

Historical datasets covering the landslide inventory back to 1990, precipitation records from three stations with differing periods of availability, and groundwater-level time series from twelve boreholes were analysed to derive site-specific threshold values for both shallow and deep-seated processes. The constraints imposed by the limited temporal overlap between monitoring stations and the landslide inventory were explicitly acknowledged in the calibration procedure. Threshold methods, antecedent precipitation indices, and the tank model were subsequently implemented in Grafana, where they are continuously updated using live meteorological and groundwater data.

Several limitations of the current framework must be recognised. The approach is strongly data-dependent, as robust threshold definition and normalisation require long and continuous time series, which may not be available at all sites. Threshold values are also highly site-specific and require local calibration, meaning they cannot be transferred directly without adjustment to local geological, hydrological, and climatic conditions. Earlier integration of the tank model framework into the sensor network design would have allowed borehole placement to be optimised for spatial representativeness across elevation zones, rather than adapted retrospectively to an existing configuration. A longer overlap period between successive monitoring systems would similarly have reduced the uncertainties associated with historical normalisation and threshold calibration. The timing of a major database migration late in the project constrained the implementation of several planned enhancements, though the transition to PostgreSQL has created a significantly more interoperable and extensible infrastructure that positions the system well for future development.

Looking forward, the most consequential development is the planned live factor-of-safety slope stability indicator, designed as the operational endpoint of the monitoring chain. The aim is a continuously updated stability indicator in Grafana that combines hydrological loading from borehole observations and the tank model with "surface deformation from GNSS and total station prism measurements and subsurface movement from inclinometers and extensometers,

providing duty staff with a single integrative indicator linking observed loading to observed slope response. Sensitivity analysis on the FoS inputs is planned as the link between modelling and monitoring design, identifying which sensors dominate the stability calculation and thereby guiding sensor weighting and prioritisation within the operational framework. Full live operationalisation awaits the completion of automated data transfer from the full set of contributing sensors.

The most important unresolved limitation, however, remains the implicit treatment of snowmelt and rain-on-snow dynamics, which are among the dominant triggering and preconditioning factors for landslides in Iceland yet remain poorly represented due to limited snow and meltwater observations. Addressing this gap through integration with numerical weather prediction outputs and hydrological runoff models is the most impactful direction for future development of the input side of the framework.

4.6.4. Take home messages

The main outcome of this activity is the strengthening of an existing operational monitoring and warning framework through targeted analytical and integration improvements. IMO operates the Seyðisfjörður monitoring instrumentation and bears statutory responsibility for landslide warnings in Iceland; the contribution of HuT was to extract more operational value from the existing monitoring network by developing a conceptual tank model for borehole observations, embedding antecedent precipitation calculations directly into the live monitoring system, and implementing all hydrological indicators within a Grafana-based environment. This shifted several previously offline analytical workflows into continuously updated operational indicators accessible to duty staff during routine monitoring.

The most transferable lessons are methodological. The approach demonstrates that meaningful operational gains can be achieved by extracting more value from existing monitoring infrastructure rather than through the deployment of additional sensors. It also shows that the value of analytical tools depends as much on their integration into established institutional warning processes as on their individual technical sophistication.

Two limitations point clearly to future work. First, deformation measurements from GNSS and InSAR are not yet integrated into the threshold logic; linking hydrological loading indicators to observed slope response is the most direct path to a more physically grounded warning framework. Second, the implicit treatment of snowmelt and rain-on-snow dynamics — among the dominant triggering factors for Icelandic landslides — remains the most consequential unresolved gap. Addressing it through integration with numerical weather prediction outputs and hydrological runoff models is the most impactful direction for future development.

4.7. DEM7 Tisza River Basin [Hungary]

4.7.1. Introduction on the activities carried out on monitoring

The flagship monitoring activity of DEM7 is grounded in the extensive observational infrastructure operated by the Middle Tisza District Water Directorate, which maintains a network of WMO-standard stations providing continuous measurements of precipitation, air temperature, relative humidity, soil temperature, and volumetric water content at multiple depths across the Middle Tisza region. The core contribution of The HuT project in this DEM has been the valorisation of this existing monitoring infrastructure for purposes beyond its original design scope, specifically the assessment of soil moisture as a dynamic preconditioning factor for municipal pluvial flood



risk, a dimension that had previously been absent from operational flood risk assessment frameworks in the area. The modelling and decision-support components that build on this monitoring foundation, including the VÍZ24 mobile application, are discussed in the companion Deliverable D4.7.

4.7.2. Main features and the link with the Nexus

The innovation of this activity lies not in the deployment of new sensors but in the purposeful reinterpretation of an existing monitoring dataset to address a question it was not originally designed to answer. Soil moisture data collected at depths ranging from 10 to 75 cm using Decagon 5TM sensors, calibrated through laboratory tests and transmitted via GPRS telemetry, were systematically cross-referenced with a catalogue of 24 pluvial flood events occurring between 2016 and 2024. This analysis demonstrated a strong and consistent correlation between elevated soil moisture conditions and the occurrence of flooding events, providing empirical grounding for the integration of soil saturation state into operational flood risk assessment. The approach is innovative in its recognition that monitoring networks designed for one hazard type, in this case drought early warning, can carry significant latent value for the assessment of a structurally different but hydrologically related hazard, provided the analytical framework is in place to extract and operationalise that value.

The activity strengthens the Nexus by establishing a direct observational link between soil moisture dynamics and pluvial flood risk, connecting environmental monitoring to the governance and decision-making responsibilities of municipalities that are statutorily responsible for flood protection but frequently lack the technical tools and expertise to exercise that responsibility effectively. By demonstrating that freely available and properly calibrated monitoring data can support more accurate and timely risk classification, the activity provides a concrete pathway for embedding observational evidence into local decision-making processes. The integration of soil moisture observations into the WP1 operational platform ensures that monitoring outputs reach the users who need them in an accessible and actionable format, completing the chain from environmental observation to risk-informed governance that defines the Nexus vision of The HuT project.

4.7.3. The HuT amplification and how to improve the approach

The implementation drew on the existing monitoring infrastructure without requiring new sensor deployments. Historical soil moisture records from stations installed from 2016 onwards were compiled and cross-referenced with the pluvial flood event catalogue, enabling a retrospective validation of soil moisture as a flood preconditioning indicator. The relatively short data record, a structural limitation imposed by the recent installation of soil moisture instrumentation at most stations, was explicitly acknowledged in the validation analysis and represents the primary constraint on the statistical robustness of the results. The validated methodology was subsequently integrated into the operational risk assessment framework and made accessible through the VÍZ24 application.

The approach is inherently transferable to other water management districts and regional contexts where comparable monitoring infrastructure exists, as it relies on standard WMO-compliant instrumentation and widely available soil moisture sensors rather than bespoke technology. The methodology of cross-referencing existing soil moisture records with historical impact catalogues to derive empirical preconditioning thresholds is replicable wherever both data streams are available and can serve as a practical template for upgrading operational flood risk frameworks in data-rich but analytically underleveraged contexts. The main constraint on scaling is the length of the soil moisture record: the correlation analysis conducted here covers less than a decade,

and longer time series will be needed to improve the statistical robustness of the derived thresholds and to capture the full variability of antecedent conditions across different seasonal and climatic regimes.

Extending the soil moisture monitoring network to a larger number of stations and initiating data collection earlier would have substantially improved the length and spatial representativeness of the dataset available for validation, addressing the most significant limitation of the current analysis. A more systematic integration of remote sensing soil moisture products, such as those available from Copernicus services, alongside in-situ observations would have provided broader spatial coverage and enabled a more robust characterisation of antecedent conditions across the full extent of the operational area. Finally, formalising the feedback mechanism between observed flood impacts and monitoring data through structured post-event analysis protocols would create a continuous improvement cycle for the threshold framework, progressively increasing its reliability as the observational record grows.

4.7.4. Take home messages

The DEM7 experience demonstrates the latent value that existing monitoring infrastructure can hold when approached with the right analytical questions. A network originally designed to support drought early warning has proven capable of providing the observational evidence needed to improve pluvial flood risk assessment, simply by redirecting analytical attention toward the preconditioning role of soil moisture rather than its deficit. The empirical correlation between elevated soil saturation and flood event occurrence, established through cross-referencing of monitoring data with a historical impact catalogue, provides a physically grounded and operationally actionable basis for more dynamic and accurate municipal risk classification. The most important lesson is structural: monitoring networks are most valuable when their data are systematically interrogated across multiple hazard types and when the institutional frameworks exist to translate observational evidence into operational decisions. In a region where municipalities bear direct responsibility for flood protection but often lack technical capacity, the availability of continuously updated, spatially referenced soil moisture information represents a meaningful and replicable contribution to local resilience.

4.8. DEM8 Ogliastro [Italy]

The Ogliastro Demonstrator (DEM8) did not conduct activities falling within the scope of Task 4.2. The DEM focused, within WP4, entirely on fire behaviour modelling under current and future climate conditions and on the co-design of land management scenarios through participatory processes with local stakeholders, complemented by the development of a prototype community-based catastrophe insurance product. These activities represent the core scientific and innovation contributions of DEM8 and are documented in the companion Deliverable D4.7. The participatory workshops, focus groups, and participatory mapping exercises conducted with administrators, fire managers, and local economic actors between 2023 and 2026 constitute a form of community engagement that partially overlaps with the citizen science dimension of Task 4.2. However, these activities were designed primarily to inform and validate the modelling scenarios rather than to systematically collect observational data on hazard occurrence, vulnerability, or impact, and are therefore not treated as monitoring activities in the strict sense adopted here.



4.9. DEM9 Dorset County [UK]

4.9.1. Introduction on the activities carried out on monitoring

The flagship monitoring activity of DEM9 focuses on the development and testing of IoT-based sensing solutions for coastal landslide monitoring along the cliffs at West Bay, Dorset, building on prior work conducted within the 5GRuralDorset project and expanding through new collaborations with Bournemouth University, Leeds University, and Dorset Council. The DEM operates in a coastal cliff environment characterised by complex rockfall and rotational landslide dynamics where predisposing factors are strongly tied to local conditions, making spatially representative and continuous monitoring particularly challenging. The ambition of the DEM9 activity was to move beyond data acquisition for research purposes and toward the provision of useful, usable, and operationally used information for the local authorities responsible for managing coastal footpaths and public access to the area. To further compliment this, wider modelling work carried out by DEM9 is discussed in the companion Deliverable D4.7.

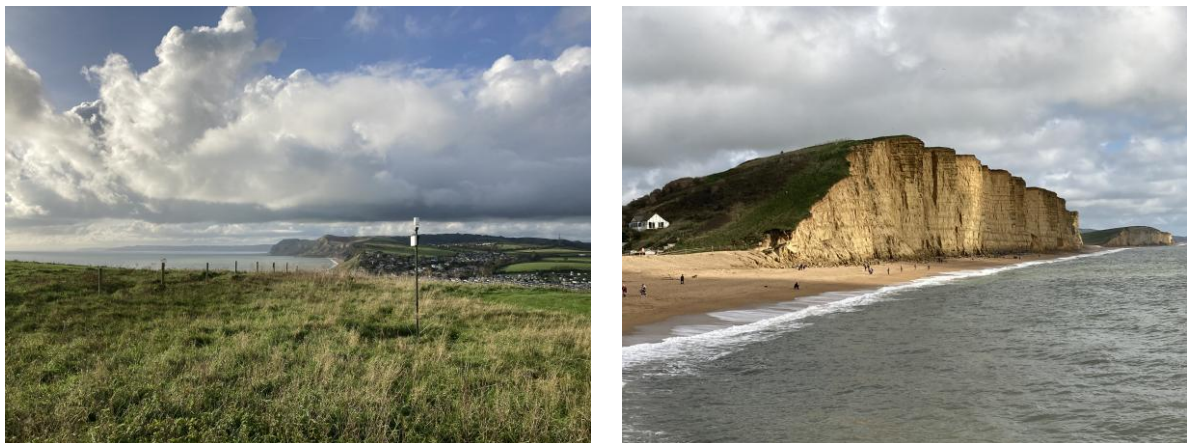


Figure 7: The installed weather station and West Bay cliffs, Dorset.

4.9.2. Main features and the link with the Nexus

The key monitoring activity addresses a well-documented gap in the application of IoT technology to landslide risk management: while numerous studies have explored sensor-based data acquisition for monitoring purposes, far fewer have examined the conditions under which such data can be effectively translated into early warning information that is trusted and acted upon by non-specialist end users. The DEM9 monitoring concept was structured around three sequential dimensions: understanding why monitoring is needed, determining what technology is appropriate and how data are collected and transmitted, and establishing how data are interpreted and communicated to those responsible for decisions. This tripartite framing reflects a maturity of approach that goes beyond sensor deployment and foregrounds the human and institutional dimensions of monitoring system design. The use of Nb-IoT narrow-band communication technology for data transmission in a challenging coastal environment, combined with a modular sensor platform capable of detecting tilt and displacement, represents a technically innovative response to the connectivity and power supply constraints that have historically limited IoT deployments in similar settings.

The activity contributes to the Nexus by placing the design and validation of monitoring technology explicitly within the context of the stakeholder relationships and governance responsibilities that

determine whether observational data can be converted into risk reduction outcomes. Engagement with the Met Office, Dorset Council, Bournemouth University, the RNLI, and local coastal communities was not peripheral to the monitoring work but central to it, providing the understanding of user needs, institutional capacities, and community risk perceptions that must inform any monitoring system intended to support early warning rather than simply generate data. By raising awareness of cliff instability risks among both permanent residents and transient visitors, and by building relationships across a diverse network of local actors, the DEM has created a social and institutional foundation for future monitoring and warning initiatives that will outlast the project itself.

4.9.3. The HuT amplification and how to improve the approach

A weather station was successfully installed at the West Bay cliff top in October 2024, providing localised meteorological data accessible to the Met Office, Dorset Council, Bournemouth University, and the local golf course. Four IoT landslide sensors were installed in July 2024 but ceased functioning prematurely due to battery problems, highlighting the practical constraints of deploying low-power sensors in harsh coastal environments. Following laboratory testing of the original sensor platform, which revealed multiple stability and security issues, a new modular platform based on proven off-the-shelf hardware was procured and is currently undergoing laboratory testing at BGS prior to field redeployment. Open-access data from offshore wave buoys were used alongside the weather station data to correlate and validate observations of cliff movement. As a linked activity, connections made during The HuT project enabled collaboration with two MSc students from Leeds University. The students conducted drone photogrammetry of a 1.2 km cliff section in July 2024, producing a detailed three-dimensional model that was able to be used by BGS to advance understanding of the role of structural discontinuities in rockfall processes at the site.

The practical lessons generated by this activity, including insights into deployment constraints, maintenance challenges, connectivity limitations, and the conditions required for reliable long-term monitoring in coastal environments, represent transferable outputs of value to other DEMs and future projects operating in comparable settings. The experience of sensor failure and platform redesign, while not the outcome originally sought, has produced a more robust and better-tested monitoring solution whose deployment at other coastal landslide sites is now better informed. The stakeholder engagement methodology, which brought together scientific, technical, governance, and community perspectives around a shared monitoring objective, provides a replicable framework for co-designing monitoring systems that are genuinely oriented toward use rather than data generation alone.

The experience also underlines a broader lesson: monitoring systems in challenging environments require iterative testing cycles and realistic timelines that account for the possibility of technical setbacks, neither of which can be adequately accommodated within the compressed implementation phases that characterise most research project schedules.

4.9.4. Take home messages

The DEM9 experience offers one of the most candid illustrations within The HuT project of the gap between the ambition of IoT-based monitoring and the practical realities of deployment in harsh and geologically complex environments. The sensor network did not achieve the level of technical success originally planned, yet the activity generated meaningful and transferable learning on sensor performance, deployment constraints, stakeholder expectations, and the institutional conditions under which monitoring data can be converted into actionable risk information. The weather station installation was successful and its data are actively used by a range of local



stakeholders. The relationships built across local authorities, emergency responders, research institutions, and coastal communities represent a durable outcome that will support future monitoring, warning, and preparedness initiatives beyond the project timeline. The most important lesson is that useful monitoring is not defined by the sophistication of its technology but by the depth of its integration into the decisions and responsibilities of those it is designed to serve.

4.10. DEM10 Berne Canton [Switzerland]

4.10.1. Introduction on the activities carried out on monitoring

The flagship monitoring activity of DEM10 consists of the installation and operation of a high-precision meteorological station in the headwater catchment of the Zulg river basin in Bern canton, Switzerland, designed to capture the fine-scale precipitation dynamics that drive flash floods and shallow landslides in this pre-alpine environment. The Zulg catchment, covering approximately 85 km², originates at the Hohgant massif at around 2000 m above sea level and flows through Steffisburg before discharging into the Aare near Heimberg. Despite the absence of dammed lakes, the catchment has a documented history of flash floods spanning decades, with runoff capable of rising from a few hundred litres per second to nearly 50 cubic metres per second in approximately five minutes, a dynamic that conventional monitoring at 10 or 15-minute temporal resolution is structurally unable to capture (fig.6). The station was installed in June 2023 and paired with the Canton of Bern official runoff gauge located approximately 10 km downstream, which was simultaneously upgraded to one-minute measurement resolution, creating for the first time a coupled precipitation-runoff observation system capable of resolving the rapid-onset dynamics characteristic of this catchment.

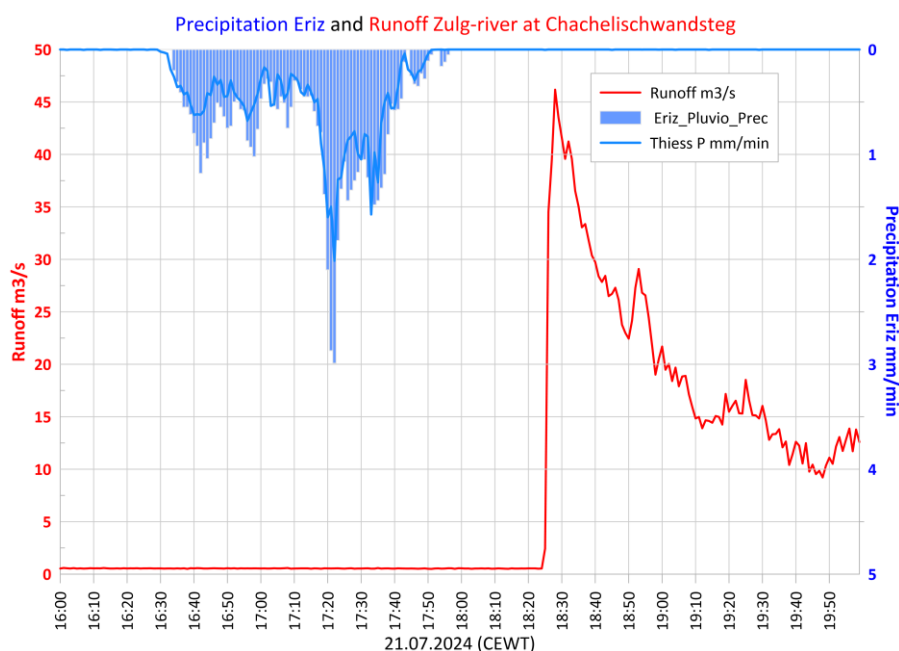


Figure 8: The pairing of the headwater precipitation station with the downstream runoff gauge at matching one-minute resolution enabled the first quantitative characterisation of flash flood dynamics in the Zulg catchment. Hourly or even 10-minutes time-resolution is too coarse for these very fast concentration times happening often in the Zulg valley, but also in other v-shaped valleys in Europe and worldwide.

4.10.2. Main features and the link with the Nexus

The innovation of this activity resides in the combination of measurement resolution, instrument quality, and variable breadth achieved at a single monitoring location. The station features a Thies disdrometer providing one-minute measurements of drop size distribution, kinetic energy, and momentum, an OTT Pluvio reference pluviometer, and a Lufft weather station, together constituting a measurement ensemble that goes substantially beyond what conventional precipitation monitoring can deliver. The disdrometer is the most distinctive element: by reconstructing the precipitation field in terms of hydrometeor number and size distribution rather than accumulated depth alone, it enables the direct quantification of rainfall kinetic energy, a variable of critical importance for understanding soil erosion processes and shallow landslide initiation but one that conventional rain gauges can only estimate retrospectively and with significant uncertainty. The capacity to discriminate snowfall from rainfall with high precision is a further operational asset in an alpine catchment where rain-on-snow events represent a particularly dangerous triggering mechanism. The pairing of the headwater precipitation station with the downstream runoff gauge at matching one-minute resolution enabled the first quantitative characterisation of flash flood dynamics in the Zulg catchment, including the July 2024 event in which discharge rose to nearly 50 cubic metres per second in approximately five minutes, and opened new possibilities for nowcasting through integration with the INCA gauge-radar-forecast merged tool.

The monitoring activity strengthens the Nexus by providing the observational foundation needed to connect atmospheric forcing with catchment response and downstream risk at the temporal scales that actually matter for early warning in flash flood prone environments. The one-minute resolution precipitation and runoff data do not merely improve the scientific understanding of hydrological processes in the Zulg basin: they represent the minimum observational requirement for any credible nowcasting or early warning capability in a catchment where the concentration time is measured in minutes rather than hours. The integration of disdrometer-derived kinetic energy data into the understanding of soil erosion and shallow landslide dynamics adds a further dimension that links the monitoring activity to land management and nature-based solution considerations, consistent with the broader Nexus framing of The HuT project (fig. 7). Data are shared with cantonal authorities and integrated into the regional monitoring network, ensuring that the observational investment made within the project contributes to the operational infrastructure of the responsible institutions beyond the project lifetime.

4.10.3. The HuT amplification and how to improve the approach

The monitoring station was installed in cooperation with local authorities, enabling the pairing of the new high-precision measurements with the official cantonal runoff gauge and their joint integration with the INCA nowcasting tool. Interviews were conducted with responsible persons at local, cantonal, and federal level to understand the existing early warning procedures and identify the gaps that higher-resolution monitoring could address. Discussions with local natural hazard consultants and farmers participating in a community-based qualitative observation network provided contextual knowledge of local process dynamics that informed both the station design and the interpretation of the data collected. Data availability has exceeded 99% since installation, reflecting the robustness of the instrumentation and the reliability of the power supply configuration.

The monitoring configuration developed in DEM10 is replicable in other pre-alpine and alpine catchments where flash flood and shallow landslide dynamics are driven by high-intensity short-duration rainfall events and where conventional monitoring resolution is insufficient to support reliable early warning. The instruments are robust, require only limited maintenance, and achieve



very high data availability, making them suitable for operational deployment beyond research contexts. The main constraint on scaling is cost: the instrumentation, particularly the disdrometer, is significantly more expensive than standard precipitation gauges, and the requirement for a reliable and relatively high-capacity power supply adds a further practical consideration for remote sites. The coupling of headwater precipitation monitoring with a downstream runoff gauge at matching temporal resolution is a configuration that could be replicated at relatively low additional cost wherever an official runoff gauge already exists, as the primary investment required is the upstream meteorological station rather than new hydrometric infrastructure.

This experience reinforces a lesson that recurs across multiple DEMs: the social and institutional dimensions of monitoring system development cannot be treated as secondary to the technical ones, and the time investment required for genuine stakeholder engagement should be planned from the outset rather than accommodated within residual project capacity.

4.10.4. Take home messages

The DEM10 experience demonstrates that a single well-designed and precisely instrumented monitoring station, when paired with an existing official gauge at matching temporal resolution and integrated with operational nowcasting tools, can generate observational insights that fundamentally change the understanding of flash flood dynamics in a catchment. The one-minute resolution precipitation and runoff data collected in the Zulg basin have made it possible for the first time to characterise the full rapidity of discharge response to convective rainfall events, providing the empirical basis for improved early warning procedures in an environment where the available lead time is measured in minutes. The disdrometer adds a dimension of process understanding, particularly regarding rainfall kinetic energy and its role in soil erosion and landslide initiation, that conventional monitoring cannot provide. The most transferable lesson is that temporal resolution matters as much as spatial coverage in flash flood prone environments, and that the marginal cost of upgrading an existing monitoring network to one-minute resolution is small relative to the improvement in early warning capability it enables.



5. Conclusions

The monitoring activities documented in this Deliverable reflect the breadth and diversity of approaches that the ten Demonstrators of The HuT project have brought to the challenge of observing, characterising, and operationalising information on weather-related hazards and their impacts. Taken together, they constitute a rich and varied portfolio that spans instrumental sensor networks, remote sensing and Earth Observation data exploitation, documentary impact catalogues, and community-based reporting systems, unified by the common thread of the Nexus philosophy that underpins the project: monitoring is always instrumental to DRR objectives and acquires its full value only when embedded in a system that connects observations to decisions.

The most widely represented monitoring approach across the DEMs is the deployment or valorisation of in-situ sensor networks measuring soil moisture, precipitation, streamflow, groundwater levels, and surface displacement. In DEM2, DEM3, DEM6, DEM9, and DEM10, field instrumentation was either newly installed or substantially upgraded within the project, with soil moisture emerging as a cross-cutting variable of particular interest. Its role as a preconditioning factor for geo-hydrological instability, recognised across the Lattari mountains, the Val d'Aran, the Icelandic fjords, and the Hungarian plain, has been one of the most consistent findings of the Task, and the working group coordinated by NGI has played an important role in consolidating this shared understanding across the consortium. The experience of DEM7 adds a further dimension by demonstrating that existing monitoring networks originally designed for drought early warning can carry significant latent value for pluvial flood risk assessment, provided the analytical framework is in place to extract and operationalise that value.

Remote sensing and freely available data products have been exploited with particular effectiveness in DEM1 and DEM3. In Valencia, Landsat-derived land surface temperature data at 30 m resolution provided the observational foundation for a spatially explicit and socially grounded analysis of urban heat exposure, demonstrating that satellite monitoring can deliver actionable information on UHI dynamics and their relationship with urban morphology and population vulnerability. In the Monti Lattari, the Soil Water Index derived from EFAS reanalysis products was used as a spatially distributed proxy for antecedent wetness conditions, offering a practical and freely replicable approach to complementing sparse in-situ networks with broader spatial coverage.

Documentary and community-based monitoring approaches have proven equally valuable in contexts where sensor deployment is not feasible or where impact data are the primary information need. The systematic reconstruction of a pluvial flood impact catalogue in Vilnius from publicly available sources demonstrated that non-traditional data can yield rigorous and operationally relevant insights into urban flood hotspots and infrastructure effectiveness. The KoBoToolbox-based citizen reporting application developed in DEM3, the Buddy System in Glückstadt illustrate the range of forms that community monitoring can take and the diversity of objectives it can serve, from georeferenced hazard impact documentation to social vulnerability reduction and educational awareness raising.

Not all DEMs have conducted activities falling within the scope of this Task, and this is by design. The portfolio of monitoring innovations across the project reflects a deliberate and context-sensitive allocation of effort shaped by local vulnerability profiles, pre-existing monitoring infrastructure, and the real socioeconomic conditions of each area. Where monitoring activities were not pursued, the reasons are transparent and the complementary modelling and governance contributions of those DEMs are documented in the companion deliverables.



Several cross-cutting lessons emerge from the collective experience. Temporal and spatial resolution matter enormously: the one-minute precipitation and runoff data from DEM10 enabled process insights that decadal monitoring at coarser resolution had failed to reveal, while the sub-catchment scale observations from DEM3 provided information that regional and national systems are structurally unable to deliver. Institutional integration is as important as technical performance: monitoring systems that are not embedded within the decision-making responsibilities of the institutions that need them will generate data but not outcomes. And the social dimensions of monitoring, including stakeholder co-design, community engagement, and the building of trust between scientists and local actors, require as much deliberate investment as the technical ones, a lesson that recurs with remarkable consistency across DEMs as different as the Icelandic fjords, the Dorset coast, and the Swiss Alps.

Looking ahead, the challenge for the final phase of the project and beyond is to ensure that the monitoring innovations developed within individual Demonstrators are maintained, amplified, transferred, and where possible formally integrated into the operational systems for disaster risk reduction that will persist after the project concludes. The foundation for this amplification has been laid: the data are being collected, the frameworks are being validated, and the institutional relationships are being built.