Deliverable Report

Enabling rapid and far-reaching change by Innovative Technologies Implementation

30.11.2025

D4.3

Authors:
Nasrin Haacke, Sandra Banusch, Daniel Wicke, Wolfgang Seis (KWB); Anna Ribera Guàrdia, Manuel Martínez Del Álamo, Víctor Puchal Bosch, Mireia Mesas Suárez, Carmen Torres Costa, Jéssica Meijide Fernández, Queralt Plana Puig, Ian Palacin Aliana (EUT); Klio Monokrousou, Christos Makropoulos, Konstantinos Koudras, Dionysis Nikolopoulos, Nikos Pelekanos, Archontia Lykou, George Karavokiros, Chris Pantazis, Ilias Chrysovergis (NTUA); Stelios Samios, Katerina Dimitrou, Christos Pouliaris (EYDAP); Josefine Filter (BWB); Aziz Hassan (SenMVKU); Francesco Bressi, Anna Paola Lonardi (MGIS); Aaron Estrada, Valentina D'Alonzo (EURAC); Giorgia Robbiati (BIM); Faye Weaver, Catherine Numa (IUCN); Jasper van Lieshout (Nelen & Schurmans); Ingrida Bremere, Daina Indriksone (BEF); Marija Stocka (Jelgeva); Stelios Manoudakis, Stathis Gerabinis (MAICh); Torill Nyseth (TFFK); Louise Vick (UiT)

Deliverable No.	D4.3
Deliverable nature	R[1]
Work Package (WP) and Task	WP4 T4.5.1, T4.5.2, T4.5.3, T4.6, T4.7.1, T4.7.2, T4.8.1, T4.8.2, T4.9, T4.10.1, T4.10.2, T4.10.3, T4.10.4, T4.11, T4.12
Dissemination level	PU[1]
Number of pages	161
Keywords	Innovative Technologies, Digital Solutions, Decision Support Systems, Environmental Monitoring, Risk Assessment, Ecosystem Resilience, Data Integration, Stakeholder Engagement
Authors	Nasrin Haacke, Sandra Banusch, Daniel Wicke, Wolfgang Seis (KWB); Anna Ribera Guàrdia, Manuel Martínez Del Álamo, Víctor Puchal Bosch, Mireia Mesas Suárez, Carmen Torres Costa, Jéssica Meijide Fernández, Queralt Plana Puig, Ian Palacin Aliana (EUT); Klio Monokrousou, Christos Makropoulos, Konstantinos Koudras, Dionysis Nikolopoulos, Nikos Pelekanos, Archontia Lykou, George Karavokiros, Chris Pantazis, Ilias Chrysovergis (NTUA); Stelios Samios, Katerina Dimitrou, Christos Pouliaris (EYDAP); Josefine Filter (BWB); Aziz Hassan (SenMVKU); Francesco Bressi, Anna Paola Lonardi (MGIS); Aaron Estrada, Valentina D'Alonzo (EURAC); Giorgia Robbiati (BIM); Faye Weaver, Catherine Numa (IUCN); Jasper van Lieshout (Nelen & Schurrmans); Ingrida Bremere, Daina Indriksone (BEF); Marija Stocka (Jelgeva); Stelios Manoudakis, Stathis Gerabinis (MAICh); Torill Nyseth (TFFK); Louise Vick (UiT)
Contributors	N/A
Contractual submission date	30.11.2025
Actual submission date	30.11.2025

Technical References

Project acronym	IMPETUS
Project full title	Dynamic Information Management Approach for the Implementation of Climate Resilient Adaptation Packages in European Regions
Call	H2020-LC-GD-2020-2
Grant number	101037084
Project website	http://climate-impetus.eu/
Coordinator	EUT

Document history

V	Date	Beneficiary	Author
V1	29.08.2025	KWB	Sandra Banusch
V2	12.09.2025	KWB	Michael Rustler
V3	10.10.2025	KWB, KWR, Thetis SpA	Nasrin Haacke Sebastiano Carrer (Thetis SpA), Lisa Andrews (KWR), Stefania Munaretto (KWR) – Quality Assurance Review
V4	24.10.2025	KWB	Nasrin Haacke
V5	03.11.2025	KWB	Nasrin Haacke
V6	12.11.2025	KWB	Nasrin Haacke
V7	20.11.2025	KWB	Nasrin Haacke
V8	27.11.2025	KWB, NTUA,	Nasrin Haacke (KWB) Dionysios Nikolopoulos (NTUA) – Quality Assurance Review
FINAL	30.11.2025	EUT	Hannah Arpke

Disclaimer

This document reflects only the author's views and the European Community is not liable for any use that may be made of the information contained herein. All logos, trademarks, imagines, and brand names used herein are the property of their respective owners. Images used are for illustration purposes only. This work is licensed under the Creative Commons License "BY-NC-SA".

Abbreviations

Abbreviation / Acronyms	Description
AdV	Adenovirus
AnMBR	Anaerobic membrane bioreactor
API	Application Programming Interface
BEF	Baltic Environmental Forum (Baltijas Vides Forums)
BF	Bank filtration
BIOPA	Industrial Park
BOD	Biochemical Oxygen Demand
CS	Connected and Sewer Mining
COD	Chemical oxygen demand
CSO	Combined Sewer Overflow
DO	Dissolved Oxygen
DT	Digital Twin
EAWWS	East Attica Wastewater System
EC	Electrical Conductivity
E. coli	Escherichia coli
EU	European Union
EURAC	Eurac Research (Accademia Europea di Bolzano)
EUT	Fundació Eurecat
EYDAP	Athens Water Supply and Sewerage Company
FC	Faecal Coliforms
FIB	Faecal Indicator Bacteria
GAC	Granular activated carbon
GER	Germany
GR	Greece
GBR	Ground-Based Radar
GUI	Graphical User Interface
HAB	Harmful algal blooms
HRT	Hydraulic Retention Time
IT	Italy
InSAR	Interferometric Satellite Acquired Radar
IoT	Internet of Things
IPCC	Intergovernmental Panel on Climate Change
IUCN	International Union for Conservation of Nature and Natural Resources (Union internationale pour la conservation de la nature)
JDC	Jelgava Digital Center
KGE	Kling-Gupta Efficiency
KPI	Key Performance Indicators
KWB	The Berlin Centre of Competence for Water (Kompetenzzentrum Wasser Berlin gGmbH)
LEGMC	Latvian Environment Geology and Meteorology Centre
LV	Latvia
LRV	Log-removal values
MBR	Membrane Bioreactor
MLSS	Mixed Liquor Suspended Solids
MSP	Main Sewerage Pipes

N	Nitrogen
N&S	Nelen & Schuurmans Consultancy B.V.
NGU	Geological Survey of Norway
NL	Netherlands
NH_4^+-N	Ammonium Nitrogen
NO	Norway
NoV	Norovirus
NO_3^--N	Nitrate Nitrogen
NTUA	National Technical University of Athens (Ethnicon Metsovion Polytechnion)
NVE	Norwegian water and energy resources directorate
NWRM	Natural Water Retention Measures
P	Phosphorus
PC	Project Consortium
RCP	Representative Concentration Pathway
PET	Physiological Equivalent Temperature
PLC	Programmable Logic Controller
RKB	Resilience Knowledge Booster
PMT	Project Management Team
PSB	Project Steering Board
PV	Photovoltaic
OGC	Open Geospatial Standards
QMRA	Quantitative Microbiological Risk Assessment
RBMP	River Basin Management Plan
RCP	Representative Concentration Pathway
RD	Royal Decree
SA	Stand Alone
SDM	Species Distribution Model
SM	Sewer Mining
SSP	Shared Socioeconomic Pathways
SWECO	Sweco Norway (Sweco Norge AS)
TC	Total Coliforms
TFFK	Troms and Finnmark County Municipality (Troms og Finnmark Fylkeskommune)
TK	Tromsø municipality (Tromsø kommune)
TN	Total Nitrogen
TMP	Transmembrane Pressure
TP	Total Phosphorus
ToC	Theory of Change
UASB	Up flow anaerobic sludge blanket
UF	Ultrafiltration
UiT	The Artic University of Norway (Norges arktiske universitet)
UV	Ultraviolet
UX/UI	User experience / User interface
VR	Virtual reality
WEFE	Water-Energy-Food-Ecosystems
WP	Work Package
WPL	Work Package Leader

WTP	Water Treatment Plant
WWTP	Wastewater Treatment Plant
ZPR	Zemgale Planning Region

Table of contents

List of tables

List of figures

Executive Summary

This deliverable presents the implementation progress and results of the innovative technologies demonstrated across the IMPETUS demo sites during the period M1-M49 of the project (01/10/2021–30/09/2025). It covers the full set of activities carried out under WP4 Tasks 4.5.1 to 4.12, which together form Bundle 2: Innovative Technologies Implementation.

Bundle 2 aims to demonstrate a suite of advanced technical solutions that increase climate resilience across diverse geographic, hydrological, and socio-economic contexts. The bundle includes decentralised water reuse systems, digital modelling tools, pathogen monitoring technologies, sediment transport modelling, multi-agent water balance models, decision-support systems for heat and flood risk, and early-warning technologies for geological hazards. These solutions collectively reinforce the broader WP4 objective of testing and validating multi-benefit adaptation innovations that can be scaled across Europe.

The 15 tasks reported in this deliverable demonstrate substantial progress toward climate-resilient water management, environmental protection, and risk reduction. Task 4.5.1 deployed a hybrid decentralised fit-for-use water reclamation system in the Coastal demo site (Catalonia), producing high-quality reclaimed water for irrigation and cleaning within a touristic complex and validating decentralised reuse under highly variable seasonal demand. Task 4.5.2 implemented a Sewer Mining unit in East Attica (Mediterranean demo site), integrating real-time data, energy-autonomous operation, and co-created adaptation services. Task 4.5.3 developed a water-energy simulation and optimisation model, enabling the operator of the East Attica system to explore climate-proof operation strategies and circular-economy pathways.

Across several additional tasks, advanced modelling and monitoring capabilities were demonstrated. Tasks 4.6 and 4.7.1 developed computational tools for sediment transport and regional water balance simulation, supporting adaptation measures under hydrological and demographic pressures. Tasks 4.7.2 and 4.10.1 - 4.10.3 delivered decision-support systems that integrate multi-layer data for WEFE-nexus planning, heat stress management, and flood risk visualisation, many of which are connected to digital twin environments. Tasks 4.8.1 and 4.8.2 tackled climate-exacerbated water quality risks by improving bathing water management during storm events and assessing drinking water resilience to pathogens. Finally, Tasks 4.11 and 4.12 implemented technologies for urban climate proofing in coastal settings facing sea-level rise and for geological and avalanche early-warning systems in the Arctic and mountainous demo sites.

Together, the technologies demonstrated under Bundle 2 provide actionable, scalable, and evidence-based adaptation options. The solutions directly support regional water resilience, enable cross-sectoral decision-making, and reduce exposure to climate-related risks. Their integration into the Resilience Knowledge Boosters, digital twins, and participatory processes strengthens the IMPETUS vision of empowering local stakeholders and decision-makers with robust, technology-driven adaptation pathways.

1 Introduction and background

IMPETUS builds on the demonstration of innovative technical, nature-based, governance, financing and public engagement solutions deployed in seven demo-sites (WP4).

The IMPETUS demo-sites (DS), as depicted in Figure 1, are designed to cover multiple biogeographical areas, vulnerabilities to climate change, weather-related hazards, as well as economic and socio-demographic conditions.

Figure 1 Overview of IMPETUS demo sites.

A short description of the targeted issues addressed in the regions:

DS#1 Continental: Berlin-Brandenburg region, GER
The Berlin-Brandenburg region consists of the capital and the surrounding municipalities of Brandenburg. The area faces increasing water stress and relies on riverbank filtration, groundwater, and groundwater recharge as sources of drinking water. However, some surface waters used for bank filtration are impacted by treated wastewater discharged upstream, creating a partially closed water cycle. With the anticipated effects of climate change, drinking water quality in the region is at risk. Additionally, a growing population and competing water demands make adaptive solutions essential.

DS#2 Coastal: Coast of Catalonia, ESP
The Catalan coast stretches 600 km along the Mediterranean Sea. The hotspot status of the DS arises from a combination of natural and social factors, driven by a diverse range of economic activities and interests. As a climate-vulnerable area, protecting the environment and conserving natural resources are crucial today and will become even more critical in the future, given the projected impacts, trends, and challenges.

DS#3 Mediterranean: Region of Attica, GR
The Attica Region, which includes the Athens metropolitan area, covers 3,808 km² and is home to approximately 3.74 million residents (as of 2019). As a typical Mediterranean region, it faces increasing impacts from climate change and other global challenges. Overpopulation and competing economic land uses place significant pressure on the environment. Rising temperatures have led to more extreme heat, higher drought risk, and reduced rainfall, affecting both people and ecosystems. Water demand for agriculture and environmental needs competes with the growing tourism and recreation sectors.

Over-extraction of groundwater has caused seawater intrusion, reducing crop yields and threatening economic sustainability. Additionally, rising temperatures have driven up energy demand, intensified flash floods, worsened air quality, and increased the risk of forest fires.

DS#4 Atlantic: Province of Zeeland and Rijnmond, NL

Zeeland is a coastal province made up of a series of islands and peninsulas. Both Zeeland and Rijnmond lie at or below sea level, making them highly vulnerable to flooding and rising sea levels. Climate change has led to increasing air temperatures, causing heat stress, particularly in large, exposed landscapes, and posing risks to public health. This challenge is especially concerning given the region's aging population and an environment that is not easily adaptable. Additionally, Rijnmond holds significant economic importance for the Netherlands, as the city of Rotterdam and Europe's largest port are located here. The region's energy consumption is substantial, accounting for 15% of the country's total.

DS#5 Arctic: Troms & Finnmark County, NO

Climate change is already having a significant impact on the Arctic region of northern Norway, particularly in Troms County. Over the past century, Norway's average surface air temperature has increased by at least one degree. Alongside this warming trend, the region is expected to experience more frequent and intense heavy rainfall, floods, landslides, and avalanches. Additionally, sea levels are projected to rise by 10–60 cm by the end of the 21st century, based on the Representative Concentration Pathway (RCP) 8.5 emissions scenario.

DS#6 Boreal: Zemgale Region, LV

Located in central Latvia, the landscape of Zemgale Region is characterized by a flat terrain and dense river network. Therefore, the region is highly vulnerable to flooding, particularly from snowmelt and heavy precipitation. During flood events, the rapid and significant rise in water levels poses substantial risks to communities, settlements, and infrastructure.

DS#7 Mountainous: Valle dei Laghi, IT

The Valle dei Laghi, in the Autonomous Province of Trento, is part of the climate-sensitive Alps. Water resource conflicts among irrigation, hydropower, ecosystem needs, and drinking water are intensifying. In summer, competition between irrigation and hydropower production is already evident. The altitudinal shift of areas suitable for vineyard cultivation will require optimized irrigation and new concessions, further fueling land-use conflicts between agriculture, woodlands, and pastures.

The solutions implemented in the DS are thematically organised in four bundles:

- Bundle 1: Nature-based Solutions
- Bundle 2: Innovative Technologies
- Bundle 3: Financing & Insurance
- Bundle 4: Governance, Awareness and Behavioural change.

This document presents the results of Bundle 2.

Bundle 2 of WP4, "Innovative Technologies Implementation", brings together a comprehensive set of technical solutions that address climate-induced pressures on water resources, environmental quality, and urban and natural systems across the seven IMPETUS demo sites. The tasks within this bundle cover decentralised water reuse, pathogen monitoring, sediment transport modelling, WEFE nexus decision-support, multi-agent water balance simulation, and digital tools for flood and heat risk management, among other things. Together, these technologies form the operational and analytical backbone of WP4's demonstration activities, providing practical, data-driven solutions to help regions respond to climate challenges.

The technological solutions developed in Bundle 2 not only serve the needs of the individual demo sites but also support the wider structure of the project. Several tools contribute directly to other Work Packages: for example, the Water–Energy Simulation Model (T4.5.3) supplies scenario outputs and performance indicators that directly support planning and assessment activities within the Region's Resilience Knowledge Booster (WP2); the Sewer Mining system (T4.5.2) integrates data from the Digital Twin developed in T4.10.4 and is embedded in stakeholder co-creation processes linked to WP1 and WP5; and the suite of decision-support tools for heat, flooding, and the WEFE nexus (T4.7.2, T4.10.1-T4.10.4) enhance regional adaptation planning and contribute to knowledge and data flows used in WP2

and WP5. The interoperability and application programming interface (API)-based design of these digital tools further facilitate integration with external platforms, supporting the project's scaling and transferability objectives.

The scope of this deliverable is to document the implementation, validation, and outcomes of all technologies demonstrated under Bundle 2 during the project period. It presents the technical achievements, operational experience, and performance results of each task, alongside the challenges encountered and lessons learned. The objectives of this deliverable are to:

- demonstrate the feasibility and performance of innovative technologies for climate adaptation in real operational contexts;
- support integrated planning and decision-making through advanced modelling, forecasting, and simulation tools;
- strengthen cross-sectoral climate resilience by enabling efficient water reuse, improving environmental monitoring, and enhancing early-warning capabilities;
- and provide transferable evidence and technical insights that contribute to the development of regional adaptation pathways and to scaling activities in other Work Packages.

Overall, Bundle 2 contributes to the WP4 mission of combining technical, environmental, and digital innovations to enable multi-benefit, long-term adaptation. The results documented here illustrate the potential of advanced technologies to improve climate resilience and provide a strong foundation for integrating these solutions into broader regional and cross-regional strategies.

Table 1 Overview of WP4 tasks in Bundle 2

Solution No.	Task No.	Task title	Lead beneficiary	Demo site #	Task description
1	4.5.1	Decentralized hybrid fit-for-use water reclamation systems for increasing water availability	EUT	2	The feasibility of increasing water availability by decentralized water treatment and reclamation systems will be demonstrated in the Coastal demo site in a touristic complex in Tamarit (Spain) (see LoS). A compact hybrid decentralized reclamation system, combining NBS and Anaerobic granular membrane treatments, will be put in place in the camping in order to produce high-quality water for irrigation and cleaning purposes. The pilot will be designed taking into account the challenges linked to seasonal occupation of the complex (from 20 to 2500 pax in summer periods) and it will be operated producing high-quality water to be reused in the complex for irrigation of a green zone and other cleaning purposes. Health risk assessment of the water produced will be conducted to demonstrate the feasibility of decentralized reuse.
2	4.5.2	Sewer Mining for multi-sector climate proofing	NTUA	3	A Sewer Mining unit will be designed, built, and deployed tapping into the East Attica system of Mediterranean demo site (as a demonstration of part of the masterplan), with water reused at the point of demand for urban greening (and climate proofing it against droughts) and municipal ecosystem services (park irrigation - heat island effect reduction). The units will benefit from access to data from the Region's Digital Twin (T4.10.4) and be supported by stakeholder engagement (also using novel AR/VR tools from previous projects such as Nextgen) and co-creation for new climate change adaptation services around the 'new' water resource.
3	4.5.3	Water-Energy simulation and optimisation model for wastewater systems acting as regional circular economy and climate resilience hubs	NTUA	3	In support of new, circular-economy objectives for treated wastewater, nutrient and energy production and environmental protection, a coupled water-energy simulation and optimisation model will be designed and deployed in the East Attica wastewater system (Mediterranean demo site) for use by its

Solution No.	Task No.	Task title	Lead beneficiary	Demo site #	Task description
					operator (EYDAP) to develop operational rules for integrated WWTP operation. The model will use both, data from the system itself (e.g., EYDAP's SCADA) but also tap into additional open datasets (weather, climate, hydrology, hydrogeology, field measurements, forecasts, abstractions, agricultural water needs, groundwater monitoring wells etc) - also through the Digital Twin of the Attica Region (T4.10.4) - and will be a basis for scenario planning and cost-benefit analysis within the region's RKB (T4.15) Advanced uncertainty-aware optimisation techniques will be embedded in the model to allow climate-proofing of the resulting operational rules under deep uncertainty.
4	4.6	Sediment transport in deltas	EUT	2	Making use of an already developed and successfully tested pilot (LIFE EBRO ADMICLIM) to by-pass sediments through Riba-Roja reservoir in Ebro River (Spain), EUT will model the irrigation system of a Delta – Estuary in the Coastal demo site through the use of Computational Fluid Dynamics (CFD). This specific site will serve to validate (reproduce the behaviour of sediments throughout the network) and improve existing computational tools that will then be available to be used in other similar environments, with the aim of proposing strategies for adaptation measures in the network to provide an efficient sediment transport. In addition, this model could be used for continuous adaptation of the network.
5	4.7.1	Interactive multi-agent regional water balance model	KWB	1	By integrating sectoral data and analytical tools assessing singular aspects of water management under changing climatic and demographic conditions into a regional water balance model, competing water uses are assessed for their impacts on water quantity and water quality. Usage scenarios will include drinking water supply from groundwater, partially augmented by river water via managed aquifer recharge and bank filtration schemes; usage of rivers as receiving water bodies for treated wastewater; increasing water demand for agriculture; water demand for cooling; large industrial users; and other scenarios identified in co-designing and co-development workshops with local stakeholders. Model results will be integrated into a large-scale

Solution No.	Task No.	Task title	Lead beneficiary	Demo site #	Task description
					model of the Berlin-Brandenburg water supply catchment, in the Continenal demo site, in order to visualize combined and eventually cascading effects of various usage and management scenarios. The visualisation will act as DSS enabling decision makers to assess the multiscale, multisectoral implications their management approaches and will be the basis for the negotiation platform and participatory approach of the decision theatre in task T4.18.
6	4.7.2	Decision Support System integrating multiple information layers for the sustainable and integrated management of regional water resource	EURAC	7	A participatory DSS for the sustainable and integrated management of the water resource concurrent uses under the framework of the WEFE nexus approach will be set up and demonstrated in the Mountain demo site. The DSS will exploit the regional Resilience Knowledge Booster and will be fed by tailored hydrological impact models, aiming at properly downscaling to the complexity of the mountain context (i) seasonal-scale operational climate services products, accounting for climate variability and (ii) decadal climate change projections. Hydrological models will exploit local-scale and satellite data, seasonal forecasts, and climate projections, provided by Copernicus and GEO Mountains platforms. Tools such as Machine Learning and Multi-Criteria Analysis will serve the DSS for an integrated mediumterm usage plan of the water resource. This will be fully informed by projected decadal trends, allowing the design of longer-term management strategies concerning smart irrigation, flood risk alert, operation of water levels in hydropower reservoirs for energy production in small and large plants, flood control and ecosystem protection.
7	4.8.1	Improving bathing water quality in extreme storm events	EUT	2	Building from the work done by IBATHWATER and the work done by the European Centre for Disease Prevention and Control, tools for the prediction, monitoring and management of increased risk of water-borne diseases will be implemented in the Coastal demo-site. A management tool of Combined Sewer Overflows episodes impact into bathing waters will be implemented combining advanced on-line pathogen monitoring (E.Coli and total coliforms)

Solution No.	Task No.	Task title	Lead beneficiary	Demo site #	Task description
					and water quality models to prevent water quality decrease in the seacoast.
8	4.8.2	Increasing drinking water plants resilience to water-borne pathogens	EUT	2	Resilience of current drinking water treatments on increased algae events in water reservoirs of the Coastal demo site will be addressed. It will be improved through 1) implementing advanced monitoring tools in water reservoirs to predict the algae bloom events, 2) implementing technology based on ultrasonic treatment to prevent the growth in the reservoirs and 3) evaluate solar disinfection for the removal of cyanotoxins during drinking water treatment (by EUT). QMRA techniques will be implemented by KWB; development of an updated version of the decision support tool will be done in order to consider the specificities of the most vulnerable coastal regions and an evaluation of the resilience of current drinking water treatment systems.
9	4.9	Changes in the spatial distribution of species	IUCN	2	By using the latest modelling techniques and analytical frameworks it will be explored how likely the species will change their distributions because associated with climate change. Taking advantage of the RKB and planning tools (WP2) an assessment of potential changes in the spatial distributions for a wide range of taxa that occur in coastal dunes and marshlands along the Catalonian coast will be carried out by comparing projected future distributional changes with past and current distribution. The assessed species including vertebrates, invertebrates and plants will be classified according their risk of local extinction/of significant decrease in local populations and their opportunities to expand their ranges. Adaptation measures to climate change that could benefit of the NBS proposed in Bundle 1 will be identified as a means of strengthening the resilience of target species and ecosystems.
10	4.10.1	Heat awareness system	N&S	4	Digital twins will be enhanced by a heat awareness system by N&S with the support from KWR in the Atlantic demo site. Environmental factors like water bodies, trees, and shade have a

Solution No.	Task No.	Task title	Lead beneficiary	Demo site #	Task description
					major impact on the stress caused by high temperatures. Historical data and temperature increase projections based on existing climate models and remote sensing observation, including probability of occurrence of heat waves, will be included. IMPETUS will be building on these recent advancements by implementing the Physiological Equivalent Temperature using the methodology developed by the National Institute for Public Health and the Environment. The resulting product will highlight locations that are vulnerable to heat stress, thereby serving as a heat awareness system. The system will support societal accountability by unlocking differences in heat stress experienced between areas.
11	4.10.2	Integrated decision support tool coupling a flood risk model onto a digital twin	N&S	4	A decision support tool will be developed to advance integrated flood risk management by combining the compelling visuals and rich geospatial data of digital twins with the predictive power of flood risk models. The flood risk model 3Di will be coupled with a digital twin of the region of Zeeland. A novel sub-grid technology (Volp et al., 2013) will be applied to include the high-resolution geospatial data in the 3Di flood models. The output of 3Di will be at the same resolution as the input and will be visualised in the digital twin. Any intervention in the digital twin will automatically be fed into new flood risk simulations so that the result is a versatile decision support tool that can be used by decision makers. Moreover, the tool will be used for gamification (https://doi.org/10.3390/w10121885) as a method for cocreating resilient flood solutions.
12	4.10.3	Multi-layer integrated flood risk management, Decision Support and Early Warning System for civil protection	BEF	6	A regional GIS-based communication system for exchange of information is extended with a real time analytical approach integrating water level (monitoring and visual evaluation) measurements to build a decision support and early warning system to support flood risk management and civil protection in case of potential flood events in the Zemgale Region (Latvia). Updating and upscaling geospatial information for precise prediction using satellite data (provided by LOB), as well as the

Solution No.	Task No.	Task title	Lead beneficiary	Demo site #	Task description
					riverbed bathymetry data and LIDAR or satellite scanning of terrain, as well as topographic surveys, upscaling of existing Jelgava city Interactive map to regional level. Interactive maps with layered flooding possibilities, embedded from the Latvian Geospatial Information Agency will be used for operative reporting. Early warning registry module for EWS will serve to provide information about potential flooding, and upscaling Jelgava City Unified Information Exchange System to a regional level. Linking the local/regional EWS module with the national monitoring system (operated by the Latvian Environment Geology and Meteorology Center) for automated data exchange and use in civil protection and daily operations. Such multi-layer system will ensure possibility to evaluate flooding risks prior the event and to provide public institutions and citizens with the necessary information package to select appropriate measures for effective protection of people, health, environment, economic activities. Making use of the regional RKB, the demonstration will be up scaled from city level to regional level through the involvement of stakeholders in co-creation to ensure a multi-governance approach.
13	4.10.4	Regional Digital Twin for climate adaptation and green business development	NTUA	3	A Digital Twin (DT) of the Region of Attica (Mediterranean demo site) will be developed and built on existing datadriven platform initiatives in the Region of Attica (led by the Ministry of Environment and Energy (GSNEW) and the Decentralized Administration of Attica (see LoS) to create as a central hub for related data and knowledge to be turned into action in a co-creation process. The DT will provide: (i) access to relevant datasets (environmental, climatic, uses of resources etc.); (ii) access to relevant climate adaptation services (e.g. climate services, services to farmers, services to municipalities) (iii) links to local and regional Communities of Practice (CoP) (iv) a repository for demonstrations of climate adaptation innovations within the region (both created in past projects – such as NextGen, DESSIN and SUBSOL – and in IMPETUS) and (v) a platform for business innovation through dedicated data-driven

Solution No.	Task No.	Task title	Lead beneficiary	Demo site #	Task description
					greenathons under the auspices of GSNEW. The development of the digital twin will leverage technologies and designs developed within WP2.
14	4.11	Climate-proofing of the city centre and of its urban water infrastructure against sea level rise	UiT	5	Low-lying coastal urban areas are at high risk of increased coastal flooding. The demonstration, complementing an ongoing programme led by the Tromsø municipality (with the engineering company SWECO as consultant) of climateadaptive development and urban rehabilitation, will experience a mix of different technical solutions, such as floating walking paths – also on the urban water system – that will allow in the short-term to minimise relocation, while providing lead time for planning future real estate and infrastructure developments. UiT will work together with the Tromsø municipality, its consultants and all stakeholders to co-develop additional technical solutions to be demonstrated in significant size. The co-design process will be carried out within the regional RKB, making also use of the digital twin of the coastal area. TFFK will incorporate the results within its planning activity and ensure the replication in other similar situations in the County. The Tromsø municipality and SWECO have signed support letters witnessing their will to collaborate with IMPETUS.
15	4.12	Early-warning system for geological and avalanche risk sites	UiT	5	The current EWS for rockslide and rockfall risk in the Artic demo site ensures a rather short lead time of warning with respect to events that may be very rapid and destructive. In Lyngerfjord, a rock slope is made unstable because of climate change driven permafrost thawing and increase precipitations, implying a modelled 40m-high wave run-up in the fjord within 10" from a massive rockslide event. In other parts of the fjord, destructive avalanches and quick-clay landslides are also impacting on living and communication infrastructure. Therefore, UiT will design the specifications and follow the implementation of innovative systems that allow to substantially extend the current anticipation time in the specific situation at the Lyngerfjord. For potentially devastating rockslides, that are already monitored, the innovation will consist of new advanced ground-based radar monitoring

Solution No.	Task No.	Task title	Lead beneficiary	Demo site #	Task description
					coupled with real-time observation of weather and climate-related parameters. For avalanches, the new system will be composed of a combination of ground-based and ground-penetrating radar generating an automatic warning. For quick-clay landslides, the system will use an array of ground penetration mapping using a CPTU (cone penetrometer), and installation of real-time piezometers to monitor groundwater pressure in risky areas identified by the CPTU. TFFK will supervise and monitor the demonstration and support the replication of the new technologies in other locations in the County, having already planned a budget for a new programme of interventions.

2 Innovative Technologies Implementation

2.1 Solution 1: Decentralized hybrid fit-for-use water reclamation systems for increasing water availability (Task 4.5.1)

The Catalan coast faces significant environmental challenges mainly due to climate change impacts like water scarcity as one of the most relevant, but also due to the impact of tourism. Related to water scarcity Catalonia faced a severe drought between 2021 and beginning of 2024 with a decrease in rainfall between 15 and 30% and an increase in temperatures with a record in the year 2024 being the third warmest year on record in Catalonia (2.1ºC above the 1961-1990 baseline), following the record-setting years of 2022 (2.7ºC) and 2023 (2.4ºC), according to a report from the Catalan Meteorological Service (Generalitat de Catalunya, 2025). Also, summer visitors concentrate on the coast and use more water per person than residents (≈163 L/day on average and up to ~240 L in luxury hotels), prompting proposals to cap tourist consumption and align it with local limits. Therefore, protecting the environment and increasing the water availability in touristic infrastructures is essential to mitigate these growing risks and ensure long-term sustainability.

A Regional Strategy has been developed by the Government of Catalonia called the river basin district management plan of Catalonia 2022-2027. It includes measures to enhance desalination, water reuse, and water treatment. In terms of water reuse, the Spanish Royal Decree 1085/2024, of October 22, approving the Regulation on the Reuse of Water must be fulfilled.

The 600 km Catalan coastline in the northeastern Mediterranean is characterized by a temperate climate and hosts a wide range of geological and biodiversity systems. The area's designation as a hotspot arises from the convergence of natural and societal factors, including critical infrastructure, industrial activities, tourism, high urban density, and agricultural production, all of which intensively compete for limited natural resources.

Touristic infrastructures both intensify and can help address water scarcity along the Catalan coast. While hotels and resorts consume far more water per visitor than residents, especially during peak seasons, they also have the capacity to adopt decentralized reuse systems. By implementing circular water management, these sites can reduce pressure on public supplies and strengthen resilience to drought.

This combination of environmental pressures such as climate-induced drought, rising tourist demand, and competing water uses has guided the selection of a decentralized treatment scheme tailored to the conditions of the Catalan coast. The system (Figure 66 in Annex 6.1) proposed within this task integrates an Upflow Anaerobic Sludge Blanket (UASB) reactor for primary organic load reduction and biogas production, an ultrafiltration (UF) unit to ensure reliable removal of suspended solids and pathogens, a nature-based solution (NBS) wetland to further polish nutrients under variable loading conditions, and a final disinfection step to guarantee compliance with reuse standards. This combination provides a robust yet energy-efficient alternative to large-scale wastewater treatment, while remaining spatially adaptable to touristic facilities. Its modularity, scalability, and alignment with Spanish Royal Decree 1085/2024 and the EU Water Reuse Regulation make it particularly suitable for supporting sustainable water reuse in coastal tourism infrastructures.

Therefore, the **objectives** of this task are:
- Obtain reused water with quality for irrigation and cleaning purposes
- Improve the vision and acceptance of the stakeholders for water reuse.
- Increase water availability in touristic infrastructures promoting decentralized circular economy solutions for water reuse.

2.1.1 Results

Different activities have been carried out in this task. First, a state-of-the-art was revised to design a bench-scale experimental set-up. After that, two different sets of bench-scale experiments were conducted during low and high occupancy seasons, respectively, to design the pilot plant in Tamarit Beach Resort campsite in Tarragona. This campsite is in the Costa Daurada region, in the south of Catalonia. Its design was carried out based on the results obtained in the bench-scale experiments. However, due to construction delays the operation of the pilot plant was delayed and after one-month and a half of operating it had to be stopped due to the closure of the campsite for winter season. The operation of the pilot plant started again once the campsite reopened for spring and summer season and was operating for 3 months. Below are the results obtained in the different activities carried out can be observed.

Bench-scale experiments:
The results from the first set of bench-scale experiments showed that the AnMBR performance had an average 70% of COD removal with effluent concentration below 15 mg/L, and the nutrient removal were very low (no total N removal observed and 4% total P removal). These experiments were performed with wastewater from low occupancy conditions. Results obtained in the second set of bench-scale experiments treating wastewater from high occupancy conditions were used to observe the performance of the system under higher COD and nutrient loading conditions and to design the pilot plant accordingly. This showed that a biofilter after the AnMBR was necessary to achieve the required water quality in the high occupancy season. Between 0,5-1 m^3/day of reclaimed water was obtained with a 70-90% removal of COD, 80 % removal of total phosphorus, and 36% removal of total nitrogen. Also, in these batch tests, the suspended solids were <10 mg/L and turbidity was < 1NTU, which are indicators of water quality and fulfilled the limits of the Spanish Royal Decree 1085/2024 for reuse of wastewater (Table 9 in Annex 6.1). No analysis of pathogenic microorganisms was carried out, since no disinfection treatment was applied in the laboratory-scale analyses due to resource constraints. Therefore, other indicators such as *E. coli, Legionella spp*., *Intestinal nematodes* and *Bacteriophages,* of the RD 1085/2024 couldn't be checked and compared.

Pilot plant implementation and results
Due to construction delays the implementation of the pilot plant was also delayed. However, to avoid a longer delay, the first unit of the treatment system at the campsite, the anaerobic reactor, was started at the end of August 2024. In this way the operation of the pilot plant would not be delayed any further, and it would be possible to work with water under high occupancy conditions at the campsite initially. The other units (UF, biofilters, and disinfection unit) were implemented between the end of September and the beginning of October 2024. However, during those months the occupancy was very low, and the pilot plant had to be stopped at the end of October 2024 because the campsite closed. The campsite reopened in April 2025, and the pilot plant started operating again. The pilot plant operated from mid-April 2025 under low occupancy conditions until the end of July 2025 under high occupancy conditions.

In Figure 2 on the left, a picture of the skid tanks of the pilot plant is shown and it is explained below the image. On the right, the first 3 units of the pilot plant can be seen:
- The anaerobic bioreactor which consists of a 4 m UASB.
- The UF membrane, on the left side of the UASB.
- The Biofilter which is in front of the anaerobic bioreactor.

Figure 2 Skid tanks of the pilot plant (left) and pilot plant (right).

The inlet of the pilot plant is stored in a tank connected to the main wastewater supply (manhole) to supply wastewater to the UASB. The UASB reactor allows for the treatment of organic matter while producing biogas, primarily methane. In this reactor, wastewater flows upward through a granular sludge bed, the biocatalyst for degrading organic pollutants *(Senadheera , et al., 2025)*. The outlet of the UASB reactor from the upper part is collected in a second tank and pumped to the UF unit. This second tank also collects the concentrated flow of the UF unit. In the UF unit the remaining solids that were not removed in the UASB are retained. Following the ultrafiltration stage, there is a third tank that stores the treated water after the UF. After this tank water goes into a biofilter which is a nature-based solution for removing nutrients from the system. This NbS consisted of a vertical wetland filled with fine gravel, sand and a protective top layer of natural river gravel/stones applied to enhance flow distribution and prevent clogging. The plants used for this NbS were 9 *Phragmites australis*. The outlet of the NbS is pumped to a fourth tank where the chlorination step is carried out. The outlet of this tank is the reused water that will be used for irrigation and cleaning purposes. The last tank on the right side of the picture (white tank) is the scrapping tank where all the water is collected and sent back to the manhole. It is used to prevent spills due to overflows in the other tanks. During the operation of the pilot plant, all the water reused produced was redirected to the manhole.

The operation of the pilot plant started with the anaerobic bioreactor only. On the 8th of April 2025 the inoculation and start-up of the bioreactor was performed, starting with the adaptation of the biomass to the wastewater. The bioreactor was inoculated with digestate biomass from a wastewater treatment plant nearby the campsite. The adaptation of the biomass is the task that should take most of the time, as the UF and the other units do not require such a complex start-up. On the 15th of April the UF started to operate together with the anaerobic bioreactor. Later, at the end of April, the Biofilter unit started to operate. And finally, on the 4th of July the disinfection step got started.

The overall results obtained from the operation of the pilot plant showed a total COD removal of 97% and an 86% removal of dissolved COD.
On the other hand, the turbidity levels obtained on the effluent were 119 NTU. These turbidity results are compliant for some uses for reused water within the Spanish law (RD 1085/2024) such as quality A.B and A.C for agricultural uses and quality U.B for urban uses. However, it couldn't be used for as quality A.A for agricultural use since the limit of turbidity for the RD 1085/2025 for these uses is under 5 NTU (Table 9 in Annex 6.1).
Conversely, in terms of the suspended solids, these were <10 mg SS/L in the effluent of the biofilter unit since the beginning of June which is within the RD 1085/2024 (10 mg SS/L). The overall removal of suspended solids in the pilot plant was 100%. Results can be observed in Figure 3.
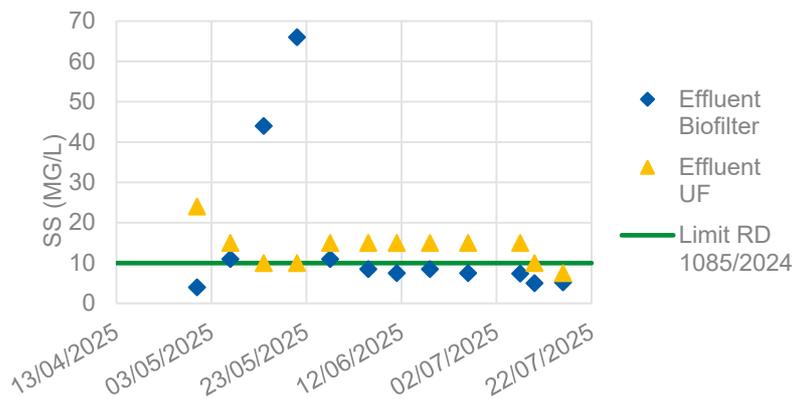
Figure 3 Suspended solids in the UF effluent and the Biofilter effluent and the limit of RD 1085/2024.

As it can be observed in the previous figure the suspended solids at the effluent of the UF unit were mostly around 15 mg/L, therefore another process was needed to remove these solids and to accomplish the limit of 10 mg SS/L of the RD 1085/2024.

On the other hand, nutrients such as total nitrogen and total phosphorus should be removed mainly in the Biofilter, however the ammonia removal of the pilot plant was 8% and there was no production of nitrate or nitrite, therefore the total nitrogen removal takes only the ammonia removal. For the case of the total phosphorus, the overall removal of total P was 58%. In Table 2 the causes and possible improvements for low nutrient removal are discussed.

Table 2 Causes and possible improvements for low nutrient removal.

Observed Issue	Likely Cause	Proposed Improvement
Low nutrient removal	Short hydraulic retention time (HRT = 8 h)	Extend HRT to 2–3 days (requires installation of an electro valve to regulate influent flow)
Incomplete nitrification due to insufficient oxygen	Limited natural oxygen transfer within vertical wetland	Force aeration/oxygenation to improve ammonia → nitrite → nitrate conversion
Lack of denitrification step	Single NBS (vertical wetland) only supports nitrification; no anoxic conditions to complete nitrogen cycle	Add a second NBS: horizontal flow wetland with gravel substrate and *Phragmites australis*, designed with anoxic zones to enable denitrification (nitrate → nitrite → nitrogen gas)

In terms of the total and dissolved COD removal in each of the units of the pilot plant, the anaerobic reactor removed 92% of total COD, and the ultrafiltration process removed 58% of the total COD entering the UF unit. On the other hand, the Biofilter was able to remove more dissolved COD than total since 50% of dissolved COD was removed in the Biofilter unit whereas only 16% of the total COD was removed in this unit. This is because most of the COD entering the pilot plant was particulate COD, which is organic matter in suspended particles, which require physical removal (sedimentation, filtration) or slow biodegradation. And the dissolved COD is the fraction of COD composed of soluble organic compounds (e.g., volatile fatty acids, sugars, amino acids). Therefore, most of the COD was eliminated in the first unit of the pilot plant, some remaining COD was removed in the second unit and in the last unit of the plant mostly dissolved COD was removed.

The RD 1085/2024 for reuse of wastewater also considers other indicators such as *E. coli, Legionella spp.*, *Intestinal nematodes* and *Bacteriophages*. These indicators have been analyzed at the effluent of the pilot plant after the chlorination step once per week during the operation of the pilot plant. These results show absence of all the indicators (results can be observed in Table 3). Also, free chlorine was controlled automatically by a chlorine analyzer every 5 minutes and it was set between 0,5 and 1ppm of free chlorine.

Table 3 Results obtained for the pathogenic microorganisms' indicators of the RD 1085/2024 for reuse of wastewater.

Coliform bacteria (ufc/100mL)	E.coli (ufc/100mL)	Clostridium Perfringens (ufc/100mL)	Legionella spp (ufc/1mL)	Intestinal nematodes (eggs/L)	Bacteriophages (UFP/100mL)
0	0	0	<25	<1	<100

On the other hand, the anaerobic reactor produced biogas with amethane content of only 1.7 -2.4% far below the 65% typically reported in anaerobic systems (Abuzir, et al., 2025) (Gao, Zhang, & Liu, 2020), indicating poor development of methanogens. Instead, NH_3 and H_2S gases were produced over 500ppmv. Ammonia stripping likely occurred due to recirculation of UASB effluent combined with UF concentrate, while the presence of hydrogen sulfide gas confirmed growth of sulphate-reducing bacteria (SRB). Since SRB compete with methanogens for substrate (Percheron, Bernet, & Moletta, 1997) and high concentrations of ammonia are toxic to methanogens (Borja, Sánchez, & Weiland, 1996). However, this limitation does not affect the projects' objectives, as energy recovery was not a primary goal of the study.

Online interviews with stakeholders as Key Actors in Water Management
Online interviews with stakeholders have been carried out during the operation of the pilot plant to obtain feedback on the proposed solution from the principal actors involved.
Four different stakeholders from different sectors related to water management and tourism in Catalonia have been interviewed. In Table 4 a description of each of the interviewees can be seen:

Table 4 Description of the company, role and city of each of the interviewers.

Interviewees	Company	Role	City
Lucia Gusmaroli	Catalan Water Partnership	Project Manager of European Projects	Girona
Joan Soler	Clarà Campsite and Bungalows	Director	Altafulla
Laura Pérez	Hotel Samba	Environmental Coordinator	Lloret de Mar
Isaac Gallego	Tamarit Beach Resort Campsite	Director	Altafulla

Aspects such as stakeholder needs and current practices, requirements, opportunities, and barriers related to decentralized systems and their application in touristic sites in Catalonia have been discussed. Some identified barriers in between all the stakeholders stated:
- Technical: Lack of knowledge about reuse technologies and their operation/maintenance.
- Social: Tourists and staff are often unaware of water scarcity and the solutions being implemented.
- Regulatory: The RD1085/2024 regulation on water reuse causes uncertainty and imposes strict, expensive analytical requirements.
- Economic: High installation, maintenance, and operation costs; insufficient or unclear subsidies.
- Spatial & aesthetic: Difficulty installing systems underground or without visual impact.

On the other hand, some opportunities arise:
- Increases water resilience at consumption points.
- Reduces potable water bills and ensures supply during droughts.
- Enables biogas production or irrigation water from treated greywater and wastewater
- Camping customers are highly aware of water issues and concerned about sustainability

However, for touristic infrastructures to start using and installing decentralized systems some actions need to be taken:
- Simplify subsidies and funding mechanisms.
- More government incentives for tech adoption and water reuse.
- Promote awareness campaigns and workshops.

- Simplify local permits and processes.
- Invest in staff training and ensure resources for ongoing system maintenance.

In conclusion, decentralized systems such as pilot plant presented here offer a practical pathway to strengthen water resilience in touristic infrastructures, but their uptake requires reducing regulatory complexity, simplifying funding, and improving technical training. Operational adaptations such as an optimization of UASB biogas production, modular UF units and flexible NBS design operation can lower costs and increase acceptance. With supportive incentives and awareness campaigns, these systems can become key tools for sustainable water management along the Catalan coast.

2.1.2 Impact

The results obtained on this task show a promising outcome as a solution to decentralized wastewater treatment and water reuse in touristic infrastructures. The proposed key performance indicators (KPI's) for this task were described in D4.1 and are the quality of treated water and achievement of the standards of the guides, the percentage of removal of the different indicators and the amount of reclaimed water. Regarding the quality of the treated water and the percentage of removal of the different indicators regulated by the RD 1085/2024 have been achieved. On the other hand, the pilot plant achieved its design capacity of 12 m³/day of reclaimed water, resulting in a 20% increase in water availability for the campsite.

To improve the vision and acceptance of the stakeholders some barriers need to be addressed related to the Catalan Institutions and Administration such as investments and fundings as well as simplification of local permits and processes. On the other hand, more awareness about decentralized systems, the technologies used in these systems and their advantages need to reach more people to be able to apply these technologies and have a more resilient use of water in tourism infrastructures.

Regarding the amount of reclaimed water, some short and long-term effects and direct and indirect impacts can be discussed:

- Short-term: Increase of 20% water availability in touristic infrastructures.
- Long-term: Increase of water availability in coastal zones. Reduction of dependence on conventional water sources in touristic infrastructures.
- Direct impacts: Water reuse as irrigation and clearing streets and smaller footprint.
- Indirect impact: The Catalan coast experiences seasonal water shortages, therefore reusing water makes the campsite more self-sufficient. Economic benefits for the touristic infrastructures since it attracts eco-conscious tourists, improving the campsite's sustainability image.

2.1.3 Lessons Learned

- The system is designed for long-term use in areas with limited access to centralized water infrastructure, including the tourism infrastructure.
- It offers sustainable water quality improvements and long-term cost reduction, addressing the increased demand for water in touristic regions.
- Its scalability allows it to serve both small and large-scale applications, easing scalability due to its modularity, although transferability may be constrained by local regulations and specific water treatment needs.
- The target audience includes municipalities, industries, touristic infrastructures, and regions facing water scarcity or lacking centralized infrastructure.
- The treatment system presented effectively addresses the challenges posed by seasonality in tourist facilities and the change in composition of their wastewater at high or low occupancy. While the system demonstrates resilience in the removal of organic matter across different seasons through the application of UASB technology, the challenges are the variations in the wastewater composition in terms of nutrients, specifically nitrogen. The incorporation of biofilters as a nature-based solution is not enough, and it can't ensure nutrient removal and turbidity. This performance is due to different reasons as design limitations and operation issues, such as short hydraulic retention times and low oxygen transfer. Therefore, improvement in another combination of nature-based solutions must be applied to ensure treated water quality.

2.1.4 Conclusion

- A second set of bench scale experiments was performed and proved the robustness of the wastewater treatment system under high occupancy conditions since nutrients and organic matter were removed, and suspended solids and turbidity fulfilled the limits of RD 1085/2024.
- The pilot plant operated for 12 weeks during low and high occupancies.
- The reuse wastewater produced from this pilot plant showed results within the RD 1085/2024 for quality classes A.B, A.C and U.B.
- Several interviews were conducted with key stakeholders in Catalonia's tourism and water sectors, and highlighted that while decentralized water reuse systems offer resilience, cost savings, and sustainability benefits, their widespread adoption is hindered by technical, social, regulatory, economic, and spatial barriers: requiring improved incentives, awareness, training, and simplified procedures to overcome them.
- The system is designed for long-term use in areas with limited access to centralized water infrastructure, including the tourism infrastructure, and offers sustainable water quality improvements and long-term cost reductions, addressing the increased demand for water in touristic regions.
- Decentralized NbS wastewater reuse systems proven robust at pilot scale should be scaled through modular designs, standardized monitoring, supportive regulation, tailored incentives, and stakeholder training to enable widespread, sustainable adoption in tourism-dependent regions.

2.2 Solution 2: Sewer Mining for multi-sector climate proofing (Task 4.5.2)

Sewer mining is an innovative wastewater recycling technology that transforms wastewater into a valuable resource, enhancing the circularity of urban environments but also boosting community resilience and supporting a sustainable transition to address projected climate change.
The core idea behind this pioneering technology is to install treatment plants where the demand lies and where the resource is readily available, given that wastewater is ubiquitous throughout a city. Specifically, wastewater is extracted from local sewers, treated directly on-site, and either reused immediately at the point of demand or stored for later use. The technology is gaining popularity due to its efficiency in treatment and its minimal space requirements for installation.

The current research explores the implementation of sewer mining technology in a real-world setting, in Markopoulo, situated in the eastern part of the Attica Region. The study conclusively demonstrates that sewer mining is a viable solution for water reuse, particularly in densely urbanized areas that face space constraints and are vulnerable to drought. By integrating sewer mining with freshwater conservation efforts, cities can significantly expand urban green spaces, helping to mitigate the adverse effects of urban heat islands and heatwaves. Furthermore, these solutions alleviate pressures on existing sewage treatment facilities. Consequently, leveraging the latent potential of sewage as a valuable resource beneath city streets emerges as a highly effective strategy for enhancing urban resilience to climate change.

Task objectives:

- Design, build and deploy a Sewer Mining (SM) unit tapping into the East Attica wastewater system for reusing water at the point of demand for irrigation and for climate proofing against droughts.
- Integrate the SM unit's knowledge and data into the Attica Digital Twin (T4.10.4)
- Enhance stakeholders' engagement in co-creating new climate change adaptation services around the 'new' water resource.

2.2.1 Results

A flexible, scalable and replicable wastewater treatment system has been conceptualised, implemented, tested and optimised in this drought-prone Mediterranean area, in the Municipality of Markopoulo, East Attica, serving as the ideal setting to demonstrate the potential of circularity in densely urban environments, as well as the effectiveness and adaptability of this solution.

The process involved extracting sewage from a local urban network drain pipe using pumps to fill a subsurface buffer tank. The collected wastewater was then treated onsite using a membrane bioreactor (MBR) unit and a UV disinfection component, producing high-quality reclaimed water suitable for irrigation, aquifer recharge, and other urban uses (see Figure 4, Figure 5, and Figure 67 in Annex 6.2).
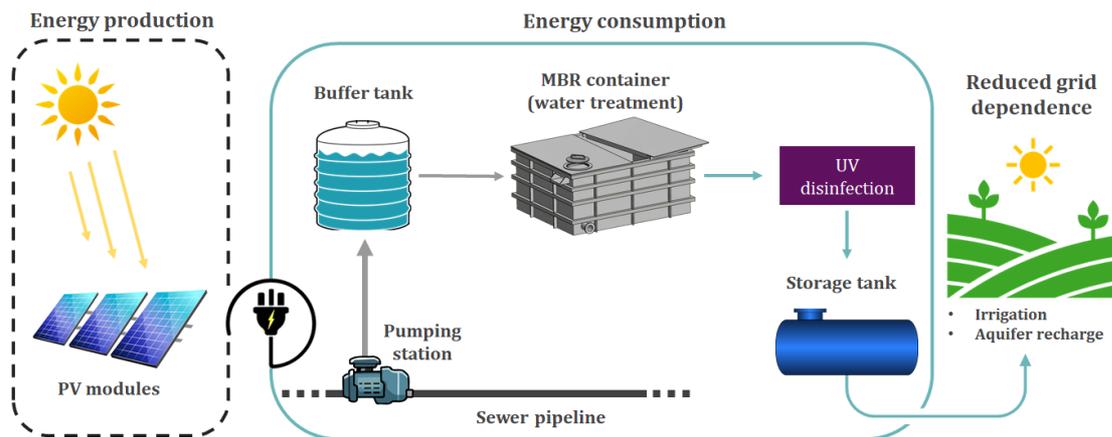
Figure 4 Sewer Mining configuration

Figure 5 Sewer Mining unit and tanks installed in the Old Railway Station park of the Municipality of Markopoulo, East Attica. View of the tanks of the treatment station (top); overall view of the treatment system container (bottom).

This system consistently supplies approximately 25 m^3 of reclaimed water daily, providing continuous irrigation to a portion of the Markopoulo green spaces. The entire process is closely monitored through dedicated sensors, including tank level sensors, pH meters, Mixed Liquor Suspended Solids (MLSS) sensors, and dissolved oxygen probes. Automation is achieved using pneumatically actuated valves, controlled by a programmable logic controller (PLC) system (see Figure 6). Additionally, the local PLC system is integrated with the Attica Digital Twin platform (T4.10.4), enabling real-time data flow and visual representation of the system's performance. Further to the online monitoring, laboratory tests are conducted for a series of parameters: COD – Chemical Oxygen Demand; BOD – Biochemical Oxygen Demand; TP – Total Phosphorus; TN – Total Nitrogen; NH$_4^+$-N – Ammonium Nitrogen; NO$_3^-$-N – Nitrate Nitrogen; TC – Total Coliforms; E. coli – *Escherichia coli* (commonly referred to as *E. coli*); pH (a measure of acidity or alkalinity); EC – Electrical Conductivity (indicates ion concentration in water); DO – Dissolved Oxygen; TMP – Transmembrane Pressure (used in membrane filtration systems). These measurements were taken on a bi-weekly basis and for dedicated monitoring and cross-validation.

The successful installation and operation of the unit were made possible through collaboration with multiple stakeholders to ensure all necessary permits were obtained. Specifically, an archaeological permit was required for excavation work related to the pumping station and subsurface tanks. Furthermore, approval from the competent regional Architectural Council was granted for the configuration's installation. Lastly, a new power supply was established through a series of internal procedures and fee payments conducted by the project consortium.
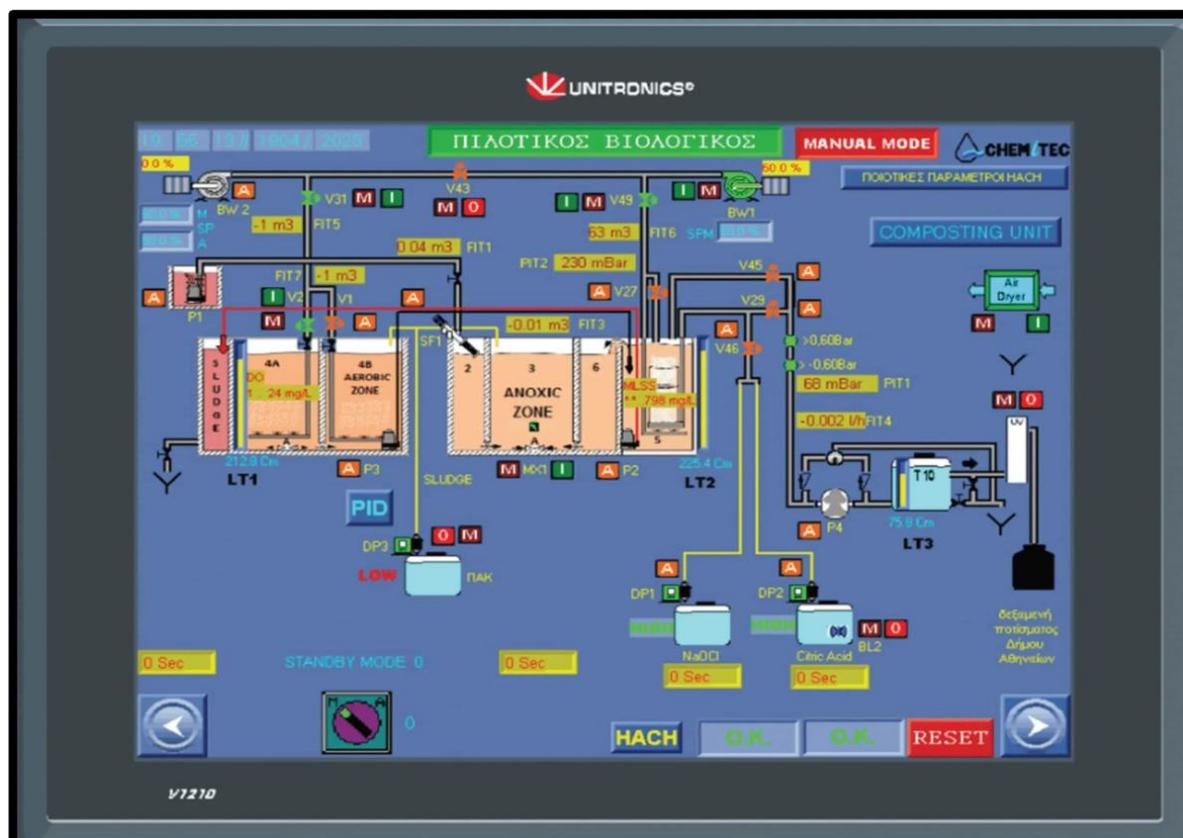
Figure 6 PLC system overview.

The whole performance of the unit and of the pumping station has shown great stability. The hybrid MBR/UV had a start period of approximately 5 weeks. Figure 7 illustrates the start-up period of the unit regarding COD removal, along with some period of early steady state conditions. Concentrations of the raw sewage show many fluctuations but that does not affect the effluent COD concentrations. Even during start up the effluent COD had concentrations of 60 mg/l, which then decreased further and stabilized at the average value of 34 mg/l. It is evident that even during the start-up period, the removal rates are higher than 90% which shows that the MBR technology is a very safe technology to use due to the great stability it provides.

Figure 8 and Figure 9 depict the MBR performance for the whole-time operation in terms of TSS and NH4-N removal, respectively. More specifically, Figure 8 shows the TSS of the inlet and the outlet, the MLSS concentration inside the MBR tank, as well as the online measurements of the installed probe. It is evident that TSS concentrations of the effluent are approaching zero while the readings from the installed online probe closely coincide with the laboratory analysis results, confirming the reliability and accuracy of the probe measurements. Figure 9 illustrates the concentrations of the NH4-N of the inlet and the outlet. It is shown that after the 33th day the nitrification started decreasing while the effluent concentrations after the steady state conditions occurred are reaching zero. Table 5 illustrates the aggregated results for the quality characteristics of the Hybrid MBR/UV effluent of the experimental system along with the limit values as set in the Greek National legislation regarding wastewater reuse for unrestricted irrigation and urban use (JMD 145116/2011).
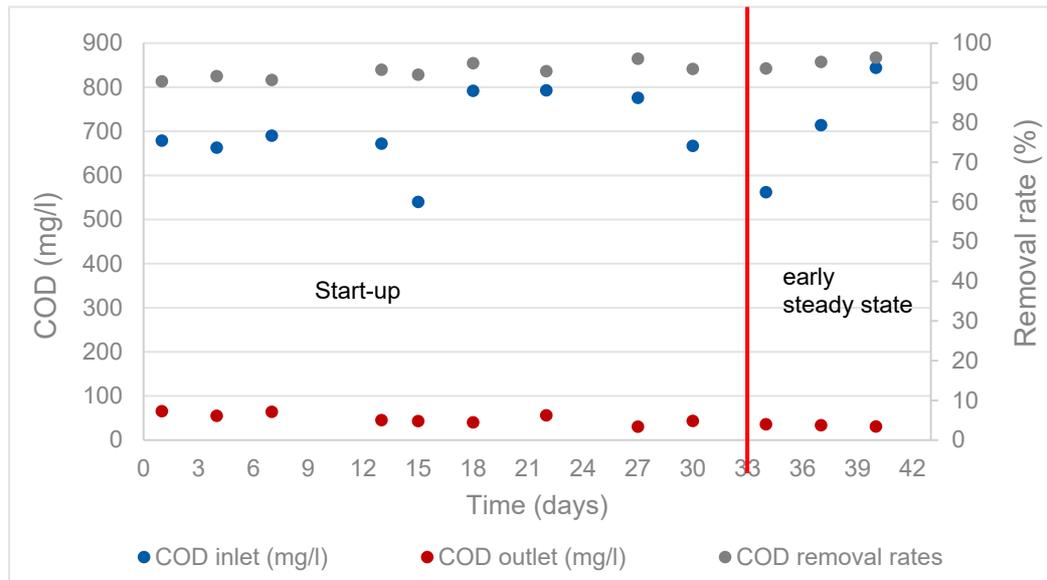
Figure 7 Start-up period for COD.
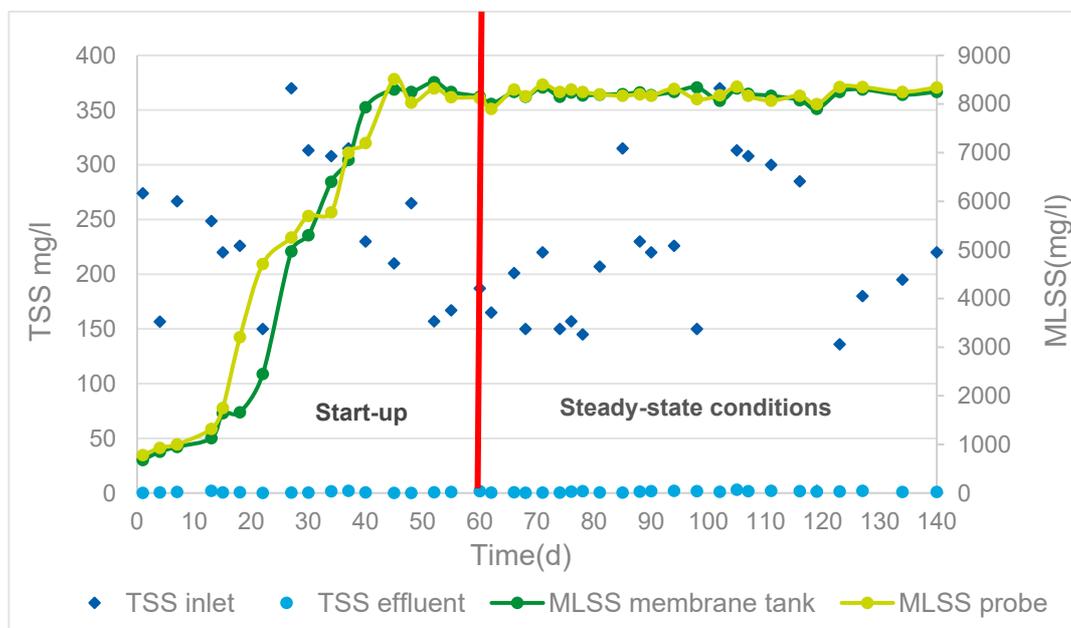
Figure 8 MBR performance in terms of TSS removal.

It is evident that the MBR effluent characteristics lie within the limits set in the Greek wastewater reuse legislation for unrestricted irrigation and urban use. Its E. coli and FC content is minimal, while its TC content is low. There are some values for Total Nitrogen and Ammoniacal Nitrogen during the start-up that are higher than the limits set in the National Legislation. This is due to nitrification-denitrification, which is a slow process to start. Therefore, it is anticipated that to achieve effluent characteristics for all the parameters system needs to find steady state conditions. For an MBR system, normally this takes approximately 5-7 weeks.
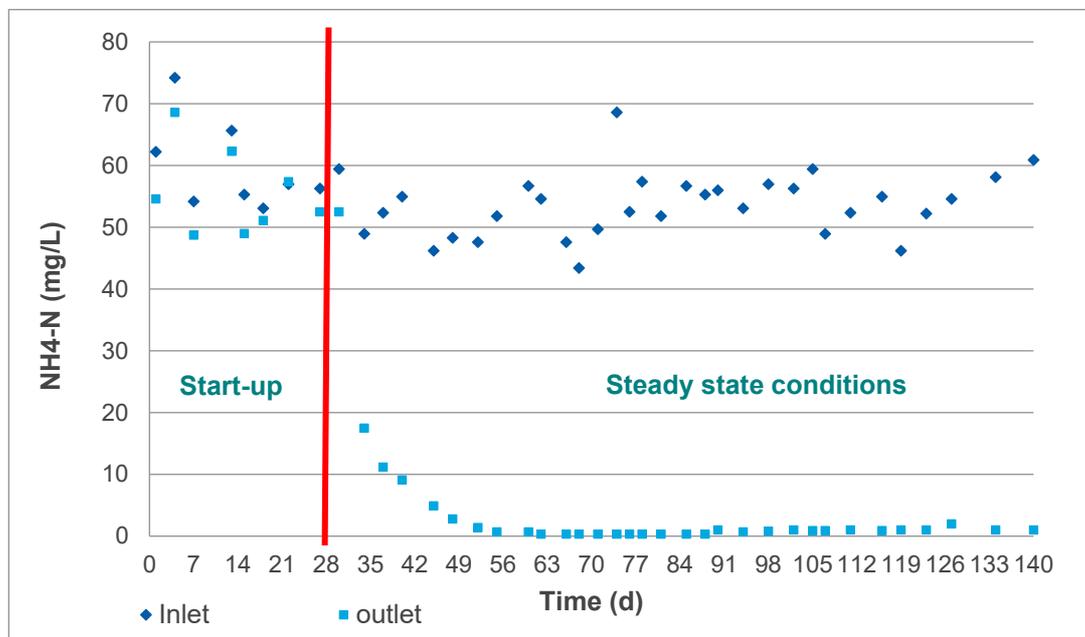
Figure 9 MBR performance in terms of NH4-N removal.

Table 5 Performance of the Hybrid MBR/UV pilot system (concentrations in mg/L, TC, FC, E. coli in cfu/100 mL, turbidity in NTU, Electrical Conductivity in µS/cm).

Parameters	Influent[a]	Effluent after UV disinfection	Legislation limits[b]
TSS	253 ±97 [c]	≤2 for 80% of samples	≤2 for 80% of samples[e] ≤10 for 80% of samples[d]
BOD$_5$	216 ±64 [c]	9(average) 9.6 for 80% of samples	≤10 for 80% of samples[d,e]
CODt	695±97 [c]	34±5 [c]	
TN	81(average)	18(average)	≤15[d,e]
NH$_4$-N	5±3 [c]	0.25±0.3 [c]	≤2[d,e]
TP	10±1.4 [c]	5.9 ±1 [c]	-
Turbidity	-	2 (median)	≤2 (median)[d,e]
Conductivity	1109±75[c]	1067±170[c]	-
pH	7.1±0.1[c]	7.5 ±0.3[c]	-
TC	>10[f]	2 for 80% of samples 9 for 95% of samples	≤2 for 80% of samples[d] ≤ 20 for 95% of samples[d]
FC	>10[f]	≤ 3	-
E. coli	>10[f]	≤ 3 for 80% of samples ≤ 3 for 95% of samples	≤5 for 80% of samples[d] ≤50 for 95% of samples[d]

[a] refer to filtered wastewater; [b] refer to the Greek legislation regarding wastewater reuse (Joint Ministerial Decision 354/8-3-2011); [c] average ± standard deviation; [d] refer to the limit values set in the Greek legislation for wastewater reuse for unrestricted irrigation and/or industrial reuse; [e] refer to the limit values set in the Greek legislation for urban reuse and/or groundwater recharge; [f] refer to the limit value set in the Greek legislation for every type of reuse for WWTPs with a population equivalent greater than 100,000.

Table 5 presents the aggregated results from October 2024 until January 2025. The results confirm what was already concluded from our previous experience that the Hybrid MBR/UV unit manages the removal of the organic content and also with high rates of nitrification. The microbial load is also completely removed after the UV disinfection unit. The UV performance is presented by providing microbial data before (MBR tank) and after the UV disinfection.

A critical operational issue of SM units is the cost of electricity, due to power consumption across all their components (pumps, MBRs, disinfection), which may constitute their economic feasibility rather questionable. To address this matter, the integration of solar photovoltaics as a potential solution was considered and various scenarios were investigated.

Two design optimization scenarios were investigated, accounting for least-cost and least-area criteria. Our analyses reveal interesting trade-offs between the area captured by the PV panels and the aggregated annual cost, estimated as the sum of depreciated installation cost of PVs and cost of electricity (grid supply). Apparently, as the area captured by the PV panels increases, higher power autonomy (defined as the ratio of daily energy production to daily demand) is ensured. On the one hand, the least area scenarios require the installation of high-efficiency modules, which come at an increased cost. On the other, the optimal cost scenarios opt for conventional, cost-effective modules, yet require larger occupied areas. Furthermore, the alternative of tilted PVs results to increased overall efficiency and reduced costs, was also examined. As a best compromise solution, a compact layout was assessed, covering the SM unit's footprint with PVs on a pergola placed above it (for an area of ~100 m2 and a ~85% power autonomy), integrating the tilted aspect in the design of the pergola, so as to achieve the minimum grid dependence in the best possible investment cost (Figure 10).
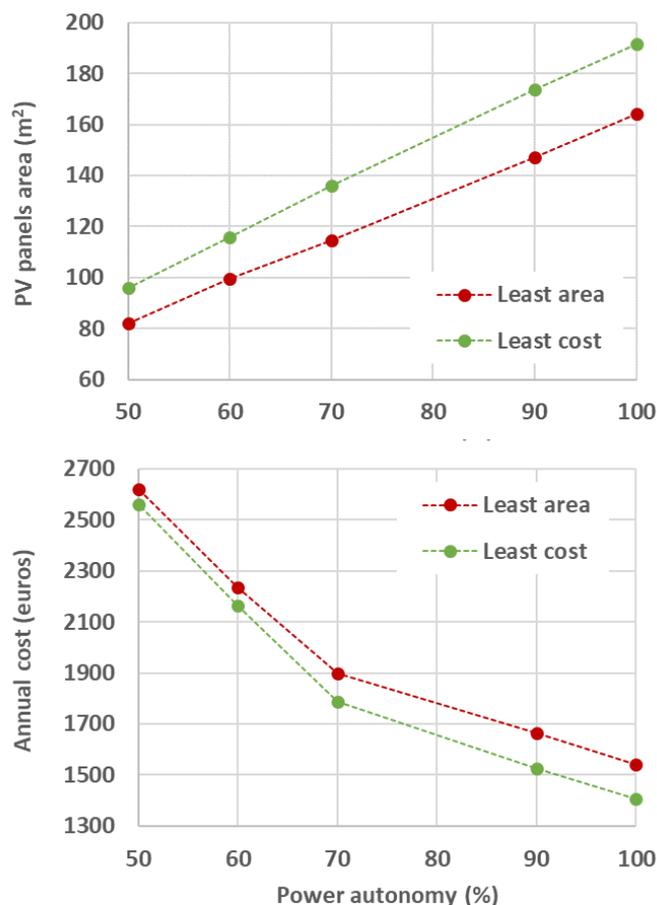
Figure 10 Graphs of the cost and PV panel area with respect to SM unit power autonomy for the two optimization scenarios (least area, least cost)

The successful adoption of such technologies requires extensive stakeholder engagement, involving not only local communities but also policymakers, regional authorities, and other potential end users. To address this need, a series of structured engagement activities were implemented in the Eastern

Attica region, with the dual purpose of presenting the technology and fostering dialogue with stakeholders who could potentially adopt it in the future.

As a first step, a comprehensive survey was conducted to introduce both the overall project and the specific pilot installation. The survey included targeted questions designed to capture perceptions, concerns, and expectations, thereby providing valuable feedback on social acceptance and potential barriers. In addition, bilateral interviews and focused discussions were carried out with interested parties, enabling deeper insights into stakeholder perspectives.

Furthermore, a series of workshops, delivered both online and in person, were organized to actively involve a wide range of stakeholders in the familiarization process. These workshops aimed not only to disseminate knowledge about the technology but also to build trust and enhance acceptance of reclaimed water use, particularly for irrigation purposes in urban environments.

Overall, these engagement activities proved highly valuable. The input and feedback provided by participants were carefully considered and incorporated into the project's implementation strategy, thereby improving both the impact and the long-term effectiveness of the intervention.

2.2.2 Impact

This technology is an innovative way to address the real-world challenge of providing autonomous, decentralized resource recovery in water scarce cities and hence 'climate-proof' non-potable water supplies (such as urban green space irrigation) against the uncertainty that is necessarily associated with water supply from natural water sources and related hydroclimatic changes.

Due to its advanced planning and flexible design, a variety of benefits are anticipated: It can relieve the overtaxed wastewater systems, trim water and wastewater infrastructure costs, reduce energy and chemical use and save potable water. Hence, the sewer mining solution seems ideal for implementing decentralised wastewater treatment and water reuse schemes at the point of demand to address real-world water scarcity issues in a dense urban environment, by transforming treated wastewater (a waste) into supply (a resource).

These technologies are implemented and tested in a real-world application and the results aim to serve as a step towards more flexible, expandable, scalable and replicable CE solutions.

2.2.3 Lessons Learned

Key Takeaways:

- It is a very efficient technology that requires very limited space thus it has a small footprint; all the equipment can fit into a small container.
- It uses waste as a source and thus it reduces the waste and increases the availability of resource. Especially in countries like Greece, with lack of water availability, this kind of technologies is a critical way of addressing water scarcity.
- It saves energy that would be used to transfer reclaimed water from a WWTP back to the city at point of demand.
- The integration of renewables within water reuse solutions constitutes a very promising prospect for dense urban environments, under the triptych of water saving, energy efficiency and circular economy.
- Taking as example the harnessing of solar energy as a means of reducing the grid dependence of sewer mining units, different PV technologies (conventional / high efficiency) were tested, to identify optimal layouts from an economic and spatial perspective.

Challenges Encountered:

- Time consuming permit procedure
- Many parties are engaged to implement solutions in real world settings.
- Engagement of stakeholders and local communities to accept such technologies is necessary but difficult to attain and time consuming. Local communities often feel uneasy about the installation of wastewater treatment plants in their towns and express concerns about potential disturbances (e.g., odors). Therefore, live demonstration activities play a crucial role in fostering

engagement and enhancing public acceptance.
- The existence of trade-offs between the occupied area of PV panels and the total cost was assessed. In particular:
  - The least area scenarios require the installation of high-efficiency modules, which come at an increased cost.
  - On the contrary, the optimal cost scenarios opt for conventional, cost-effective modules, yet require larger occupied areas.

Future Recommendations:

- Start planning, design and permit procedures from a very early stage of the project
- Engage involved parties early to solve any hesitations and address any issue or limitation.
- All examined scenarios favour the integration of PVs, thus minimizing grid dependence.

Barriers to Transferability:

Generally, the sewer mining technology is a very transferable solution. Some barriers are listed below:

- Existing pipe of the sewage urban network to be near the unit and at the place of demand.
- The quantity of wastewater in the adjusted network is sufficient for the needs of the green area.

2.2.4 Conclusion

The key findings can be summarised as follow. Firstly, the technology consistently produces high-quality water that meets both national and international standards for unrestricted irrigation and urban use. Moreover, the compact design of the entire configuration requires minimal space, resulting in a small footprint intervention that can be installed in dense urban environments to increase green spaces. Additionally, the process inherently saves energy by extracting, treating and reusing water at the same location, thereby contributing to sustainability efforts. Furthermore, the controlled filtration process effectively retains essential nutrients such as ammonia and nitrates within the treated product, resulting in a beneficial increase in the development of plants and on the biodiversity of the surrounding ecosystem. Plants irrigated with the treated water exhibit notably superior development compared to those irrigated with potable water.

2.3 Solution 3: Water-Energy simulation and optimisation model for wastewater systems acting as regional circular economy and climate resilience hubs (Task 4.5.3)

The East Attica Wastewater Treatment System (EAWWS) project tackles the urgent need for sustainable wastewater management in East Attica, in a region highly vulnerable to climate change. It presents a unique opportunity to establish a hub for Circular Economy through the new EAWWS infrastructure. The task's main goal is to develop a coupled energy-water simulation model that quantifies both resilience and energy requirements of the future EAWWS. This model supports climate-proof services for connected settlements and is being implemented at the IMPETUS Mediterranean demo site for use by its operator (EYDAP).

The model integrates data from multiple sources: EYDAP's SCADA system, weather and climate records, hydrological and hydrogeological inputs, field measurements, forecasts, groundwater monitoring, and agricultural water demands. Further, bibliographic data, technical approved studies by EYDAP (Table 10 in Annex 6.3), elements of other studies, and surveys are listed in the Annex of this document. It was built using the HYDRONOMEAS framework (Figure 68 in Annex 6.3) and incorporates climate change scenarios (Table 11 to Table 16 in Annex 6.3), population projections (Table 17 in Annex 6.3), and wastewater reuse options to ensure a robust, adaptive design.

The model also evaluates climate risk, feasibility, and energy consumption, while assessing the potential of innovative technologies such as sewer mining. Advanced, uncertainty-aware optimization techniques were applied under varying climate futures and analytical scenarios.

Finally, the model supports the development of the regional Master Plan for wastewater reuse and contributes valuable data to the Attica Digital Twin, offering a foundation for informed decision-making and future planning.

2.3.1 Results

2.3.1.1 Conceptual model – Methodology and assumptions

The model encompasses all wastewater infrastructure in East Attica, existing, under-construction, and planned. It covers WWTPs, local and central sewage networks, pumping stations, reuse systems (urban, industrial, and irrigation), treated water storage, and groundwater recharge zones using infiltration or percolation methods.

In line with EYDAP Board Decision No. 18989/29-7-2016, the redesign of the following WWTPs in East Attica was approved:

    i.   WWTP of the Municipality of Marathon
    ii.   WWTP of the Municipalities of Rafina-Pikermi and Spata-Artemida
    iii. WWTP of the Municipalities of Paiania - Koropi
    iv. WWTP of Markopoulo
    v.   BIOPA of Kalivia (Kalivia Industrial Park)

2.3.1.1.1 HYDRONOMEAS Model

The analysis employs HYDRONOMEAS, a stochastic simulation tool, developed by NTUA and previously applied in research projects. It models hydrological systems as networks of nodes (e.g. reservoirs, wells, demand points) and branches (pipelines, pumping stations) simulating 50 hydrological years (Oct 2021 – Sep 2071) under multiple scenarios with annual time steps.

Design Phase

The model was configured with data from EYDAP studies (e.g. Master Plan), technical reports and georeferenced diagrams compiled into a unified database and the system is illustrated in Figure 68 (Annex 6.3).

The system includes the settlements, main sewerage branches (Main Sewerage Pipes - MSPs), pumping stations, operational and planned wastewater treatment facilities (WWTPs and Sewer Mining units), treated water distribution networks, aggregate water demands, underground reservoirs, boreholes, and relevant objectives and constraints for energy and water balance calculations.

Model objectives & Priorities

HYDRONOMEAS evaluates **water reuse potential** by analyzing demand, coverage, reliability, and energy use. When resources are limited, water allocation follows these priority levels:

    i.   Industrial reuse (aggregated at a node).
    ii.   Minimum groundwater reservoir levels
    iii. Irrigation needs
    iv. Urban-suburban water demands

The approach supports EYDAP's circular economy goals, optimizing reuse from treated wastewater, while simultaneously storing excess underground to enhance overall system sustainability.

Climate change – Simulation under deep uncertainty

To explore the energy–water nexus in East Attica, climate uncertainty is integrated into the simulation. Reuse of treated wastewater improves water resilience, reduces freshwater dependency, and boosts efficiency.

Climate scenarios: Rainfall & Temperature

Climate change simulations were conducted using Shared Socioeconomic Pathways (SSPs) developed by the IPCC:

- SSP1-2.6 (sustainability)
- SSP2-4.5 (middle-of-the-road)
- SSP5-8.5 (fossil-fueled development)

Each scenario includes eight realizations (2021–2071), benchmarked against stochastic data from 13 local meteorological stations, accounting for population growth and treated wastewater availability. HYDRONOMEAS handles complex future scenarios and supports climate-resilient water management, informing East Attica's master plan and digital twin development. This approach aligns with the EU Green Deal and Adaptation Strategy and offers a scalable model for other vulnerable regions.

The HYDRONOMEAS model of the East Attica Water and Wastewater System (EAWWS) was key for developing a coupled energy-water conceptual model, a digital twin, and the regional master plan. This integrated approach exemplifies the EU Green Deal in a climate-vulnerable hotspot and supports the European Commission's Adaptation Strategy to protect people, nature, and livelihoods from climate impacts.

The generation of synthetic time series was carried out using the R package anySim (Tsoukalas et al., 2020), which offers a wide range of stochastic simulation models and time series disaggregation methods (Kossieris et al., 2019; Tsoukalas et al., 2017, 2018a, 2018b, 2019).

Population Projections

Population growth was estimated using a trimmed mean approach (excluding extreme forecasts), combined with expert judgment to reduce outlier influence. Municipal census data from 1991, 2001, and 2011 were used, with the 2021 census as validation. Six forecasting methods were applied per municipality:

- Three (3) data extrapolation techniques (utilizing historical data, regression models).
- Two (2) share-based methods (Constant Share, Shift Share model), and
- Constant population scenario.

A conservative approach is employed to estimate the population over the next 50 years (2021 to 2071), based on which the simulations of the model in design were conducted. Six forecasting methods were employed to determine the future population:

- Three (3) data extrapolation methods (utilizing historical data, regression models).
- Two (2) share methods (Constant Share, Shift Share model).
- Assumption of constant population.

This approach projects a 150% increase of the current population by 2070, in contrast to EYDAP's estimate of a 220% increase by 2060.

Treated wastewater effluents

Monthly treated effluent estimates were derived from the Kiourka WTP consumption data, assuming sewage generation at 70% of water use in summer and 80% in other months of the year. A 1,000-year stochastic series was divided into 20 segments of 50 years to calculate monthly peak coefficients ($\lambda H \approx 2.25$). This base series (X) was scaled for each settlement using the following process:

- Based on the population estimates of each settlement, we calculate the effluent flows QE (2021) and QH (2071), assuming an average water consumption of 200 L/(cap·d) and $\lambda H=2.25$.
- With the aforementioned average flow of 2021, a 50-year sewage effluent time series Yo is estimated for each settlement.
- Finally, a trend was given to the Yo time series so that the maximum value, which most possibly occurs in the summer months of the last years, aligns with the calculated QH (2071).
- Seasonal population is taken into account with multiplier-coefficient (based on studies by EYDAP) indicating the corresponding increase in population in dry seasons as a result of seasonal variations, such as tourism and temporary summer movements.

- The daily water consumption volume per capita during the 5-month period May-September was adjusted by a 6.5% increase coefficient for each unit change (1°C) in temperature, and when the average monthly temperature exceeds 20°C.

This procedure ensures the final wastewater time series reflects long-term population trends, seasonal demand, and climate-driven consumption variations, supporting robust system simulations under future scenarios.

2.3.1.1.2 Implemented Methodologies and Assumptions

The study evaluates wastewater reuse options in the region focusing on various parameters, such as:

- Plant water needs
- Urban and suburban reuse potential
- Projected industrial use
- Artificial aquifer recharge.

Methods were chosen for efficiency, practicality, alignment with natural processes, and compatibility with HYDRONOMEAS. Key assumptions by category are provided in Table 18 (Annex 6.3).

Developed scenarios and simulation

The study outlines the various scenarios developed to simulate the performance and impacts of the East Attica Wastewater System (EAWWS) under different conditions and variables such as WWTP configurations and connectivity, irrigation demands and climate projections. For the assessment of the performance of the EAWWS, four main scenarios were developed, namely:

- SA100 (Stand Alone, 100% of Irrigation Demand)
- CS100 (Connected & Sewer Mining, 100% of Irrigation Demand)
- SA200 (Stand Alone, 200% of Irrigation Demand)
- CS200 (Connected & Sewer Mining, 200% of Irrigation Demand).

Each scenario was assessed under three climate pathways (with eight (8) realizations each):

- SSP1 – "green road" sustainable scenario with continued progress on the sustainable development goals.
- SSP2 - "middle of the road" scenario, with continued economic growth and development, and gradual improvements in inequality and sustainability.
- SSP4 – "fossil-fuelled development" scenario, defined by unconstrained growth in economic output and energy use.

From "Moderate climate change scenario" being the SSP1-2.6 to "High climate change scenario" being the SSP5-8.5, the aforementioned projections consider varying levels of temperature increase and changes in precipitation patterns, affecting water availability and demand.

A total of ninety-six (96) simulations were conducted (4 scenarios x 24 runs for each scenario) to offer insight into the EAWWS's adaptability and performance under future uncertainties.

The Key Performance Indicators (KPIs) can be recapitulated into the following:

- System Resilience
- Energy Consumption

The coverage of the needs is calculated as a net percentage (%) based on the calculated deficit each month and is as follows:

$$Coverage = 1 - \frac{Deficit}{Demand}$$

Energy results are expressed in GWh as average annual values over a 50-year period, calculated under the scenario framework described above.

Resilience of the EAWWS

Figure 11 shows the mean annual deficits for all different EAWWS configurations under different climatic scenarios over a 50-year period, ranked from highest to lowest.
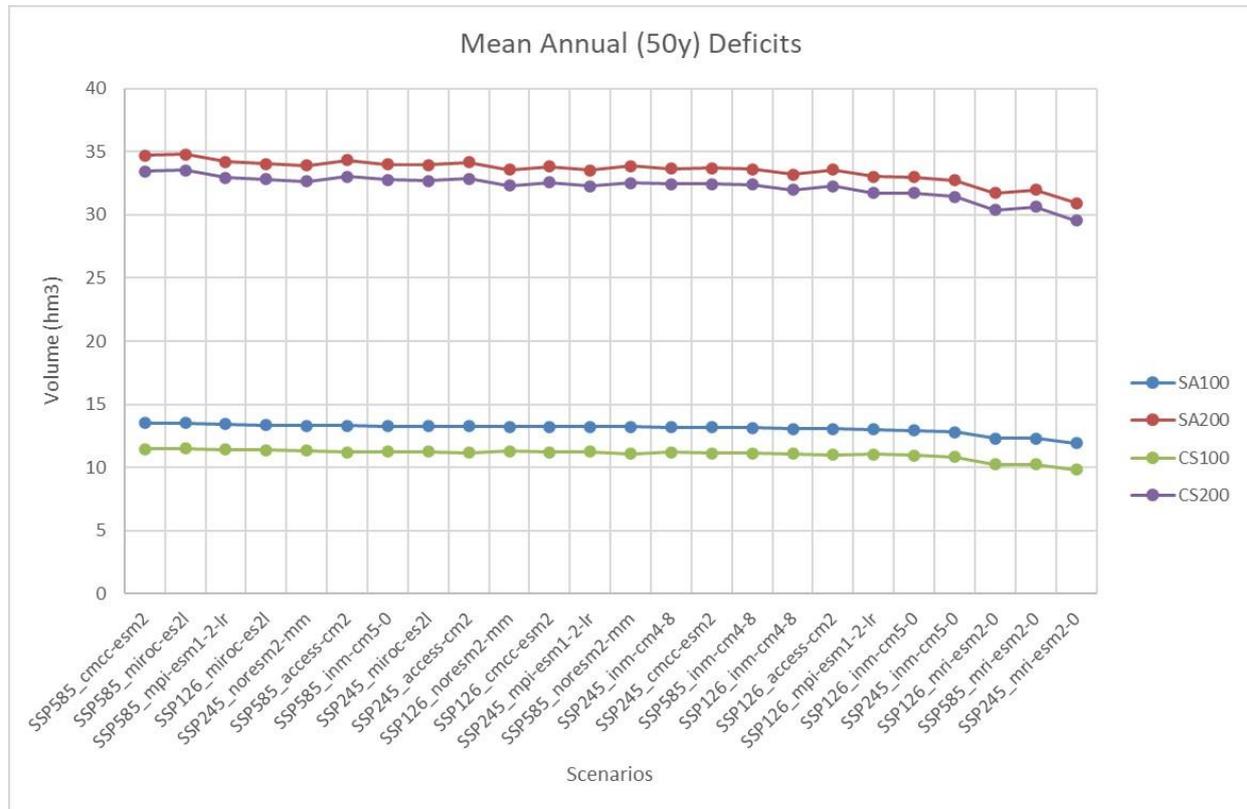
Figure 11 Mean annual (50y) deficits.

The SA100 and SA200 consistently exhibit the highest deficits among all climate models, with SA200 having the highest. This is maintained by the factor that WWTPs cannot cross-serve the existing demands, even if the resource is there.
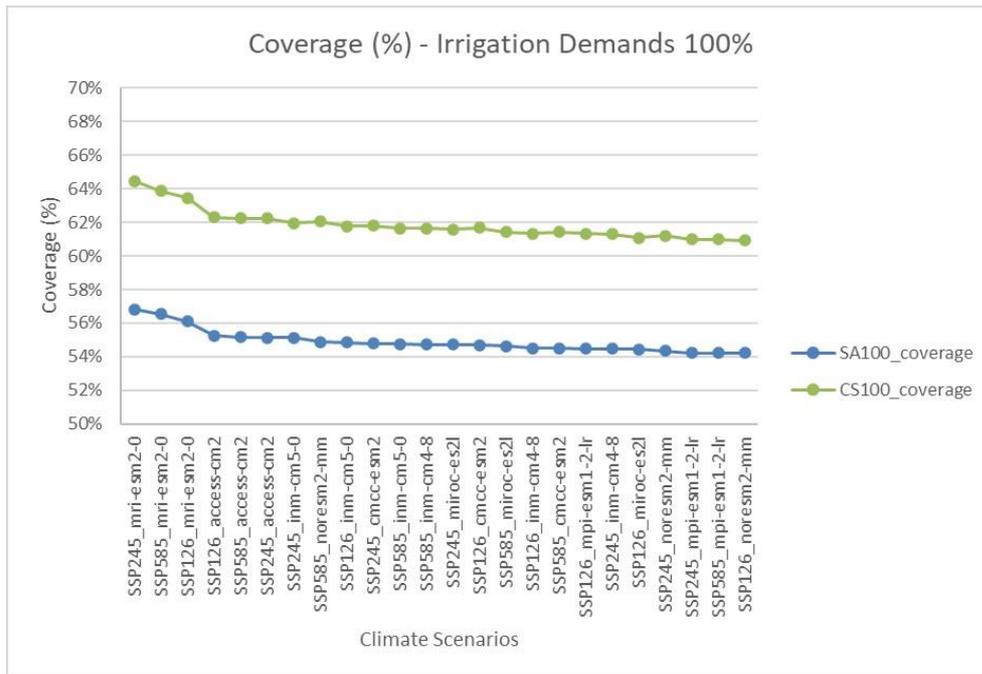
Figure 12 Coverage (%) of total needs, Irrigation demands 100%.

The Connected and Sewer Mining configuration indicates lower annual deficits in both the 100 and 200 scenarios, substantially reducing the annual deficit for approximately 2.1 hm^3 and 1.3 hm^3, respectively, thus highlighting the benefits of system interconnections and the deployment of the sewer mining units.

In Figure 12, the coverage percentage for total demands (and for 100% of the irrigation demands proposed by EYDAP) is depicted across the different climate models. Some key observations include that the Connected and Sewer Mining configuration provides consistently a 5-6% in coverage.

As for the percentage of coverage of total demands, after doubling the irrigational needs (200% of demands proposed by EYDAP), the benefit that can be derived by the implementation of the CS configuration is estimated up to 4-5% (Figure 13).
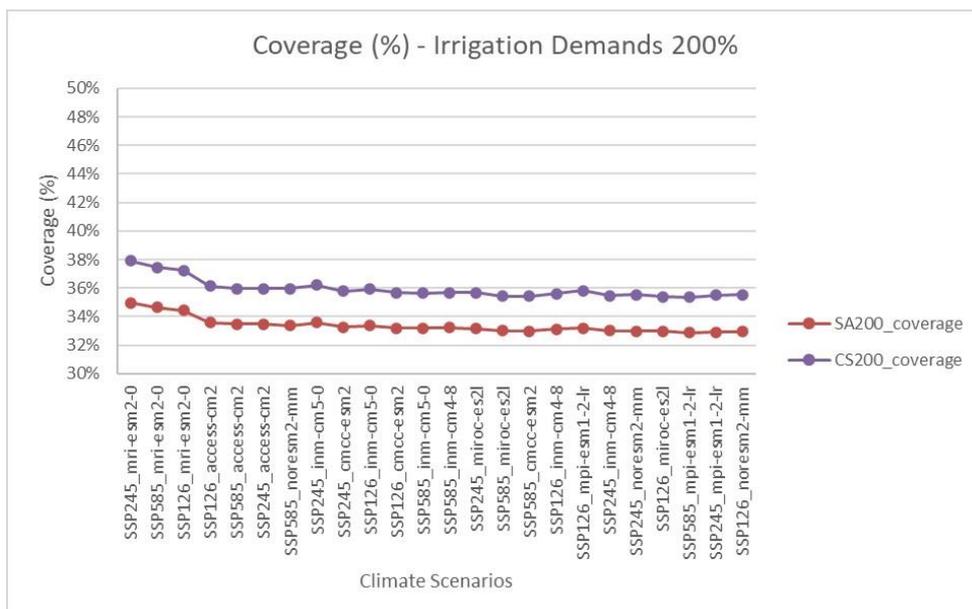
Figure 13 Coverage (%) of total needs, Irrigation demands 200%

All configurations can meet 34–65% of East Attica's non-potable water demand with reclaimed resources. The configuration chosen e.g. CS, can lead up to 14.8% increase in coverage comparing it to each SA counterpart.
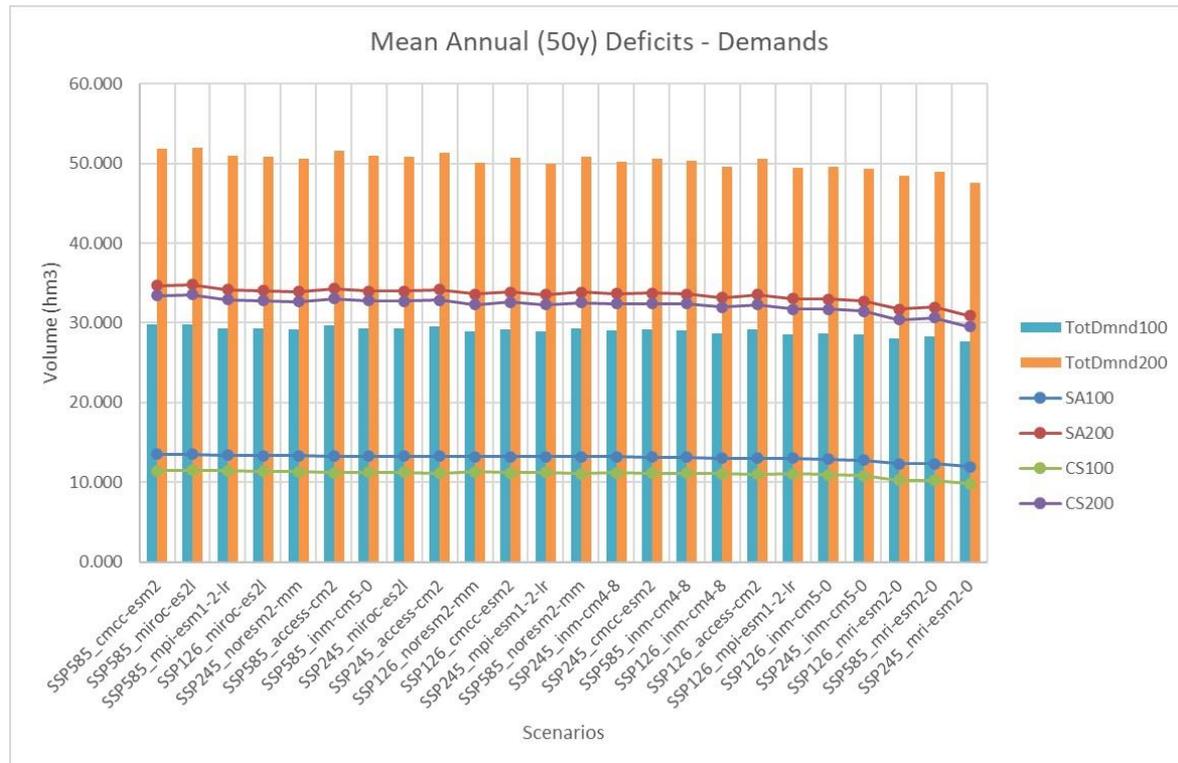
Figure 14 Mean annual (50-years) deficits – Demands

It's worth noting that the projected population growth (independent of climate scenarios) over the 50-year period contributes to closing the gap created between the different climate patterns, reinforcing the robustness and resilience of the system.

The EAWWS appears to be climate resilient. Though the ability of EYDAP covering for the potable water needs (later to be reclaimed effluents) is under dispute. This could possibly change the above image e.g. extreme climate scenarios of the SSP5, could possibly mean a considerable reduction in sewage treated as assumed in the above cases.

Comparing Figure 11 and Figure 14 shows that higher demand does not always translate to greater deficits. Climate factors (temperature, rainfall) influence both inflows and irrigation needs. Consequently, the ranking of scenarios by deficit does not align with that of total demand or coverage.

Energy Consumption of the EAWWS
With regard to the findings of the Energy Consumption KPI of the EAWWS, in Figure 15, the 50-year mean annual energy consumption, for all the different configuration and climatic scenarios (as presented in the above section) is depicted, in order of SSPs (from SSP-1 to SSP-5). Overall, the system energy use fluctuates between 1.1-1.2 GWh/year (excluding the energy required for WWTPs and sewer mining units).
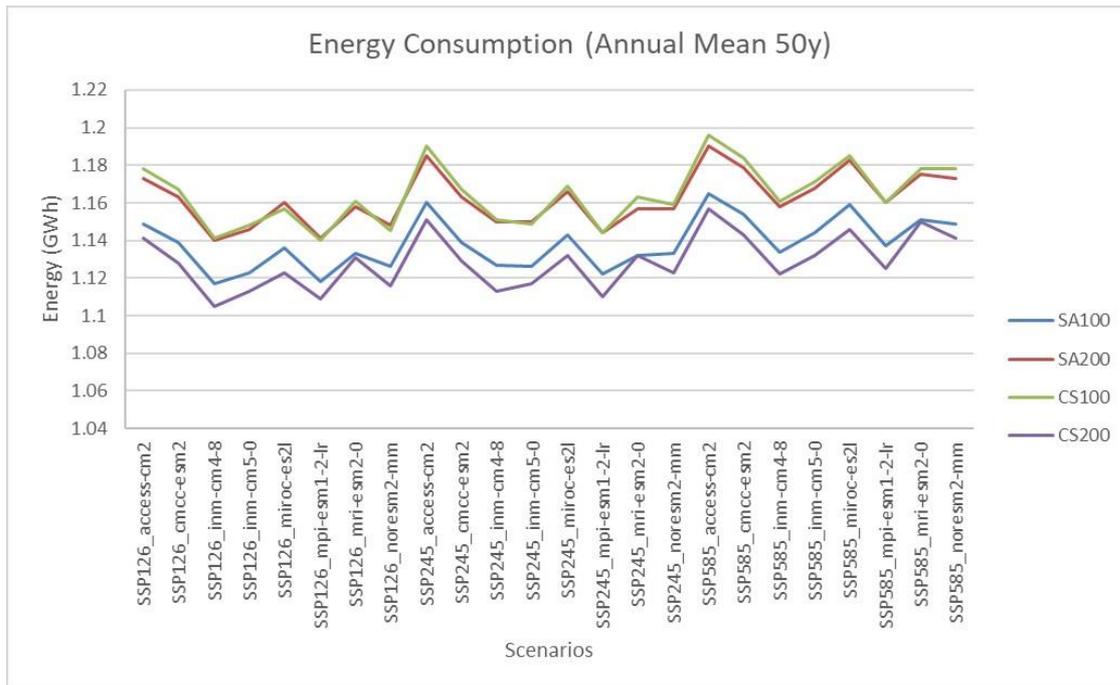
Figure 15 Mean annual (50y) energy consumption

The CS100 scenario consumes more energy than its counterpart SA100, whilst CS200 requires considerably less than both SA200 and CS100. This indicates that targeted interconnections can improve efficiency especially under scenarios with doubled irrigation demand. For example, prioritizing high-demand areas like Spata-Loutsa may yield greater coverage with lower energy use. Such trade-offs would probably pose a point of contention or conflict between the stakeholders and operational rules should be implemented. Interestingly, similar mean annual energy consumption is observed between CS at 100% irrigation demand and SA at 200%. However, the total energy demand of CS is expected to be higher once the sewer mining units' energy use is included.

2.3.2 Impact

The EAWWS project introduces a sophisticated, coupled energy-water simulation model tailored for the East Attica region, advancing resilience, efficiency and circular economy practices:

- Resilience: Quantifies system performance under multiple climate scenarios, accounting for population growth and extreme events (droughts, floods)
- Energy Optimization: Evaluates long-term energy needs through simulation, supporting climate-proof wastewater operations and energy-efficient planning and decision-making across various system components.
- Circular Economy: Assesses reuse options (e.g., sewer mining), reducing freshwater abstraction and positioning East Attica as a CE hub for sustainable resource use.
- Data-Driven Planning. Feeds outputs into the Attica Digital Twin and Master Plan, enhancing digital governance, and ensuring transparent, replicable, and adaptive decision-making.

Transferability & Scalability

- Applicable to semi-arid regions with water scarcity, rapid population growth, or aging infrastructure.
- Best practices: adapt inputs to local conditions, engage stakeholders early, and phase deployment through pilots.
- The HYDRONOMEAS-based model is modular and can be scaled to regional/national systems, integrating stormwater or nutrient recovery.
- Success requires robust data infrastructure, training, and institutional coordination.

Limitations

1. **Data Dependency:** Accuracy relies on high-quality datasets (SCADA, field monitoring).
2. **Technical Complexity:** Requires specialized hydrological and modeling expertise, which is quite challenging in smaller municipalities or developing contexts.
3. **Context-Specific Factors**: Governance structures or fragmented services may hinder uptake (e.g., multiple operators, lack of coordination).

2.3.3 Lessons Learned

Key Takeaways

- The coupled energy–water model improved insight into system resilience and sustainability.
- Climate data proved wastewater planning must link with urban, agriculture, and energy systems.
- Reliable, diverse datasets (SCADA, climate, hydrology, population) are critical.
- Reuse technologies (e.g., sewer mining) offer benefits but need tailored feasibility and stakeholder support.

Challenges

- Data gaps or inconsistencies in external datasets (e.g., groundwater, agricultural use)
- Stakeholder engagement delays due to institutional processes
- Model generalization versus local specificity

Recommendations

- Invest in SCADA, IoT, and remote sensing for stronger data and real-time use.
- Start with core simulation, then expand (e.g., irrigation, sewer mining).
- Involve local staff to ensure long-term ownership.
- Engage policymakers early for integration into Master Plans and strategies.

Barriers to Transferability

- Regions lacking reliable monitoring networks may face difficulties replicating the model
- Advanced modelling requires skilled personnel or external support
- Divided water governance complicates coordination
- High upfront costs in infrastructure or monitoring may be a limiting factor in low-income areas

2.3.4 Conclusion

The current deliverable aims to assess the energy-water nexus and its implications for sustainable urban development and environmental management. By utilizing treated wastewater for multiple purposes, the project seeks to enhance water resilience, reduce dependency on freshwater resources, and promote resource efficiency.

The setting in East Attica provides a unique context for implementing such a project, given its population density, industrial activities, and environmental challenges. Various settlements in the region stand to benefit from the improved water management practices and the implementation of circular economy principles.

Throughout the study, there is a focus on integrating climate change considerations, uncertainty analysis, and stakeholder feedback from the engaging regional events and workshops to ensure robust decision-making and effective implementation strategies.

Taking all the above into consideration, by implementing the CS configuration, the EAWWS can ensure a more reliable and sustainable water supply for East Attica, even in the face of climate change and increased water demand pressures.

2.4 Solution 4: sediment transport through irrigation networks (Task 4.6)

The river Ebro, one of the most important rivers in the north-east of the Iberian Peninsula located in Spain, flows into the Mediterranean Sea in the region of Catalonia. The intensive use of its water for irrigation during periods of drought can have negative consequences for the environment and ecosystems. In this context, one of the main climate adaptation challenges is the sustainable management of water resources and the preservation of river and coastal ecosystems in the face of increasingly frequent water scarcity scenarios. If a large amount of water is used to irrigate delta fields, some of the river sediment is diverted into irrigation channels. The reduction in the amount of sediment means a reduction in the concentration of sediment at the river mouth. This could lead to a reduction in the size of the Ebro delta or even its disappearance, negatively affecting biodiversity and ecosystems in the area. In the framework of the European Impetus project, which aims to accelerate the transformation of climate resilience in pilot regions across Europe, a one-dimensional model has been developed using Python software to study the influence of the volume of water used in the right and left irrigation channels on sediment transport. The two channels are connected to the River Ebro at the upper side of the village of Cherta by means of sluice gates, which regulate the flow of water used to irrigate the fields of the Ebro. The water flowing through the channels is distributed into smaller channels in order to facilitate access to irrigation water in different areas of the delta.

This model contributes to the resilience of the Demo Site by providing a simulation tool to assess how water management decisions affect the physical stability of the delta, as well as its ability to adapt to climatic stresses. The model solves the steady-state hydrodynamics of the river using Bernoulli's equation, obtaining the water column and velocity profiles from Riba-roja to the mouth. In addition, the reduction in flow due to the use of irrigation channels and the Van Rijn sediment transport equations have been considered.

Data collection

Bernoulli's equation solves the hydrodynamics on a streamline (a set of consecutive points). To calculate a particular point, information about the height at which it is located with respect to the reference zero is required in addition to the distance from the previous point (Figure 16).
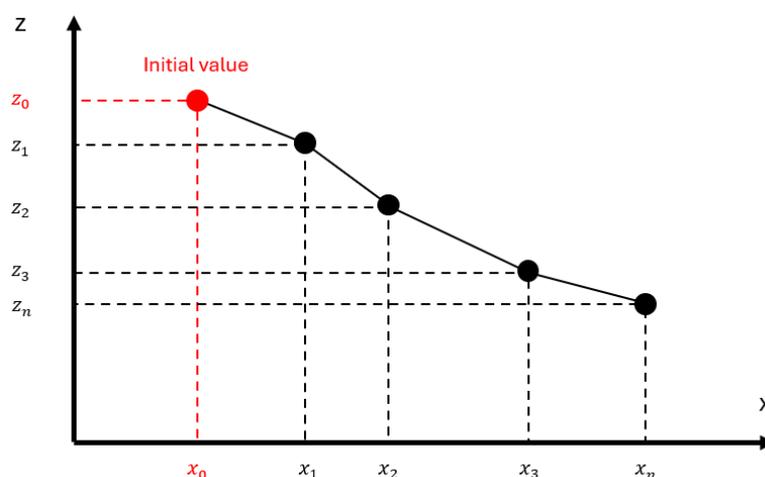
Figure 16 Schematic diagram of the resolution of a current line by Bernoulli.

Resembling the streamline of a river, the data required are the height of the river surface with respect to sea level and the distance between points. It is very difficult to measure the evolution of the surface height along the river. As an approximation, it is assumed that the difference in height between two points corresponds to the variation of the height of the terrain or topography. The terrain elevation data used were taken from the open database TessaDEM (https://tessadem.com/; consulted: 30/05/2025). A total of 636 points have been defined from Riba-roja to the mouth of the river. Subsequently, the values have been smoothed using a Savitzky-Golay filter. In Figure 17, it can be seen how a smoothing of the data allows a more accurate estimation of the height variation at the river surface.

River surface and bottoms distribution	Smoothed bottoms distribution
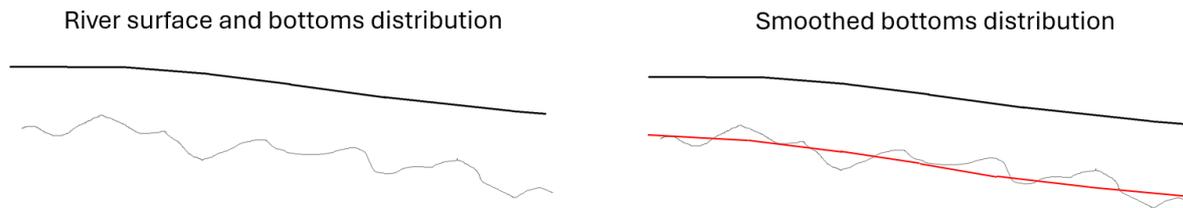
Figure 17 Schematic of topographic data smoothing.

This method adjusts each point from neighboring points by means of a polynomial using the least squares technique. The parameters of the Savitzky-Golay filter have been adjusted in such a way that the height of each represented point is lower than the height of the previous point, thus, avoiding upward slopes. After smoothing the data, the resulting curve was adjusted to a polynomial of 5th degree, allowing a more uniform curve to be obtained (see Figure 18). On the other hand, from the latitude and longitude values, the distance between the 636 points has been determined using the Haversine formula.
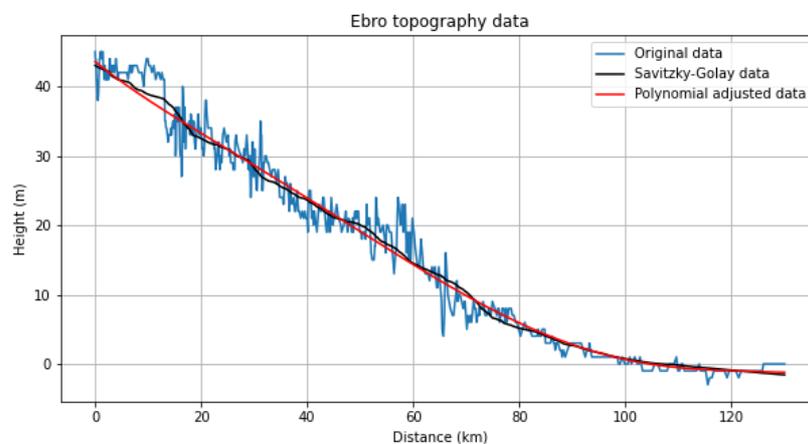
Figure 18 Results obtained in the treatment of the topographic data of the Ebro River.

Hydrodynamics & sediments transport models
As mentioned above, Bernoulli's equation (Annex 6.4) has been used to solve the hydrodynamics from Riba-roja to the mouth. It performs the mechanical energy balance between the points of a streamline, considering the terms of pressure, kinetic energy, potential energy and external friction losses.

On the other hand, sediment transport in the river has been determined from semi-empirical Van Rijn correlations oriented to one-dimensional hydrodynamic models. These equations allow sediment transport to be estimated in a simple manner and are normally used for modeling large natural rivers where changes in hydrodynamics along the river section are smooth (Van Rijn, 1993). In the model, suspended sediment transport and bed-load transport are estimated separately. Suspended particles are those that are continuously suspended in the fluid. On the other hand, bed-load particles move along the bottom do so by rolling, sliding or by little jumps.

The use of the two models Bernoulli and Van Rijn implies a series of simplifications with respect to the real systems, which can be seen in *Table 6*.

.

Table 6 Assumption made by the hydrodynamics and sediment transport models

Fluid hydrodynamics (Bernoulli)	Sediment transport (Van Rijn)
• Flow along a streamline (1D) • Steady-state flow • Incompressible flow • Constant flow properties • Constant flow rate • Constant river width (it could be adjusted to vary along the course of the river) • Constant river rugosity	• No lateral or vertical transport (1D) • Steady-state transport • Not suitable for highly dynamic systems • Semi-empirical equations • Constant sediment properties • Constant particle size distribution • Bed-load height representative estimation • Vegetation effects are neglected

Both models require specific input data in order to solve the equations involved, which are shown in *Table 7*. Furthermore, to simulate the effect of the gates, the width of each of the irrigation channels in the starting section must be known.

Table 7 Input parameters required for the hydrodynamics and sediment transport models

Fluid hydrodynamics (Bernoulli)	Sediment transport (Van Rijn)
• Smoothed topography data • Flow rate • Width • Gravity • Fluid viscosity and density • Estimated river rugosity	• Slope, velocity, and depth profiles along the river • Particle diameter (average 50% size) • Particle diameter (biggest 10% size) • Gravity • Fluid viscosity • Fluid and sediment density • Geometric standard deviation of bed material • Maximum volume particle fraction • Constant of Von Karman

As output data of the hydrodynamics model, the water depth and velocity profiles of the river along its course are obtained. On the other hand, by adding the sediment transport part, the bed-load and suspended-load mass flow rates are estimated. The opening of the irrigation gates reduces the flow of water in the River Ebro, which translates into a decrease in its level and velocity. Fluid velocity is a key parameter in sediment transport capacity; the lower the turbulence, the lower the resuspension of particles and the concentration of sediments in the fluid. Therefore, the expected results imply a reduction in sediment concentration along the river's course and more pronounced reductions when the irrigation canal gates are opened.

2.4.1 Results

From the suspended sediment mass flow rate profiles obtained (see Figure 69 - Figure 73 in Annex 6.4) the equivalent concentration of sediments has been calculated. In order to appreciate the influence of the opening percentage of the irrigation gates, different opening situations are reproduced below.
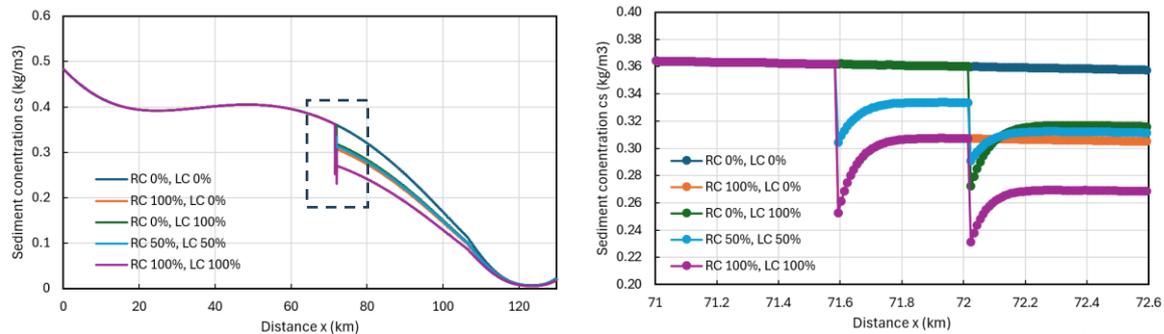
Figure 19 Sediment concentration profiles for different opening situations in irrigation gates of the right (RC) and left (LC) channels.

Figure 19 shows a significant reduction in sediment concentration when the irrigation gates are opened in different situations. The most significant case is when both gates are opened to 100% of their capacity, reducing the concentration by 36.1% from 0.362 to 0.231 kg/m^3. Subsequently, it rises again in the next 200 meters up to 0.269 kg/m^3. On the other hand, near the mouth of the river, the different concentration profiles are closer to each other. This is due to the fact that the velocity decreases noticeably in all cases, thus decreasing the transport capacity of the river in the different scenarios.

The results provided by Van Rijn's equations have been calibrated using field data from the Delft Hydraulic Laboratory in the Netherlands. In addition, Van Rijn validated his equations with field and channel data, which demonstrates a good reliability of the results.

2.4.2 Impact

The model effectively fulfilled its main objectives, to simulate river hydraulics and sediment transport under irrigation influence, and to assess downstream sediment availability at the delta.

- The results revealed a clear and measurable relationship between upstream irrigation practices and the reduced sediment supply to the delta.
- The model allowed forecasting of sediment deficits at the river mouth under different irrigation scenarios, contributing to long-term delta conservation strategies.
- By offering a practical tool for assessing trade-offs between irrigation flow and conservation of the Ebro Delta, the model can serve as a valuable decision-support system for irrigation communities and the Ebro River Basin Authority.
- Provides a replicable model, which can be extended to similar river-delta systems facing sediment deficits.
- The modeling approach is scalable to larger or more complex river systems.
- The model allows the estimation of sediment transport in rivers from hydrodynamic conditions; however, it does not allow the definition of a boundary condition at the beginning of the course. Thus, it is not possible to validate the results with pilot tests based on sediment injections.

In the following, the meetings held with the different stakeholders involved in the project are shown.

- Online meeting with the Water Catalan Agency (ACA, regional public administration entity) on the end of 2022 to 1 person (technical expert).
- Online meeting with Universidad Politécnica de Madrid on the 8/11/2023 to 1 person (technical expert).
- Online meeting with Universitat Politècnica de Catalunya on the 8/11/2023 to 2 people (technical experts).

2.4.3 Lessons Learned

Key Takeaways

- Integrated Modeling enhances the understanding of the river's sediment transport capacity in different scenarios, using Bernoulli's equation with Van Rijn's sediment transport formulations allowed for a holistic understanding of the river's hydraulics and sediment dynamics.
- There is a clear link between water use and sediment supply: the model demonstrated how irrigation significantly reduces sediment mass transport and sediment concentration along the river.
- Delta vulnerability is quantifiable, the reduction in sediment load reaching the delta due to upstream water withdrawals was successfully quantified, highlighting risks to delta sustainability.

Challenges Encountered

- Data scarcity, no public bathymetric data of the Ebro River is available. As an alternative, for solving the Bernoulli equation, smoothed and adjusted topographic data have been used.

Future Recommendations

- Development of higher order hydraulic and sediment models to obtain more accurate information about how the intensive use of irrigation water can affect the river morphology.
- Enhance monitoring networks by improving data availability by installing sediment and flow monitoring stations along key river reaches.
- Stakeholder engagement, involve local water users and delta conservation authorities from the beginning to align objectives and ensure model relevance.

Barriers to Transferability

- Model data is region-specific, due to river-specific parameters (e.g., sediment characteristics, hydraulic geometry, topography data), recalibration of the model is necessary for other studies.

2.4.4 Conclusion

The development and implementation of a one-dimensional mathematical model, integrating Bernoulli's equation and Van Rijn's sediment transport expressions, provided critical insights into the hydraulic behavior and sediment dynamics of the river system under the influence of irrigation. The model successfully simulated the flow and sediment transport along the river and demonstrated a quantifiable link between upstream irrigation practices and reduced sediment delivery to the river's delta.

On the other hand, the results obtained seem to be optimistic, however, it is important to remember that the one-dimensional models are useful to know the order of magnitude of the variables but might not be sufficiently detailed to faithfully determine the consequences of the intensive use of irrigation water. In this case, the development of future models that allow the estimation of sediment transport in two dimensions is not ruled out. Moreover, it is important to remember that the model includes some simplifications such as the Bernoulli equation being a succession of points, and the smoothing and adjustment of the topographic data used.

2.5 Solution 5: Interactive multi-agent regional water balance model (Task 4.7.1)

The metropolitan Berlin-Brandenburg region is located in a transitional zone of continental climate due to its proximity to the Atlantic, resulting in large variations and uncertainties of projected precipitation and river flows in climate projections. This was confirmed by outcomes of the analysis of climate projections for the Berlin-Brandenburg region regarding precipitation and flow projections done as part of task 3.1, resulting in a wide spread from getting drier to getting wetter. Prolonged drought periods in recent years demonstrated that low values of projections for precipitation and flows are already a reality. Main rivers flowing through Berlin are the Spree, Havel, and Dahme, highly managed by weirs and sluices. Average flow is relatively low, and increasing temperatures and changing precipitation patterns

have led to higher evaporation rates and drought periods, resulting in reduced river flows. In addition, the nearby open-pit mine in Lausitz has stayed dry by pumping its groundwater into the Spree for more than 100 years. On average, one-third of the Spree River flow entering Berlin (flow at gauge "Große Tränke", 1991-2017) is coming from the open-pit mine. Due to Germany's decision to exit coal production until 2038, the pit mine in Lausitz will also end its operation, resulting in further reduced river flow in the Spree River.

For the production of drinking water, Berlin mainly relies on riverbank filtration and managed groundwater recharge using surface water as the main source. As some of the surface waters used for bank filtration are impacted by treated wastewater discharged by upstream wastewater treatment plants, the water cycle is partially closed. When river flows decrease e.g. due to summer droughts or pit mine closure, the water quality in affected rivers deteriorates due to higher shares of treated wastewater resulting in increasing challenges for water management. As the region is growing with increasing population and industry, water demand is projected to increase putting additional pressure on the system.

To address these challenges (*Figure 20*), Berlin developed the "Masterplan Wasser", Berlin's comprehensive strategic framework for future water management, published by the senate in 2022 (SenUMVK 2022). The plan includes over 30 concrete measures for securing drinking water supply, protecting water bodies, and adapting wastewater management. To evaluate the effects of future flow conditions or proposed measures, modelling is needed. In this task T4.7.1, four modelling approaches were used, improved and developed to support the evolution of this framework and the strategic plans of Berlin senate and water utility (BWB) in order to advance climate mitigation for the region.
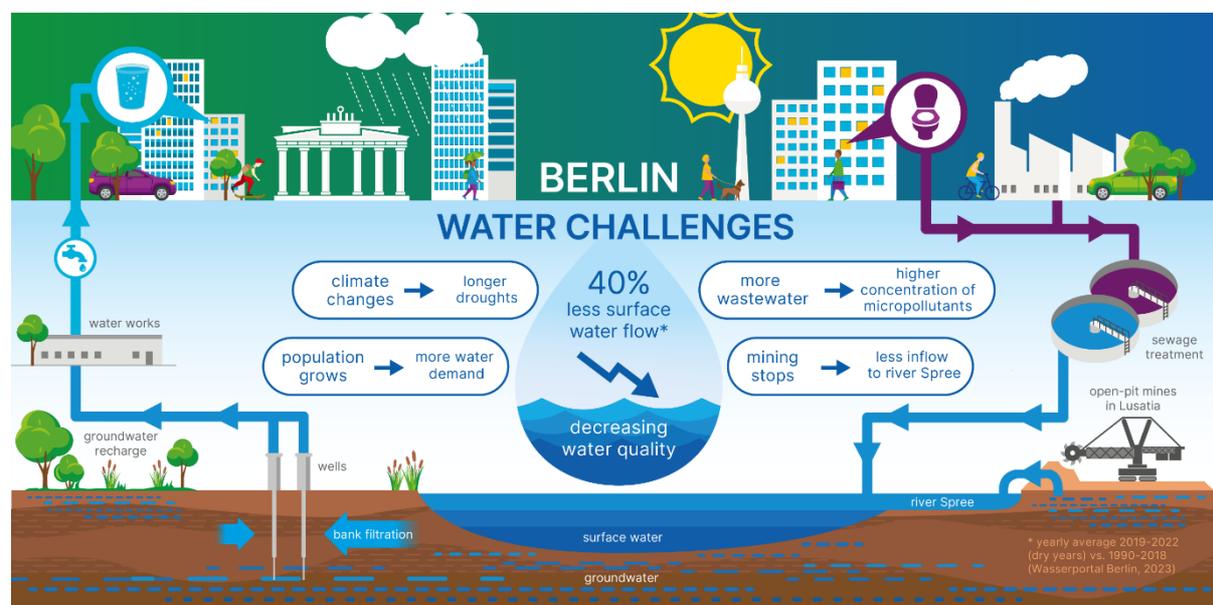
Figure 20: Overview of challenges for Berlin's water resources as source for drinking water.

2.5.1 Results

The situation of Berlin's water resources and dependencies on ground- and surface waters are complex. Understanding future changes thus requires a multi-model approach, as no single model is able to fulfil all requirements. Therefore, modelling activities were carried out with different approaches at different levels of complexity, tailored for the respective questions. These include detailed and complex hydro-dynamic models for groundwater (2.5.1.1) and surface waters (2.5.1.2), able to delineate flow paths or changes in water levels but requiring long calculation times, as well as simplified modelling approaches such as the static and dynamic mixing models (2.5.1.3 and 2.5.1.4). For visualization and easier communication of results, a tool generating a map view for surface water results was developed (2.5.1.5).

2.5.1.1   Detailed groundwater modelling with FEFLOW

To support sustainable drinking water management under climate stress and rising demand, a detailed groundwater flow model was applied to the Friedrichshagen waterworks catchment within the Berlin

Demo Site. The modelling focused on bank filtrate dynamics in Berlin's semi-closed urban water cycle, where up to 70% of drinking water is derived from bank filtration and managed aquifer recharge using surface waters from the Spree, Dahme, and Havel rivers.

Scenario development and implementation
At the start of the IMPETUS project, no groundwater model was available that covered the entire Berlin region. To enable a robust analysis of bank filtration dynamics under changing hydrological and operational conditions, the Friedrichshagen waterworks catchment in eastern Berlin (Figure 74 in Annex 6.5 was selected as a representative sub-domain. This site was chosen due to the availability of a well-calibrated FEFLOW model provided by Berliner Wasserbetriebe (BWB), and its significance for drinking water supply.

The modelling aimed to explore how the share of bank filtrate responds to varying groundwater recharge and pumping rates. A review of earlier investigations had identified typical response types among Berlin's well galleries, shaped by site-specific hydrogeological conditions. The new FEFLOW scenarios were developed to complement this understanding by testing whether these types could be reproduced and how they behave under future stress conditions.

More than 20 scenarios were simulated to assess the effects of changing groundwater recharge and abstraction conditions. Groundwater recharge rates of 107 mm/year (baseline), 87 mm/year (−19%), 70 mm/year (−35%), and 54 mm/year (−50%, extreme case) were combined with increased pumping rates of up to 30% relative to the 2019 abstraction level. The year 2019, an exceptionally dry year with particularly low groundwater recharge rates and high water demand, served as the hydrological reference year. While the configurations from 2010, 2015, and 2019 were used to reproduce known behaviours, all forward-looking scenarios were based on the 2019 well field configuration to ensure consistency in evaluating stress responses.

The scenario matrix was thus designed not only to test model consistency with previously published patterns but also to quantify how changes in abstraction and recharge affect the spatial extent of well catchments and the share of bank filtrate in total extraction. For each scenario, flow pathlines were simulated to delineate contributing areas and assess system responses across configurations.

Results and key findings
The FEFLOW model results confirmed that both groundwater recharge and abstraction rates strongly influence the share of bank filtrate in total drinking water extraction. As expected, reduced recharge scenarios led to higher bank filtrate shares, while increased recharge diminished the relative contribution of surface water. This trend was consistent across historical configurations and future scenarios based on the 2019 setup. Conversely, increasing abstraction volumes amplified the bank filtrate share, as more induced infiltration from nearby surface waters was required to meet demand (Figure 75 in Annex 6.5)6.5.

Some scenario combinations, particularly those combining low recharge (e.g. 70 mm/year or less) with high pumping rates, resulted in numerical instabilities, highlighting both system stress and model limitations under extreme conditions. These instabilities suggest that more extreme future combinations (e.g., longer droughts in combination with increasing demand) will exceed the resilience of the current system and underscore the need for cautious interpretation of results under such stress conditions.
Pathline analyses revealed that the spatial extent of well gallery catchments expanded significantly under low recharge and high abstraction scenarios. In some cases, this led to partial overlap between galleries or to the expansion of capture zones beyond their expected spatial extent, suggesting increased hydraulic connectivity and competition for resources during dry conditions.
By comparing model outcomes with previously observed behaviours, six characteristic types of bank filtrate response were confirmed (Figure 76 in Annex 6.5). Their confirmation supports their use as a conceptual tool for classifying well behaviour in Berlin. However, this approach should be further tested

by applying it to additional groundwater models in other catchments to verify whether the identified relationships hold under different hydrogeological conditions.

2.5.1.2 Detailed hydraulic modelling of surface waters

In order to simulate the spatial and temporal dynamics of flow and water levels in Berlin's surface water network under current and future conditions, the hydrodynamic 1D modelling system HYDRAX was applied. Developed and maintained by the German Federal Institute of Hydrology (BfG), HYDRAX solves the full Saint-Venant equations using an implicit Preissmann scheme, enabling both steady-state and unsteady simulations across complex river structures such as weirs, sluices, retention zones, and branched networks. The model was implemented within the GERRIS/HYDRAX framework, using high-resolution hydraulic and topographic input data for Berlin's interconnected rivers and canals. To ensure comparability with the Berlin Master Plan Water, the March to November 2019 low-flow period was selected as the hydrological reference. This period reflects an extended drought phase with exceptionally low streamflow of the Spree, Dahme, and Havel rivers.

Scenario development and implementation

A comprehensive document was developed between stakeholders/task partners containing main open questions, background data including comparison with previous studies, and derivation of scenarios on inflows and water use – serving also as a staging ground for future analysis, as not all scenarios can be modelled within IMPETUS. The simulations carried out were based on a scenario family that was agreed between the main stakeholders to maximize usability of the results, focusing first on modified routing and increased volumes of treated wastewater from major wastewater treatment plants such as Ruhleben and Stahnsdorf, and the effects on flow thresholds for ship locking and fish migration aids. Scenarios integrate the reference hydrological conditions of 2019 and incorporate progressive inflow reductions (–25%, –50%, –75%) from the Spree, Dahme, and Upper Havel to represent potential drought and post-mining discharge regimes.

All scenarios were simulated using HYDRAX's unsteady flow solver, with adapted boundary conditions reflecting abstraction demands, structural interventions, and climatic pressures. In addition, configurations were added to assess the hydraulic effects of alternative wastewater discharge routes:

- temporary closure of the Kleinmachnow sluice, combined with drainage of treated wastewater from WWTP Stahnsdorf via the Teltow Canal under two discharge variants: one assuming 50% of the treated volume, and another assuming 100%.
- further simulations tested the impact of routing treated effluent from both Stahnsdorf and Ruhleben into the Teltow Canal.

The effects of these configurations were analyzed with respect to two critical system performance indicators:

- Daily lock operation frequencies at Mühlendamm sluice (i.e., number of openings and closings),
- Flow conditions for fish migration aids, based on whether hydraulic thresholds for upstream and downstream passage were maintained under projected 2050 demand conditions.

These scenario combinations enabled a targeted analysis of how redirected treated effluent, under simultaneous low-flow and high-demand conditions, affects reverse flow tendencies and infrastructure operations in the Berlin surface water network.

Key findings

- Under reduced inflow and without the additional discharge from WWTP Ruhleben or Stahnsdorf (see Figure 77 in Annex 6.5), a decline in lock operation frequency was observed, indicating limitations in navigation capacity. The inclusion of these additional discharges helped restore or increase lock activity, particularly under high-demand conditions.
- Routing 50% or 100% of treated wastewater from Stahnsdorf into the Teltow Canal (upstream of the Mühlendamm and Kleinmachnow sluices) significantly influenced system hydraulics, with

> measurable impacts on lock operation dynamics and fish passage conditions (see Figure 77 in Annex 6.5).

- Reverse flow occurrences were observed in specific sections of the network when effluent of WWTP Stahnsdorf was routed to the Teltow canal under reduced inflow and closure of the Kleinmachnow sluice. While such reversals occur only rarely under drought stress alone, the presence of treated-wastewater inflows into the Teltow canal amplified their frequency and intensity. However, their magnitude remained smaller than Ruhleben-driven reverse flows, consistent with Stahnsdorf's lower discharge compared with Ruhleben. These findings highlight the system's sensitivity to structural/operational settings and to the location and rate of discharges.

Modelling results support strategic decisions regarding water management for Berlin as part of the Masterplan Water. Furthermore, the established and improved model setup can be used for future post-IMPETUS scenario calculations.

2.5.1.3 Static mixing model as simplified modelling approach

The assessment of changes in volume flows (Q) and share of treated wastewater (TWWS) due to climate adaptation measures can be quickly estimated using a straightforward mixing calculation. The share of treated wastewater (TWWS) resulting from the mixture of two flows with an individual share of treated wastewater (TWWS$_{1/2}$) is calculated as:

$$TWWS = \frac{TWWS_1 \cdot Q_1 + TWWS_2 \cdot Q_2}{Q_{1+2}}$$

For Berlin, a static mixing model has been established at BWB for various balance points (see Figure 78 in Annex 6.5). This model incorporates the extraction of bank filtrate from surface waters by waterworks, allowing for direct estimation of impacts on these facilities. Additionally, the model integrates the assessment of potential backflows within the water system under low flow conditions.

This type of static approach represents a worst-case scenario, as it always considers a steady state, which may not necessarily occur in reality, especially for large water bodies such as lakes. Nevertheless, this approach is beneficial for estimating the impact of various measures.

To derive meaningful statements regarding water quality, the calculation of a conceptional proportion of treated wastewater within the water cycle (as shown in Figure 79 in Annex 6.5) must be related to specific quality parameters, such as critical trace substances with corresponding limits. The concept of critical treated wastewater share (TWWS$_{crit}$) has been applied in evaluating the modelled share of treated wastewater. According to Karakurth et al. (2019), this can be calculated depending on the share of bank filtrate (BFS), the concentration of a critical substance in the effluent of wastewater treatment plants as well as its health-related indicator value (HRIV). The dependency of these parameters is shown in Figure 80 (Annex 6.5). Furthermore, the efficiency of additional barriers removing the substance from the water cycle are considered (e.g. removal during bank filtration):

$$TWWS_{crit} = \frac{HRIV}{BFS \cdot c_{WWTP} \cdot (1 - barrier)}$$

Calculated example scenarios are presented in Figure 21. Within the IMPETUS project, the model has supported scenario selection for more complex hydrodynamic modelling, scenario calculations for adaptation pathways, establishment of the dynamic mixing model, and visualization of scenario results on the IMPETUS platform. This comprehensive but simple approach aids in understanding the implications of climate adaptation measures on water quality and resource management in urban environments.
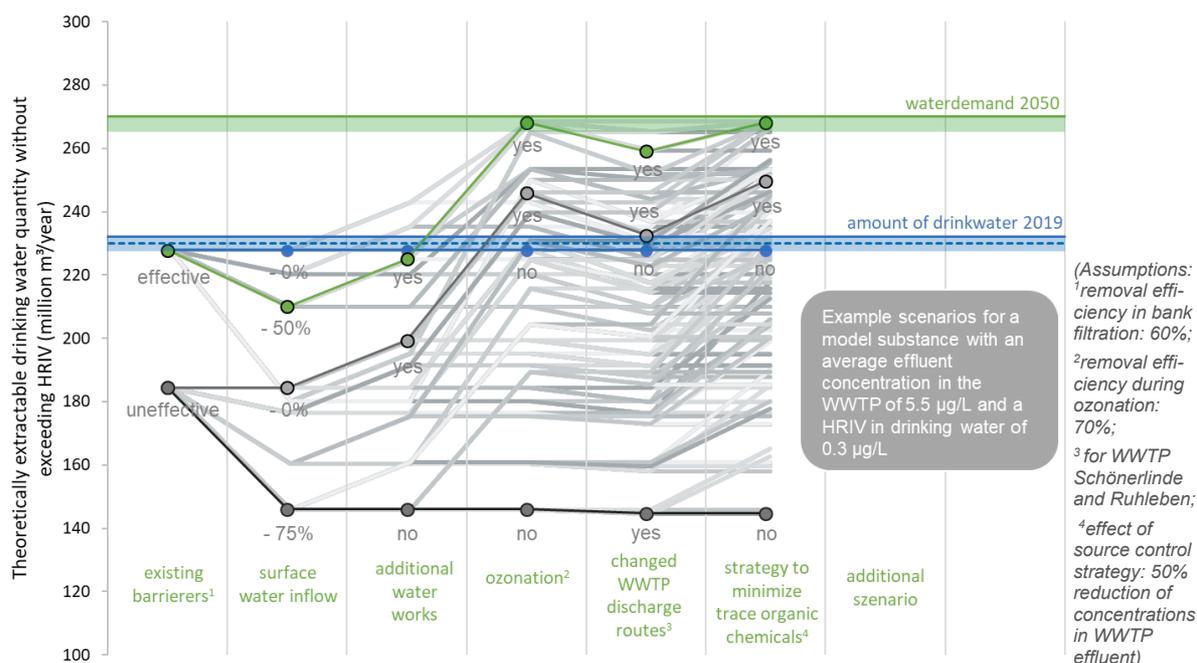
Figure 21: Theoretically extractable quantity of drinking water for different measures. The amount of bank filtrate abstracted in 2019 for each waterworks was adjusted according to the excess of the critical share of treated wastewater, in order to meet the quality requirements set by the health-related indicator value (HRIV) of 0.3 µg/L, based on an average effluent concentration of 5.5 µg/L in wastewater treatment plants.

2.5.1.4 Berlin Water Model (dynamic mixing model)

The Berlin Water Model was developed as a simplified model of Berlin's water bodies that considers WWTP effluents, stormwater runoff, combined sewer overflow discharges (CSOs), and waterworks abstractions in order to calculate flows, shares of inputs (WWTP, stormwater runoff, CSOs), and pollutant concentrations in surface water sections. It therefore extends the static mixing model with the highly dynamic inputs of stormwater runoff and CSOs that require a dynamic modelling approach and high time resolution (hourly or daily). In addition, lake volumes are considered in calculations of concentrations (instead of flow shares only as implemented in the static model, see 2.5.1.3), better reflecting conditions in lakes with variable or changing inputs. This is relevant for Berlin, as several water works are located at lakes using lake water via bank filtration for drinking water production.

The model was implemented in R (r-project.org) and is accessible through GitHub. All inflows and outflows to/from surface water sections are included as separate data (rainfall, CSOs, WWTP effluent, waterworks abstractions), allowing calculation of shares of each input category in every section. Configuration of the network, input data and relevant boundary conditions is highly flexible via csv-files for easy adaptation and calculation of scenarios. Bank filtrate shares can both be considered with fixed values (provided by BWB), and dynamic bank filtration shares derived from FEFLOW results (see 2.5.1.1) to account for the dependence of abstraction rates on BF shares.

A schematic view of the Berlin Water Model network with all inputs and outputs is shown in Figure 22. Berlin's surface water network is divided in 33 sections that receive the described inputs that are mixed in each section for each time step. Mathematical basis is a mixed reactor model of completely mixed volumes. Simplified differential equations (that include degradation rate k for substances, if values are available) are used to calculate concentrations as a function of the time. As flow in certain sections can become negative during low flow conditions (when abstraction via bank filtration is higher than inflow to the section), backflows can occur that the model must account for. Future improvements include the consideration of evaporation in lakes, and calculation of the water balance between abstracted groundwater volumes and natural groundwater recharge (intersecting to be determined catchment areas of all well galleries/waterworks with spatial data on natural groundwater recharge available at the senate).

Results include the determination of overall shares of stormwater runoff for all sections (Figure 23 right; Figure 81 in Annex 6.5), monthly analysis of runoff shares in comparison to shares of WWTP effluents (Figure 82 in Annex 6.5), and shares of CSO in the affected surface water sections (e.g. Spree at former waterworks, Figure 83 in Annex 6.5), illustrating the relevance of stormwater runoff and CSO inputs for certain sections of the network.

The model will be a useful tool for the Berlin senate, water utility (BWB) as well as research institutes, usable after the project to assess scenarios of flow developments and measures for water management.

Figure 22: Simplified network of Berlin surface waters with all inputs and outputs (wastewater, stormwater runoff, CSO, waterworks abstraction) – schematic view of Berlin Water Model (dynamic mixing model).

2.5.1.5 Map visualisation tool for model outputs

A map visualisation tool was developed and extended for the visualisation of results for all Berlin surface waters. The tool, implemented in R, was adapted to be able to use the detailed results of the hydrodynamic HYDRAX model (see 2.5.1.2) as well as results of both the simplified static and dynamic mixing models (see 2.5.1.3 and 2.5.1.4) as input data for analysis and subsequent map view. Analysis includes durations of exceeding thresholds, deviations from target value or averaging values over time. Results are displayed as different coloured streams with adjustable ranges of colours for the visualized parameter (see Figure 23). The tool facilitates easy and simple communication of complex results comprising of huge data amounts (e.g. high-resolution time series in complex surface water network), supporting communication activities and decision making.

Figure 23: Exemplary map visualisations of model results: left – average share of treated wastewater in Berlin surface water network for flows 2019 -50% (results of Hydrax/QSim); right: exceedance duration of 15% share of stormwater runoff in surface waters for 2002-2022 (results of Berlin Water Model).

2.5.2 Impact

The work and outcomes of this task make a significant contribution to addressing the water-related challenges identified for Berlin water resources, particularly by supporting and advancing the implementation of the "Masterplan Wasser" as Berlin's most important strategy to address the challenges for the regional water resources. Through detailed scenario modelling, specific measures from the Masterplan – such as optimized discharge routes for treated wastewater – could be assessed, refined, and adapted to changing environmental conditions. These modelling efforts provide evidence-based guidance for decision-making processes and strategic planning.

A central outcome of the project is the development and improvement of hydrological models and a visualisation tool, both of which are designed for long-term use by the Berlin Senate and Berliner Wasserbetriebe (BWB). These tools enhance the ability of authorities to assess the impacts of different management strategies and environmental developments, thereby ensuring the sustainability of Berlin's water system.

The modelling results will also serve as a key input for stakeholder workshops carried out in Task T4.18. These workshops will play a vital role in facilitating dialogue among relevant actors, enhancing mutual understanding, and fostering collaborative solutions. The improved collaboration among stakeholders through IMPETUS (especially senate and BWB as most relevant stakeholders in regard to water management) is one of the major impacts of the project and lays the groundwork for continued joint efforts.

In addition, the developed visualisation tool with its main feature of generating map-based figures from outputs of three different models will help communicating the complex challenges and potential impacts of various measures to both technical and non-technical audiences.

There is strong interest from both the Senate and BWB in continuing to use the developed tools and models beyond the project's duration. Furthermore, the conceptual approaches and methodologies – such as identifying the critical share of treated wastewater – are transferable to other regions facing similar water management challenges, especially those characterized by a semi-closed water cycle and low surface water availability.

2.5.3 Lessons Learned

Key Takeaways:

The project highlighted the critical importance of early and sustained collaboration between research institutions, local authorities, and utility companies. Once established, these partnerships proved highly effective, enabling the integration of scientific modelling into practical water management planning. The joint development and application of tools and scenarios fostered mutual understanding, and the relationships built during the project will be valuable for future cooperation.

Challenges Encountered:

Establishing content-related cooperation with local authorities within a European project framework posed several challenges. First, the availability of relevant staff at the local level was often limited due to competing responsibilities, and hiring new personnel through project budgets involved lengthy administrative procedures. Second, the handling of sensitive and critical data, such as the BWB groundwater models that contained critical georeferenced metadata for each drinking water well, required legal agreements, which delayed access and progress.

In addition, the administrative aspects of participating in European projects presented difficulties for local authorities. Tasks such as reporting, documentation, and coordination are often conducted in the national language, creating barriers in an international context. A designated support within local authorities would help streamline such processes in future projects.

Establishing consistent communication workflows among all actors needed more time than anticipated. Nonetheless, once these structures were in place, collaboration between authorities, utility and research partner became very effective, and established contacts will definitely help for future collaborations. Main takeaway here is: communication is key and takes time!

Future Recommendations:

During task work, a need emerged for legal frameworks to define responsibilities in relation to modelling uncertainties and their implications for decision-making. Furthermore, establishing a support office or coordination position within local authorities could significantly improve their ability to participate in large-scale European research initiatives. Another recommendation is the systematic installation and maintenance of sensor networks by authorities to monitor key parameters for water management, such as water flows, water level, and quality parameters, as well as rain gauges collecting valuable data on the spatial distribution of precipitation. These data are essential as input data for reliable modelling.

Barriers to Transferability:

While the project provides valuable insights, many aspects are highly specific to Berlin, including the models, measured data, and infrastructure conditions. The use of long-term, spatially distributed datasets, such as rainfall and flow measurements, is critical for model performance, but often unavailable elsewhere. Additionally, some tools and datasets are not openly accessible.

Nonetheless, certain conceptual approaches, such as identifying the critical share of treated wastewater within a semi-closed water cycle, are transferable to regions with similar hydrological conditions, provided appropriate data and models are available.

2.5.4 Conclusion

The modelling approaches developed and refined through close collaboration between the Berlin Senate, Berliner Wasserbetriebe (BWB), and Kompetenzzentrum Wasser Berlin (KWB) are essential for assessing the future development of Berlin's water resources. They provide a sound scientific basis for decision-making in water management and directly support the further development of the "Masterplan Wasser" – Berlin's key strategy for climate adaptation in the water sector.

Nevertheless, substantial uncertainties remain in climate projections for regions such as Berlin-Brandenburg, which lie in a transitional climatic zone, particularly regarding precipitation patterns, surface water flows, and groundwater recharge. This presents ongoing challenges for the Berlin-Brandenburg region, which is characterized by lowland rivers with relatively low natural flows that are highly managed, and large upstream catchments – factors that add complexity to reliable predictions. Because of this, recent extreme events continue to serve as critical reference points for developing future adaptation strategies.

With the improved and developed models and tools now available, the continuation of improved scenario-based modelling is possible. These efforts will provide an essential basis for dynamic, forward-looking water management in Berlin and contribute to the long-term resilience of the city's water infrastructure in the face of climate change.

2.6 Solution 6: Decision Support System integrating multiple information layers for the sustainable and integrated management of regional water resource (Task 4.7.2)

Recent research highlights the urgent need for **integrated water management systems** in mountain regions, where **climate variability** and **complex hydrological dynamics** challenge traditional approaches (Viviroli et al., 2011; Beniston and Stoffel, 2014). Developments in hydrological modelling, climate service tools, and Decision Support Systems (DSS), especially those leveraging machine learning (Drogkoula et al., 2023), remote sensing, and multi-criteria analysis, have significantly advanced. Initiatives like **Copernicus Climate Services** and **GEO Mountains** provide valuable data inputs, while **participatory approaches** are gaining traction in climate-smart water governance. Increasingly, research emphasizes the **WEFE nexus** approach (Water-Energy-Food-Ecosystems), recognizing interdependencies in climate adaptation planning.

Despite progress, several **gaps** remain:

- Lack of downscaled hydrological models adapted to mountain topography.
- Insufficient integration of concurrent water uses (irrigation, hydropower, ecosystem needs, flood control) into a single operational system.
- Limited participatory tools for co-designing water governance strategies with local stakeholders.
- Data harmonization issues and weak interoperability between local, satellite, and forecasted datasets.
- Inadequate real-time monitoring infrastructures for efficient water use in agriculture and energy sectors.

The Decision Support System developed in this task addresses such gaps by **combining fine-scale modelling with participatory decision-making**, real-time monitoring, and multi-objective planning under climate uncertainty.

In particular, the deployed solution is a participatory **DSS for the sustainable and integrated management of water resources in Valle dei Laghi**, whose main objectives are:

- Developing tailored hydrological models that integrate local, satellite, and climate forecast data.
- Providing seasonal-scale and decadal projections to inform decisions under climate uncertainty.
- Supporting multi-user water management, mainly balancing smart irrigation, hydropower operations, flood risk reduction, and ecosystem need.
- Demonstrating real-time monitoring (e.g., of irrigation systems, groundwater, and river discharge).
- Fostering stakeholder engagement via workshops and the Resilience Knowledge Booster to ensure relevance and uptake.

Valle dei Laghi demo site is facing **rising water use conflicts due to climate-induced pressures on agriculture, hydropower, and ecosystems**. The DSS directly targets these issues, enhancing local climate adaptation capacity, reducing risk, and contributing to regional climate policy (e.g., the Strategy for Mitigation and Adaptation of the Province of Trento). Its **modular and participatory design** ensures replicability across Alpine and other mountain regions, aligning with the broader goals of the IMPETUS project.

2.6.1 Results

DSS back-end

The **Digital Twin of Valle dei Laghi** (hereafter DT) is an advanced tool that digitally reproduces the dynamics of the water resource recharge system within the Sarca hydrographic basin. The DT comprises a set of modelling solutions capable of replicating the physical processes that regulate the entire water cycle, thereby providing detailed information on each phase of the water cycle. The system accounts for both natural and anthropogenic characteristics of the study basin, enabling the digitalization of complex systems such as the Sarca River basin. This basin features 5 main derivations, 3 gather water from intakes located in lateral valleys and 2 convey water from a reservoir (Figure 24). The entire

system is served by 20 intakes that divert the natural flow for agricultural and hydroelectric production purposes.
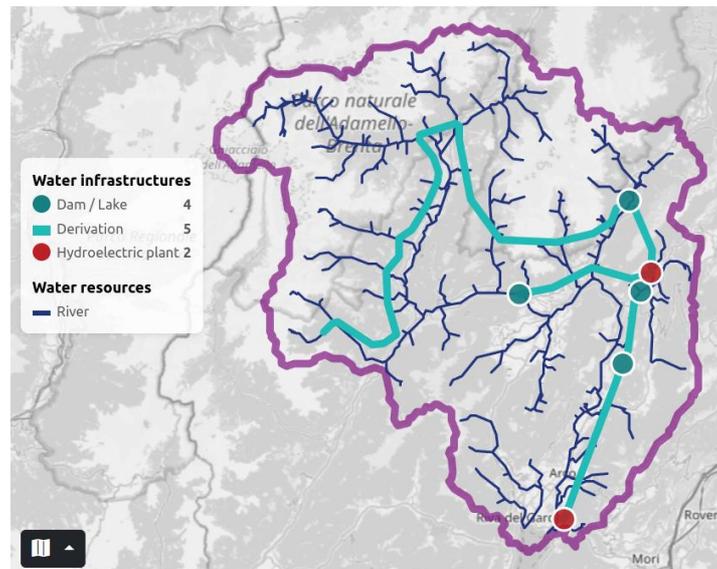
Figure 24 Simplified scheme of the hydraulic works in the Sarca River basin.

At the foundation of the DT are physical models (namely hydrological models) that simulate the residence times of water in the terrain, i.e., how the precipitation translates into infiltration and surface runoff according to the hydrographic network. The computational grid is defined through a geographical analysis of the Digital Elevation Model (DEM) of the area of interest.

Input data requirements

To provide comprehensive information about every stage of the water cycle (liquid precipitation, infiltration, snow, glaciers), the DT receives as input hydro-meteorological variables according to the desired output.

➢ **Meteorological datasets**
- *Historical data*: high-quality observational data, including precipitation, temperature, and evapotranspiration time series, are essential for DT calibration. These data were sourced from the local provider Meteotrentino (https://www.meteotrentino.it/index.html#!/home);
- *Seasonal forecast*: the system generates monthly 6-month seasonal forecasts of hydrological outflows to support medium-term water resource management, utilizing ECMWF (https://www.ecmwf.int/) seasonal meteorological forecasts (SEAS5 – https://www.ecmwf.int/en/elibrary/81237-seas5-user-guide);
- *Climate projections*: long-term projections were produced using CORDEX (https://cordex.org/) datasets provided by project partner Lobelia. Bias correction was applied to improve local accuracy using global ERA5 reanalysis data, followed by refined downscaling against observations at the model's calculation centroids.

➢ **Hydrological datasets**

The calibration of the hydrological model was done on the official hydrometer data from the Ufficio Dighe of the Autonomous Province of Trento (https://www.floods.it/public/homepage.php).

➢ **Key model features**

A critical aspect of this work was the attempt to accurately represent the basin's physical processes, comprising both the environmental complexity (i.e., snow seasonality, karst systems, etc.) and the anthropic complexity, e.g., the presence of numerous hydraulic works that divert the natural course of water. This was done through a comprehensive calibration strategy incorporating two major technical features:

- *Snow melt modelling*: to ensure robust simulation of snow dynamics, the snow module of the hydrological model was calibrated using, as a target, a highly accurate snow water equivalent dataset present in the study area (Tranquillini et al., 2019);
- *Hydraulic system modelling*: the model simulates, in a simplified way, the impact of the anthropogenic features, including three major water collection systems ("gronde") with approximately twenty associated intakes. Due to the unavailability of direct operational data, these flow targets were instrumental in formulating and validating hypotheses regarding operational rules and regulation patterns of the four main reservoirs.

Summary of results on Digital Twin development

o *Developing tailored hydrological models that integrate local, satellite, and climate forecast data*. The calibration process of the DT targeted both snow dynamics and runoff and achieved Kling-Gupta Efficiency (KGE) scores greater than 0.7 for most target hydrometers. These results demonstrate the model's reliability for historical analysis. A significant achievement was overcoming the lack of direct operational data (that are unavailable because the hydraulic infrastructure is managed by private entities that do not release information) by using publicly available downstream flow data to inform hypotheses on reservoir management.

o *Providing seasonal-scale and decadal projections to inform decisions under climate uncertainty*. After calibration, the DT integrates seasonal inflow forecasts (for the next 6 months) and climate projections based on RCP scenarios (2.6, 4.5, 8.5) for key future timeframes (2050, 2075, 2095). These projections are probabilistic, providing average values and uncertainty ranges (20th-80th quantiles). A key insight is that future changes will likely affect seasonal water distribution more than total annual availability, with wetter springs (notably March) and drier summers, increasing the risk of summer droughts (Figure 25).

o *Supporting multi-user water management, mainly balancing smart irrigation, hydropower operations, flood risk reduction, and ecosystem need*. The work produced a fully functional workflow capable of delivering continuous water intelligence. The system provides historical context, seasonal forecasts that enable early detection and prevention of drought periods to avoid water scarcity and potential conflicts over water access, and strategic long-term climate projections for planning – all from a single user-friendly interface. The hydrological model's computational mesh was simplified from 336 sub-basins to 29 representative hydrological areas to enhance user experience. Users accessing the digital platform can set meteorological scenarios (below average, above average, or average conditions) and adjust hydraulic system operational rules to assess how water would be distributed throughout the basin, highlighting critical areas in terms of droughts or excess water that could be wasted.
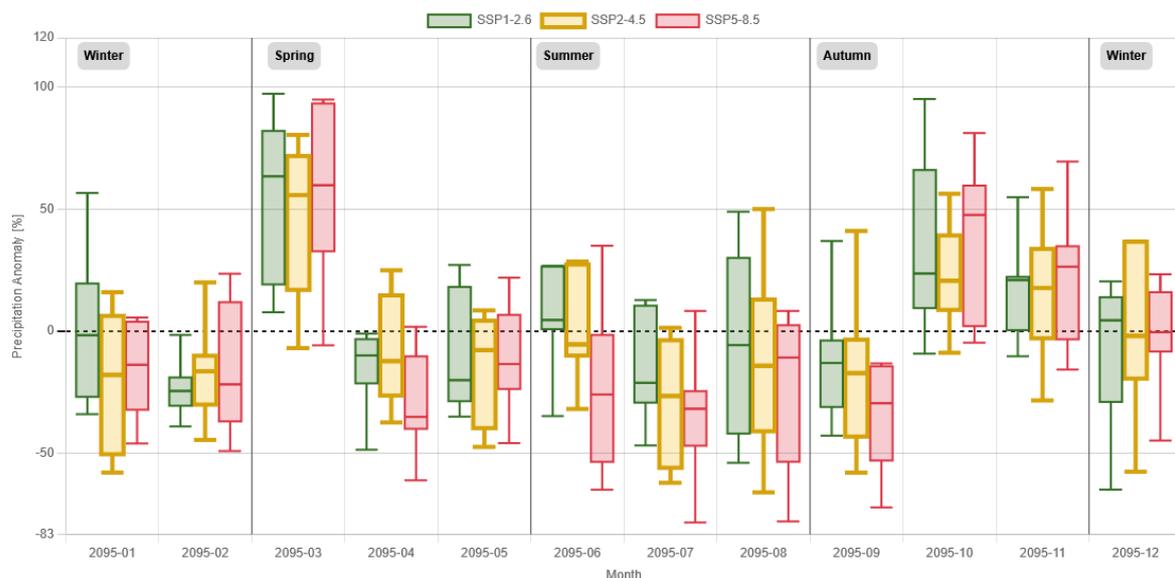
Figure 25 Monthly precipitation anomalies for three climate change scenarios showing the shift toward increased spring rainfall and reduced summer precipitation by 2095.

DSS front-end application

All datasets available for the DT described above are accessible through an Application Programming Interface (API). To provide easy access and interaction with these datasets, a user-friendly, web-based frontend application has been developed (Figure 26, https://climate-impetus.eurac.edu/). This platform enables users to visualize results from the DT across the various zones within the Sarca hydrographic basin. This platform enables users to visualize results from the DT across the various zones within the Sarca hydrographic basin. The displayed information, aggregated from multiple spatial areas, is rendered on an interactive map, facilitating a spatial understanding of the data and underlying models. Users can also select specific areas to access detailed time-series data, providing valuable insights into the temporal evolution of environmental variables within the basin.

Summary of results on DSS front-end application

o *Historical data visualization*. Users can visualize historical data by selecting one of the available variables for a specific month. The datasets are updated monthly and currently span from 2002 up to the previous month, offering a long-term perspective for analysis.

o *Seasonal forecast visualization*. The platform enables users to view seasonal forecasts by selecting a variable, the month in which the forecast was generated, and the forecast target month. The statistical modelling approach behind the forecasts includes three percentile ranges (below average, on average, above average) of the predicted distribution, which supports uncertainty visualization and helps users understand the possible range of outcomes.

o *Climate projections*. Users can explore climate change projections for the years 2050, 2075, and 2095, based on different SSP-RCP scenarios. This allows for comparative analysis across future climate pathways and supports scenario-based planning and risk assessment.

o *Scenario simulations of forecasts*. The platform also includes the capability to simulate different weather forecast scenarios, allowing users to explore how varying weather conditions and hydraulic infrastructure configurations (e.g., reservoir management parameters) impact the basin's hydrological and environmental responses. For example, the model can simulate prolonged hydro-meteorological droughts characterised by below-average precipitation and snowfall levels (calculated for the reference period 2002–2024), combined with high evapotranspiration rates. Once these meteorological inputs have been set, users can manipulate the system's anthropogenic components, such as opening and closing water diversions, and adjusting the flow of water from hydroelectric power plants via turbines. This enables them to evaluate the impact of these interventions on water distribution in the Sarca basin.
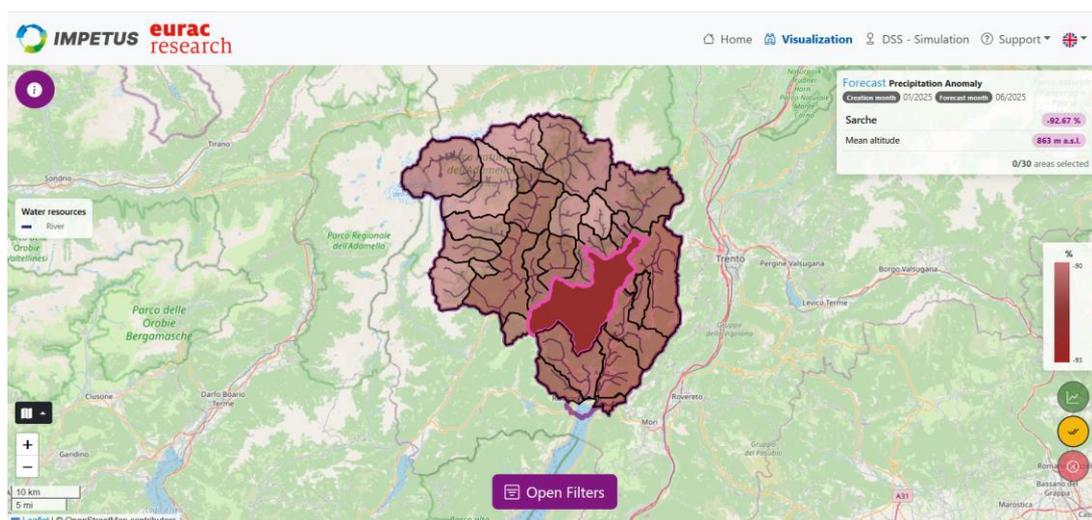
Figure 26 Visualisation dashboard of the DSS of Valle dei Laghi.

Stakeholder engagement

The stakeholder engagement process in Valle dei Laghi consisted of three thematic workshops and several bilateral meetings aimed at improving agricultural and integrated water management in response to recurring droughts and growing resource conflicts.

- The **first in-person workshop** (April 2023) focused on sustainable water management in agriculture and was structured in two sessions. The first closed-door session involved key stakeholders from the private sector (i.e., irrigation consortia) and public administrations; it centered on raising awareness about water management issues such as poor source monitoring and lack of coordination. Participants proposed adaptation measures to address water scarcity like improved monitoring, inter-consortia collaboration, and Internet of Things (IoT) training. The second open session targeted farmers and members of irrigation consortia, offering hands-on training on soil-water management and open debate. A total of 56 participants attended the two sessions of the workshop.
- The **second in-person workshop** (December 2023) introduced a prototype of a Decision Support System (DSS) for integrated water management. A diverse range of public and private stakeholders, including water basin authorities, provincial and municipal administrations, research institutes, environmental engineers, and irrigation consortia, was engaged. Around 25 participants tested the platform through practical exercises and provided feedback to improve its usability and functionality.
- The **third workshop** was held in two parts (2024, April – online – and December – in person) and focused on best practices for sustainable rainwater and groundwater management through Natural Water Retention Measures (NWRM), showcasing real-world examples successfully applied in nearby regions. It targeted local administrations and technical staff of the valley communities "Valle dei Laghi" and "Alto Garda e Ledro", as well as representatives of the municipalities within the Sarca catchment basin, gathering 35 participants overall. Although Nature-Based Water Retention Measures are not included in the DSS, they represent a promising response to water management challenges and could be integrated in future development phases.
- In addition, seven **bilateral meetings** with 33 stakeholders from the public and private sector helped validate project activities and strengthen local cooperation.

The IMPETUS workshops and meetings contributed to develop a participatory process aimed at promoting dialogue and raising awareness on integrated water management at the local level, leading to the reactivation of second-grade irrigation consortia located in the upper part of Valle dei Laghi (i.e., "Val del Vent" and "Pedegazza") and the beginning of inter-consortium collaboration. As part of the ongoing process, the consortium of municipalities BIM Sarca, project partner, entered into formal agreements to consolidate the collaborative governance and initiate additional field monitoring activities outlined in the amendment (i.e. smart irrigation and groundwater monitoring), foreseen as part of the response to the critical drought events of 2022–2023. The signed agreements are:

> **Smart agriculture**

On the 22nd of April 2025, BIM Sarca signed a collaboration agreement with the second-grade irrigation consortium "Alto Garda", the largest in the southern part of Valle dei Laghi (1,500 hectares, over 3,000 members). The partnership establishes a **pilot site to test a climate adaptation strategy** combining a predictive hydrological model with Irrigation 4.0 technologies (i.e., wireless soil sensor networks, smart irrigation controllers), aiming to enhance resilience to climate extremes like the 2022 drought. The pilot covers **156 hectares** irrigated by the Albola stream and includes **19 experimental areas**, selected based on crop types and soil water retention (Available Water Capacity – AWC). Two types of moisture sensors (fork-type and bulb-type) are being installed, along with hydrometers and solenoid valves to monitor and optimize irrigation. This setup enables precision irrigation, reducing unnecessary water use and potentially **saving up to 30% of water** compared to traditional systems.

Data from soil sensors and weather stations are combined through a **smart irrigation software** and integrated into the project DSS platform. Additionally, a radar probe and telemetry system are being deployed to monitor the Albola stream flow, ensuring environmental flows are maintained. The agreement will remain valid until the 30th of September 2027, supporting continued data collection

beyond the IMPETUS project and aligning with its Data Management Plan to secure long-term monitoring and research.

➢ **Integrated groundwater monitoring system**

Currently, water withdrawals and groundwater levels in the Valle dei Laghi area are poorly monitored, hindering effective water governance. To address this, BIM signed an agreement on 7 June 2024 with the second-grade irrigation consortia "Val del Vent" and "Pedegazza" to improve **groundwater monitoring** in the northern sector of the demo site, where aquifers are the primary irrigation source. A preliminary well survey was carried out and a shared monitoring protocol for minor irrigation wells was established, enabling systematic manual measurements. **11 wells** are currently being monitored manually, excluding those structurally unsuitable or designated for remote monitoring. Data have been regularly collected (at least monthly) since July 2024, revealing that pumping activity is the main driver of groundwater level fluctuations. On the 14th of May 2025, an addendum extended the agreement to include **continuous monitoring of 4 wells** using a web-based remote-control platform. These data will be integrated into the project DSS platform to enable historical analysis. As per the Data Management Plan, monitoring will continue for at least two years post-project to ensure robust data for future research.

2.6.2 Impact

Impacts/effectiveness in reaching the objectives

- The calibration of a reliable hydrological model with high accuracy (KGE > 0.7) can improve the capacity of regional authorities to anticipate water dynamics in complex Alpine environments, strengthening the scientific basis for sustainable water management and future climate adaptation policies.

- By overcoming the lack of operational diversion and reservoir data with an innovative reverse-engineering approach, the project has set a replicable precedent for other Alpine and data-scarce basins, enabling more realistic and effective water resource modelling in contexts where transparency or data availability are limited.

- The integration of historical, seasonal, and long-term climate information into a unified DSS can empower decision-makers with a practical, forward-looking tool, enhancing their ability to both prevent short-term crises like droughts and design long-term climate adaptation strategies, thereby increasing regional resilience.

- A structured stakeholder engagement process involving workshops and bilateral consultations has strengthened collaboration among key regional actors, particularly between the public and private sectors. This cooperation was formalised through two dedicated agreements and translated into concrete territorial initiatives, such as enhanced irrigation efficiency and improved water resource monitoring by integrating data into Decision Support Systems (DSS). These measures contribute to more effective integrated water management and help to reduce potential conflicts over resource allocation.

Foreseen effects

- **Short-term:**
  - *Enhanced operational management and risk prevention*. Seasonal forecasts will enable water managers to anticipate drought periods and implement preventive measures to mitigate their impacts, improving water security.
  - *Increased awareness and strengthened governance*. The workshops and the interactive DSS platform have already raised awareness of water-related issues and fostered greater collaboration among stakeholders.
- **Long-term:**
  - *Climate-resilient strategic planning*. Long-term climate projections will provide the Autonomous Province of Trento and other planning authorities with the robust, scientifically grounded tools needed to develop more effective climate change adaptation strategies.
  - *Enhanced economic and environmental sustainability*. More efficient water management will contribute to the long-term sustainability of key economic sectors like agriculture and

hydropower production, while simultaneously preserving vital aquatic ecosystems by ensuring environmental flows.

○ *Long-term and multi-purpose water management*. The availability of reliable monitoring data on irrigation withdrawals from both surface and groundwater sources will facilitate optimized multi-purpose water resource planning.

Transferability, scalability, and adaptability of the solution:

The methodological framework (combining hydrological modelling, stakeholder engagement, and DSS platform development) is highly transferable to other regions with similar hydrological and socio-economic characteristics. The use of global datasets like CORDEX makes it straightforward to extend the analytical methods to other regions. However, a significant challenge to seamless transferability lies in the local, in-situ data required for model calibration. These datasets (e.g., from local weather providers and river gauges) are not easily accessible and require a dedicated data ingestion and processing pipeline for each new provider and location.

2.6.3 Lessons Learned

Key takeaways

- *Integrated modelling is crucial*. The value of the DSS lies in its integration of physical processes (snow, runoff), multiple time scales (historical, seasonal, climate), and anthropogenic impacts. A siloed approach would not have captured the complex interdependencies of the water system.
- *Co-design ensures relevance and uptake*. Engaging stakeholders from the beginning was not just a complementary activity but a core component of the project. Their feedback was essential for designing a user-friendly interface and for validating model assumptions, which in turn fostered trust and increased the likelihood of the tool's adoption.
- *Innovation can bridge data gaps*. The project demonstrated that a lack of measured data should not be a complete barrier. The creative use of downstream public data to infer upstream private management rules is a key[1], transferable lesson for modelling in real-world, data-scarce environments.
- *Innovation must function across multiple levels to be truly effective*. This entails integrating digital tools and platforms with on-site demonstration activities, aimed at reinforcing water monitoring systems and improving responsiveness to environmental challenges.

Challenges encountered

- *Data scarcity and accessibility*. The primary challenge was the absence of official, shared operational data for the numerous water intakes and reservoirs. This required significant effort to develop and validate workarounds and highlights the pervasive issue of limited data sharing in water management.
- *Fostering sustained stakeholder collaboration*. While ultimately successful, maintaining engagement and building trust among diverse stakeholders with potentially conflicting interests (e.g., agriculture vs hydropower) required continuous effort, tailored communication, and dedicated facilitation.
- *Calibrating for multiple complex processes*. Accurately calibrating a model for a complex Alpine basin that is heavily influenced by both snow dynamics and a dense network of hydraulic works is technically demanding and requires a multi-stage, iterative approach.
- *Initial mismatch between interface complexity and user needs*. An initial version of the DSS platform, while technically robust, presented a level of detail and complexity suited for scientific users. The main challenge was to find the best way to simplify a highly complex hydrological system and turn it into an operational tool that could be used effectively by non-technical stakeholders. The project had to adapt and dedicate resources to simplify the interface at a later stage, a process that could have been more efficient if stakeholder comprehension levels had been assessed from the outset.

---

[1] It was verified that the derived operational rules remained within the limits defined by the provincial concessions using data from APRIE (the Agency for Water and Energy Resources of the Autonomous Province of Trento).

- *Not foreseen project issues*. The delayed approval of the project amendment hindered the timely launch of field monitoring activities, resulting in insufficient time for effective data collection. As a compensatory measure for project delays, data collection will be extended for two years beyond the duration of the IMPETUS project, in alignment with its Data Management Plan, to ensure long-term monitoring and support continued research efforts

Future recommendations
- *Formalize data-sharing agreements early*. For future projects, establishing formal, legally sound data-sharing agreements with all relevant public and private entities at the outset would streamline the modelling process and reduce uncertainties.
- *Merge technological tools with field-based practices*. Combining digital tools with practical, on-site implementation activities to ensure both technological innovation and tangible engagement with local stakeholders.
- *After-project life*. For a digital tool as the DSS, it would be beneficial to identify and engage (from the early project phase) a local organisation that can continue to use, maintain, and disseminate the tool beyond the project period. This would help to ensure the tool's long-term sustainability and impact.

Barriers to transferability
- *Dependency on local calibration data*: The model's accuracy is fundamentally dependent on the availability and quality of local, in-situ meteorological and hydrological data for calibration. The approach is not applicable in regions lacking this baseline monitoring infrastructure.
- *Requirement for high-level technical expertise*: Setting, calibrating, and maintaining a Digital Twin of this complexity requires a dedicated team with specialized expertise in hydrology, data science, and software engineering; it is not a "plug-and-play" solution.
- *Institutional and political context*: The success of the participatory approach is contingent on a pre-existing willingness of stakeholders to collaborate. In regions characterized by deep-seated conflicts or a lack of institutional trust, implementing such a tool would face significant non-technical barriers.

2.6.4 Conclusion

The development and deployment of the Digital Twin (DT) and Decision Support System (DSS) for the Valle dei Laghi demonstrated a robust, **integrated approach to climate-resilient water management in complex Alpine environments**. The system successfully combined fine-scale hydrological modelling, real-time monitoring, seasonal and long-term climate projections, and participatory planning to address **critical water governance challenges in a multi-user context**.

Technically, the DT achieved high calibration accuracy, providing reliable simulations of historical water dynamics. The platform's user-friendly interface, developed through a co-design process with stakeholders, facilitated broad engagement and uptake. Workshops and bilateral meetings led to strengthened regional cooperation, the revival of dormant irrigation consortia, and the signing of new agreements to support smart irrigation and groundwater monitoring. The DSS also integrated new pilot initiatives on precision irrigation and continuous groundwater monitoring, linking strategic planning to operational actions. The task provides a **scalable and replicable methodology**, offering a powerful example of how integrated modelling and participatory governance can enhance water resilience in mountain regions facing increasing climate stress. Future success will depend on early data-sharing agreements, continued user training, and cross-sector collaboration.

2.7 Solution 7: improving bathing water quality in extreme storm events (Task 4.8.1)

Climate change is increasing the frequency and intensity of extreme weather events, including heavy rainfall (Giorgi et al., 2019). These conditions contribute to the overflow of untreated wastewater into coastal waters, posing significant microbiological risks. In order to propose a technologically viable solution to address the impact of this challenge, a Quantitative Microbiological Risk Assessment (QMRA) model was developed and tested in the context of Barcelona's coastal bathing waters. The QMRA specifically addresses the health risk derived from Combined Sewer Overflow (CSO) events and their impacts on water quality and public health.

The framework is a Mediterranean coastal biogeographical region. The case study or physical domain proposed is the bathing waters near a combined sewer overflow in an urban beach of the city of Barcelona. Barcelona, with a population of 1.6 million, has a Mediterranean climate characterized by intense rainfall events occurring especially in autumn and spring seasons. One major issue is the existence of a combined sewer system. In a combined sewer system, both stormwater and sewage are transported together. Under normal conditions, wastewater is directed to a treatment facility. However, during intense rainfall or extreme weather events, the system can become overwhelmed, leading to direct discharges into nearby water bodies to prevent urban flooding. CSO events introduce untreated sewage, pathogens, and pollutants into recreational and ecological environments, increasing risks of waterborne diseases, contamination, and ecosystem degradation (Lehmann et al., 2015). In an average year, the volume of untreated water discharged onto the beaches through CSO events is approximately 9 million cubic meters. With rising global temperatures and more frequent extreme rainfall events, CSO occurrences are expected to increase by 20% in frequency and severity in Barcelona city, necessitating improved monitoring and management strategies (RESCUUE, 2021). In addition, rising temperatures promote rapid bacterial growth, but also increase mortality rates due to the effect of temperature itself and solar radiation. Pathogen contamination from CSO includes bacteria such as *E. coli* and enterococci, protozoa such as Cryptosporidium and viruses like Norovirus (NoV) and Adenovirus (AdV). Recent studies confirm the expected predictions regarding the increase in the frequency of CSO scenarios. studies claim that the intensification of precipitation patterns due to global warming leads to more frequent sewer overflows, increasing pathogen loads in coastal waters (Fortier et al., 2014). Similarly, some studies (Addison-Atkinson et al., 2022) demonstrated that high-resolution hydrodynamic models integrating climate projections improve the accuracy of pathogen transport simulations in urban coastal environments, aiding in early warning systems and public health protection.

The EU LIFE iBathwater project that previously investigated this topic did not consider pathogen degradation in its model, and the risk assessment was not integrated with dynamic data such as discharge flow rate and duration. One key objective of this IMPETUS task is related to the need for improved Faecal Indicator Bacteria (FIB) pathogen ratios for better risk estimation. These provide a relationship between the concentration of bacteria and viral quantities in the water, thus allowing the risk of exposure to be determined. In this way, Nov and AdV presence can be estimated with higher representativeness from the concentration of FIB. The FIB is more easily monitored, and even real-time analysis methods are available and were tested in the study area. In some studies (Federigi et al., 2019), the use of FIB (coliforms, *E. Coli,* and intestinal enterococci) to estimate pathogens has been reported. In these cases, the application of pathogen-to-indicator ratios to calculate the concentration of reference pathogens and the associated risk has been reported. Therefore, the hypothesis is that this potential monitoring of FIB in the CSO discharge point can feed dynamically the transport model to estimate pathogen concentration evolution maps. This allowed us to base the risk assessment on more realistic concentration data.

Current risk assessment models lack a real-time prediction that integrates climatic and hydrodynamic data into deterministic models. Besides, there are limited studies assessing seasonal variations in pathogen persistence and public health risks.

The following are the main specific objectives tackled during the work done in the task:

- To allow the monitoring and management of waterborne diseases.
- To provide support for risk prediction associated with extreme storm events.
- To build upon the combination of advanced online pathogen monitoring and water quality models to prevent waterborne outbreaks in the seacoast.
- To validate the tool in the demo site in Catalonia coast.

2.7.1 Results

The general workflow of the developed QMRA model is illustrated in Figure 27. The tool includes the following features:

- Input data of CSO events: flow rates and contamination levels. Six sampling campaigns were done under storm weather conditions in the discharge point, during CSO events, for FIB and pathogen analysis. These data were also used to calibrate the model. For the sampling campaigns and the early warning of the CSO events, we collaborate with the Water Cycle Control Centre (BCASA), which manages sewage, drainage, and beach conditions.
- Input data of environmental conditions: sea currents velocity and direction, temperature, pH, salinity, and UV radiation data. Lobelia, a project partner company, also provided historical data and projections.
- Advection-diffusion module: simulating pathogen transport under varying environmental conditions. The model developed consists of two interlinked calculation domains. In the first step, transport along the length of the discharge channel is determined. The result obtained is the concentration of pathogens at the mouth of the channel, which is the input for the second model of open water transport or bathing area.
- Degradation functions: including temperature, salinity, and UV degradation rates for FIB and viruses.
- Risk assessment module: implementing dose-response models to estimate infection probability.

The model was tested for the bathing waters around the CSO point in Bogatell Beach in Barcelona. The following are the key findings:

- The model produces the pathogen concentration evolution along the breakwater channel, helping us to understand contamination spread, see Figure 28. These outcomes feed the transport model in the domain of open waters, obtaining the concentration map in the area around the breakwater, see Figure 29.
- Based on the risk assessment module, CSO discharges significantly increase pathogen concentrations, exceeding safe limits for up to 48 hours, depending on the intensity of the overflow and the marine conditions.
- Pathogen persistence varies seasonally; the degradation rates would be higher in summer due to increased ultraviolet exposure. However, hydrodynamic conditions influence contamination spread, with currents playing a major role in dilution. The patterns of current speed and direction during spring and autumn would imply faster dispersion of pathogens, reducing the risk of infection faster in these seasons (Figure 30).
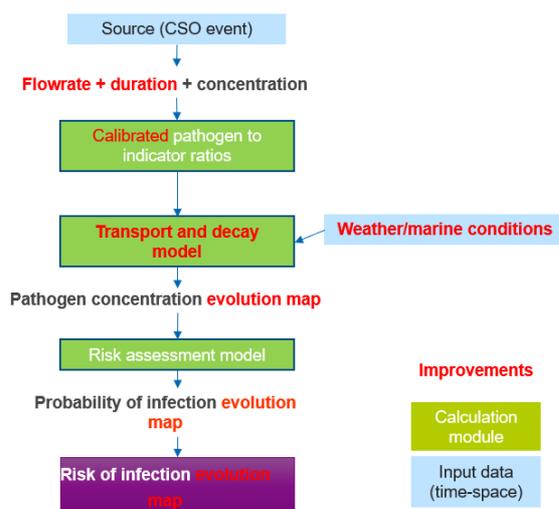
Figure 27 Outline of the model workflow, upgrade highlighted in red.
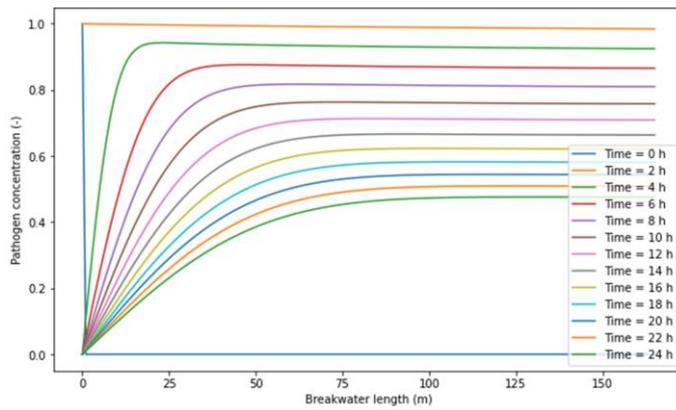
Figure 28 Pathogen concentration evolution along the breakwater channel.
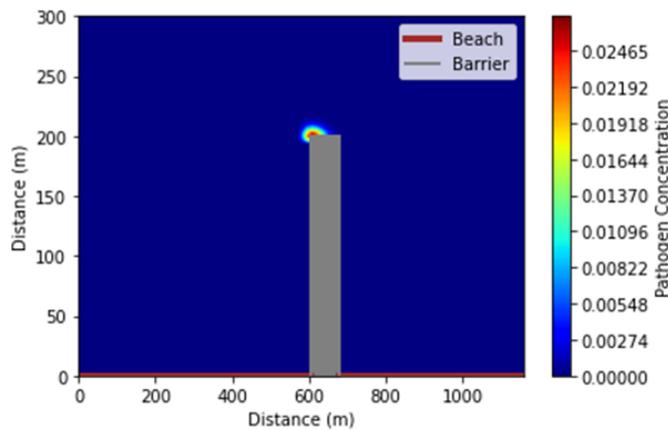
Figure 29 Pathogen concentration map in the bathing area around the breakwater (the break water is indicated in grey).
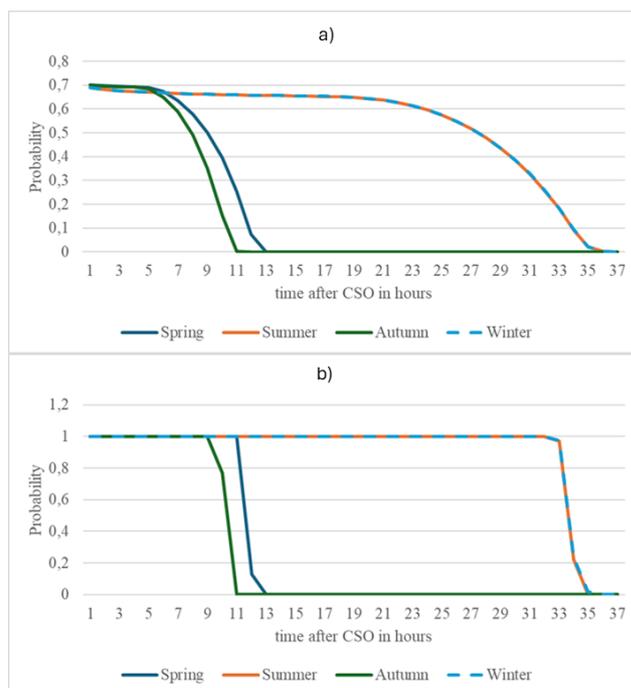
Figure 30 Risk of pathogen infection for child swimming: a) Norovirus and b) Adenovirus.

The functionalities and potential of the QMRA model developed in this project were presented in:
- Online training workshop on case studies in practical knowledge of monitoring and analysis of wastewater. Conducted on December 16, 2024 to approximately 50 people (technical experts). The content is available in the OneHealthWatch platform.
- Online meeting with the Water Catalan Agency (ACA, regional public administration entity) on the 11/02/2025 to 7 people (technical experts).
- In person meeting with Catalan Agency of Public Health (ASPCAT) on the 21/01/2025 to 4 people (technical experts).
- Online Sixth Open Training Session, Heat and Health: Building Resilience for a Hotter Future coordinated in the framework of the REGILIENCE project on the 20/02/2025 to 40 people (technical experts).

Stakeholders from public health and water agencies valued the tool's potential to anticipate contamination events and guide beach management decisions. They appreciated the intuitive risk visualizations but emphasized the need to align the tool with existing monitoring systems and regulations. Their feedback has helped prioritize improvements in usability and data integration in future developments. Concerns about the conservative nature of predictions were noted, and future versions will aim to better communicate uncertainty to support balanced decisions.

2.7.2 Impact

The presented results effectively address the development of tools for the prediction, monitoring and management of increased risk of water-borne diseases in the Coastal demo-site. Overall, the project outcomes show potential advanced pathogen monitoring and QMRA modelling to improve safeguarding of public health in coastal areas. Specifically:
- The refinement of FIB-to-pathogen ratios represents a significant step forward in assessing microbial risks, enhancing the ability to estimate pathogen presence based on indicator bacteria.
- The development of a 2D transport model for pathogen dispersion, incorporating decay processes, has provided an essential tool for representing contamination dynamics. This model, coupled with the dose-response risk module, enables the creation of exposure scenarios under varying environmental conditions. By integrating these elements, the QMRA framework contributes to preventing waterborne outbreaks through more precise simulations of contamination spread and associated health risks.
- The calibration of the model using real CSO event data from Barcelona demonstrates its reliability and applicability in real-world scenarios. The ability to compare simulated pathogen concentrations with actual field measurements strengthens confidence in the model's predictive capabilities.
- This validation process supports the final objective of implementing and testing the tool in the Catalonia coastal demo-site, confirming its effectiveness for decision-making in beach water quality management.
- Future work should focus on integration of machine learning strategies to predict CSO intensity and duration to feed the model, so using historical rainfall and sewer data we can incorporate the forecasting of risk levels.
- Refined forecasting capabilities will allow us to make simulations of climate scenarios so making projections and trends of risk of infections given the climate scenarios projected by climate services.
- The methodology and workflow developed in this study are transferable to other locations facing similar challenges, allowing for the adaptation of the QMRA model to different water basin environments affected by CSO events and extreme weather conditions.
- Contacts with the relevant administration (ACA & ASPCAT) have been established to present the developed QMRA model and its functionalities in order to discuss with them the potential of the model and also its potential for transferability and application. The feedback received was positive because the tool developed is a feasible and useful alternative for predicting future scenarios in CSO situations. Future meetings will be organized.

Given the KPI established for the task:

- As short-term impact, the QMRA model enhances real-time monitoring and prediction of human health risks associated with bathing water quality, which could support municipal decision-making during extreme storm events.
- The tool is highly transferable; it only requires adaptation of the geometry of the discharge channel and the coastal zone. The direct impact consists in that the tool successfully identifies the number of events where water quality poses a health risk, which can help authorities to implement timely interventions such as beach closures or public announcements.
- As long-term impact, the methodology and workflow developed can be transferred to other coastal areas with adjustments, ensuring broader implementation where pathogen concentration monitoring is available, reinforcing resilience against climate-induced water quality threats.
- As indirect impact, integrating advanced pathogen monitoring with water quality models, the tool contributes to identify the need to design preventive measures to reduce the frequency and severity of waterborne disease outbreaks, benefiting public health and tourism-dependent economies.

2.7.3 Lessons Learned

Key Takeaways:
- The integration of QMRA modelling with real-time environmental data provides a valuable tool for proactive water quality management.
- Predictive modelling enhances decision-making processes, allowing authorities to act before contamination events pose significant health risks.

Challenges Encountered:
- Lack of high-resolution real-time pathogen data impacted model calibration. The model needs to be fed with FIB monitoring data (or predicted data) at the point of discharge to measure the intensity of the emission. Currently, authorities in the case study do not register this information.
- There is uncertainty derived from the variability in pathogen persistence according to different bibliographic sources, differences in seasonal conditions required adjustments in the risk assessment framework.

Future Recommendations:
- Automated pathogen sensors to improve model accuracy and early detection capabilities.
- Machine learning integration to allow prediction of the discharge intensity given patterns in weather and sewer system conditions.

Barriers to Transferability:
- Differences in wastewater management systems across regions may require minor model adaptation due to infrastructure variability.
- Data availability: Successful implementation in new locations depends on real-time pathogen monitoring capabilities or specific predictive tools based on local historical data to produce discharge intensity forecasting.
- In terms of economic feasibility, limited funding for advanced monitoring technologies or developing of predictive tools could hinder widespread adoption.

2.7.4 Conclusion

The work done in T4.8.1 highlights the importance of integrating real-time data and modeling approaches to enhance decision-making in bathing water quality management. The QMRA model developed in IMPETUS offers a comprehensive assessment of microbiological risks associated with CSO events, providing a valuable tool for municipal authorities and public health organizations. By

incorporating FIB-pathogen ratios, hydrodynamic transport modeling, and dose-response risk assessments, the framework offers a promising basis for predicting contamination levels and potential health risks. Its reliability will increase as it is further calibrated with additional field data collected during CSO events and fed with real-time environmental information.

A key contribution of this work is its applicability to different coastal environments, enabling broader adaptation in regions experiencing similar climate-related challenges. The validation of the model using real CSO event data ensures reliability, while the integration of machine learning techniques offers potential enhancements for predictive capabilities. Despite challenges such as data availability and regulatory constraints, the project demonstrates that QMRA-based approaches can be successfully implemented for early warning systems and proactive risk mitigation.

Future work should focus on refining predictive accuracy through improved data collection techniques, including the use of real-time pathogen sensors and enhanced environmental monitoring systems. Additionally, expanding the model's geographic scope and integrating it into policy frameworks will maximize its impact in supporting climate adaptation strategies and protecting public health in urban coastal settings.

2.8 Solution 8: Increasing drinking water resilience to water-borne pathogens (Task 4.8.2)

Harmful algal blooms (HABs), driven by toxic algae, have become a growing environmental challenge due to climate change and the rising CO_2 levels, posing major risks to ecosystems, water quality and human health. These blooms can trigger toxin release, reduce oxygen levels in the water, and disrupt food chains, affecting biodiversity. In addition, HABs in water reservoirs can cause several problems for conventional drinking water treatment plants, including higher coagulant demands, shorter filter runs due to clogging, and management of disinfection by-products. They also contribute to the development of unpleasant tastes, odors, and toxins, while increasing the risk of microbial regrowth throughout the distribution system.

A deep knowledge of the water reservoirs -whether natural or artificial- and past cyanobacteria and cyanotoxin levels equips utilities to implement proactive and preventive strategies for water treatment. Analyzing physic-biochemical patterns with the algae ecosystem -such as water quality and the identification/quantification of algae species- enables the generation of timely alerts, such as HAB warnings with advisory guidance levels.

Effective management of cyanobacterial growth in the water reservoirs requires a strategic and multifaceted approach. The appropriate alternative depends on ecological conditions, cost-effectiveness, seasonal variations, and the potential water use (i.e., irrigation or recreation).

- Nutrient level control: Phosphorus and/or nitrogen often play a critical role in promoting bloom formation, so their regulation is essential for the sustainable control of cyanobacterial growth in drinking-water sources. Effective watershed management minimizes nutrient inputs from wastewater effluent/agricultural runoff, including reducing fertilizer use in the catchment area.

- Artificial mixing/aeration of source waters: Intermediate- to long-term strategies for controlling the growth of scum-forming cyanobacteria, such as Microcystis, in water bodies with stable thermal stratification. By disrupting thermal layers, this method limits the presence of cyanobacteria into light-optimized zones; thus, reducing bloom formation. After aeration ceases, cyanobacterial blooms may resurface promoting the proliferation of other species better adapted to the altered conditions.

- Use of agents to precipitate cyanobacteria: Short-term strategy for controlling cyanobacterial growth at the early stages, particularly in reservoirs. Copper sulphate is the most frequently used algicide, although other options such as copper chelates and hydrogen peroxide are utilized in different treatment approaches. Nevertheless, algicides can cause a rapid die-off of numerous cells, triggering the release of significant quantities of toxins.

Effective control requires proactive and adaptive strategies to remove cells, reduce toxins, and minimize health risks. Recommended actions should be adapted to bloom intensity and site-specific conditions as part of an integrated treatment approach:

- Optimize coagulation and flocculation processes: Selecting the appropriate coagulant type and dose, based on water quality factors like pH, turbidity, and organic matter, enhances clarification. Additionally, pre-oxidation treatments (e.g., with potassium permanganate, chlorine dioxide, or ozone) can boost efficiency by breaking down organic matter, weakening cell walls, and limiting toxin release.
- Don't recycle backwash water: Recycling filter backwash water during cyanobacterial blooms can reintroduce cells and toxins into the treatment process, increasing operational risk and compromising water safety.
- Slow sand filtration: Effective barrier against cyanobacteria, promoting the biological removal of cells and associated toxins through natural microbial activity within the filter bed. Its low operational intensity and high removal efficiency make it especially valuable during bloom events.

To address these challenges, the water reservoir supplying the Manresa drinking water treatment plant, situated inland in the Catalan coast region (DS2), has been chosen as a demo site. The facility operates by a conventional treatment train consisting of raw water intake, pre-chlorination, coagulation–flocculation, sand filtration, and post-chlorination. This configuration provides an operational setting for regional drinking water practices and offers a robust platform to assess the integration and performance of innovative solutions under real-world conditions. At this location, an integrated strategy combining monitoring, predictive modelling, disinfection technologies, and quantitative microbial risk assessment (QMRA) was implemented to mitigate risks related to HABs. This coordinated approach enhances early detection, strengthens system resilience, and supports informed decision-making by water utilities, public health authorities, and environmental agencies to safeguard public health and water quality in a region increasingly exposed to these environmental threats. to safeguard public health and water quality in a region increasingly exposed to these environmental threats.

2.8.1 Results

The real-time on-site monitoring campaign at the water reservoir was designed by Eurecat to capture a holistic view of water quality, focusing on physicochemical parameters (temperature, dissolved oxygen, redox potential, pH, turbidity, and electrical conductivity), hydro-chemical factors (nitrate levels), and algal composition (green, red, and blue algae). All real-time monitoring data were integrated with the outcomes of periodic sampling campaigns, enabling a comprehensive and nuanced analysis of the system's environmental dynamics over time.

A comprehensive analysis of the formation and driving factors behind harmful HABs has provided valuable insights into the dynamics and seasonal behaviour of algal communities. The study revealed a typical successional pattern observed in eutrophic and hypertrophic lakes, beginning with diatoms, followed by the proliferation of green algae or euglenophytes, culminating in dinoflagellates or cyanobacteria (blue-green algae). This progression is influenced by annual variations in temperature and precipitation.

Data collected through a multiparameter probe and laboratory-based algal identification allowed for the distinction of two main HAB types (Figure 31):

- Cyanobacterial blooms (Cyanophycean): Predominantly occurring in late summer (August to September). These blooms are associated with elevated temperatures and stagnant conditions.
- Green algal blooms: Marked by a significant increase in biomass, these blooms emerge from spring through autumn, with green algae dominating during the warmer months and other taxa such as diatoms more prevalent in early spring.
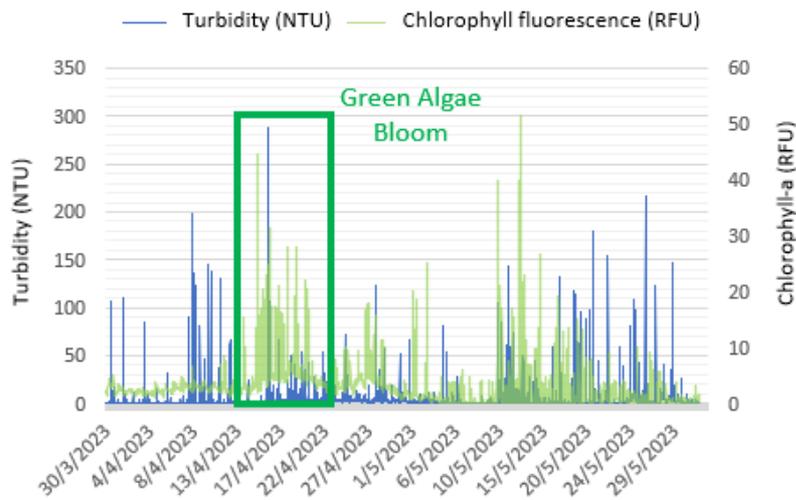
Figure 31 Occurrence of green algae blooms identified through turbidity and chlorophyll-a fluorescence signals.

These findings highlight the need for targeted monitoring and intervention strategies to mitigate bloom development and protect water quality throughout the year.

2.8.1.1 Model development for algal bloom prediction

Using data gathered from the monitoring campaign, Eurecat has developed a prototype predictive model (Figure 32) to support proactive water quality management. Its predictive reliability is limited by the small amount of available input data, primarily resulting from the relatively short monitoring period and the absence of continuous, high-frequency measurements for critical parameters. As the dataset expands, significant improvements in accuracy and performance are expected, enabling more reliable forecasting. Meanwhile, the visualization dashboard is still being developed in the context of WP2 to offer intuitive, real-time access to the model's outputs. The dashboard will be integrated in the final RKBs platform.

Based on the measured concentrations of chlorophyll and phycocyanin, a color-coded alert system has been implemented to classify water quality conditions and trigger appropriate management responses. The color code is structured into three levels: **green** (chlorophyll ≤ 10 µg/L and phycocyanin ≤ 30 µg/L), **orange** (chlorophyll between 10–25 µg/L and phycocyanin between 30–90 µg/L) and **red** (chlorophyll ≥ 25 µg/L and phycocyanin ≥ 90 µg/L). Additionally, each level is associated with a specific set of recommendations. Under the green code, no action is required, as the values are within safe limits for water quality and public health. The orange code indicates moderate risk, and the system displays targeted recommendations focused on controlling the proliferation of cyanobacteria in water reservoirs. In the red code scenario, the system prompts the application of advanced management strategies. These include interventions to control cyanobacterial growth in the water resource, such as the use of algicides/precipitation agents and operational adjustments in drinking water treatment.
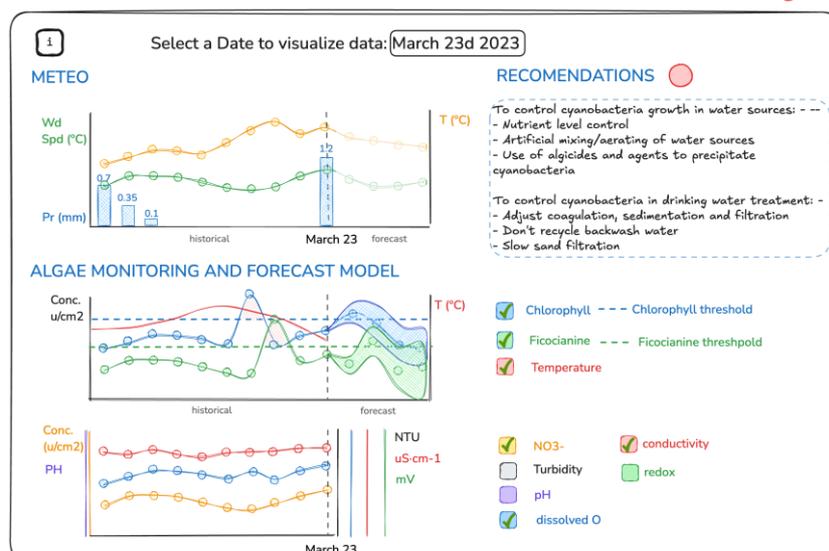
Figure 32 User interface of the HAB prediction model developed within the IMPETUS project

2.8.1.2   Design/synthesis of TiO₂-based photocatalysts

As part of its strategy to explore innovative technologies for mitigating harmful algal blooms and related cyanotoxins, the **IMPETUS project** explored materials for water treatment, with photocatalysis emerging as a particularly sustainable and promising approach. Within this framework, the project evaluated the potential of TiO_2-based photocatalysts supported on floating carriers, which offer practical advantages for application in open-water systems.

To this end, Eurecat developed a floating photocatalyst prototype inspired by methodologies reported in recent literature (Pestana et al., 2023). To obtain the photocatalyst, glass beads were coated with a thin layer of g-C_3N_4 using a sequence of cleaning, mixing, and calcination procedures. This fact ensured strong adherence of the coating material and consistent photocatalytic properties. The development of scalable photocatalyst designs provides proof-of-concept for advanced treatment solutions and establishes the basis for future pilot testing under real environmental conditions.

2.8.1.3   Cyanotoxins removal by solar disinfection

A lab-scale solar disinfection system has been designed by Eurecat with the objective of eliminating cyanotoxins from water, specifically targeting compounds such as **microcystins and anatoxins**. This system leverages solar energy as a sustainable and low-cost method for the degradation of these hazardous substances, which are increasingly being recognized as a threat to water quality and public health, especially in surface water sources affected by harmful algal blooms.

Microcystins are among the most detected cyanotoxins in European inland waters and are often used as a representative indicator of cyanobacterial contamination (Filatova et al., 2020). They are particularly prevalent in countries such as Italy, Spain, Poland, and Greece, where eutrophication and rising temperatures favor the proliferation of toxic cyanobacteria. Anatoxins, reported less frequently, have been identified in trace concentrations in reservoirs and lakes, especially in regions like Spain, Poland, and Russia (Filatova et al., 2020).

In this context, the **solar disinfection system** was tested using both microcystins and anatoxins as target contaminants, aiming to simulate real-world conditions and validate the system's effectiveness under various scenarios. The project not only demonstrates the potential of solar-based water treatment technologies but also highlights the importance of addressing a broad spectrum of cyanotoxins in efforts to ensure safe and reliable water supplies.

The experimental setup consisted of a continuous-flow solar UV reactor with a working volume of 6 liters. The system operated at a feed flow rate of 2 L/min, allowing for steady exposure of the water matrix to solar-simulated ultraviolet radiation. To assess the degradation kinetics of the target

compounds, samples were collected at three points: initially (t = 0), after 30 minutes, and after 60 minutes of treatment. To evaluate the influence of the photocatalyst on the degradation process, three different conditions were tested: Photolysis control (no catalyst added) to quantify the effect of solar UV radiation alone, a low catalyst dose of 0.16 g/L and a higher catalyst dose of 0.32 g/L.

Photolysis demonstrated a promising performance in the degradation of cyanotoxins, achieving approximately 80% removal of both compounds within 60 minutes of treatment. At a photocatalyst concentration of 0.16 g/L, the removal efficiencies for the two target cyanotoxins were remarkably similar: anatoxin-a reached 82.6%, and microcystin-LR achieved 81.25%, demonstrating consistent performance and effective degradation across both compounds.

However, when the photocatalyst dosage was increased to 0.32 g/L, a slight decrease in removal efficiency was observed for both toxins. This suggests that beyond a certain threshold, higher catalyst concentrations may hinder process performance, potentially due to factors such as light scattering, reduced photon penetration, or catalyst particle aggregation. These results highlight the importance of optimizing photocatalyst dosage to maximize treatment efficiency while avoiding performance losses linked to excessive loading.

This design allowed for a comparative assessment of the system's performance under varying photocatalytic loads, as well as the isolated contribution of direct photolysis.

2.8.1.4 Theoretical QMRA study of cyanobacteria

The primary goal of the QMRA conducted within the **IMPETUS project** by KWB was to apply an updated version of a quantitative microbial risk assessment tool to support evidence-based decision making in the water supply sector. To achieve this, the tool was used to compare different water treatment configurations (two scenarios) at the Manresa drinking water treatment plant, evaluating their effectiveness in reducing microbiological health risks.

Current Treatment System: Consists of optional pre-chlorination (only during high organic matter load), clarification, rapid filtration, and mandatory final chlorination (as established by Spanish legislation, the system must maintain a minimum residual chlorine level of 0.2 mg/L across the entire distribution network)

Proposed Future System: Includes pre-ozonation, enhanced clarification, ozonation, granular activated carbon (GAC) filtration, and mandatory final chlorination.

The exposure assessment was based on literature values compiled in an open-source database from the AQUANES project (http://www.aquanes-h2020.eu/). The source water quality was modelled using lognormal distributions based on literature values due to the absence of local data. These distributions reflect annual variability in pathogen concentrations and report the 2.5th and 97th percentiles as minimum and maximum values. Treatment performance (Figure 33 and Figure 34) is measured using log-removal values, where each unit represents a 90% reduction in pathogen concentration.
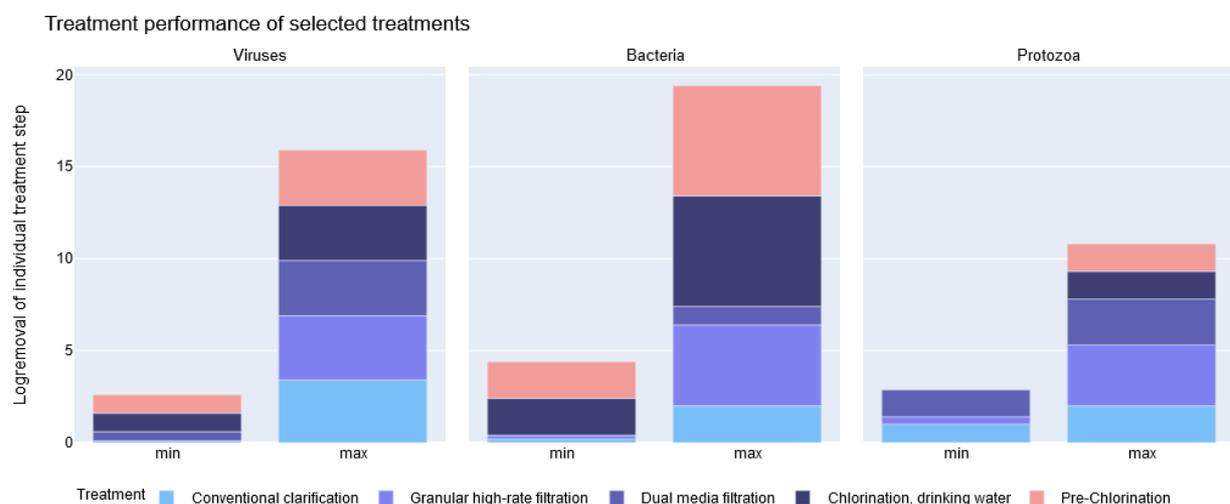
Figure 33 Overview of assumed log-removal values of the current drinking water supply
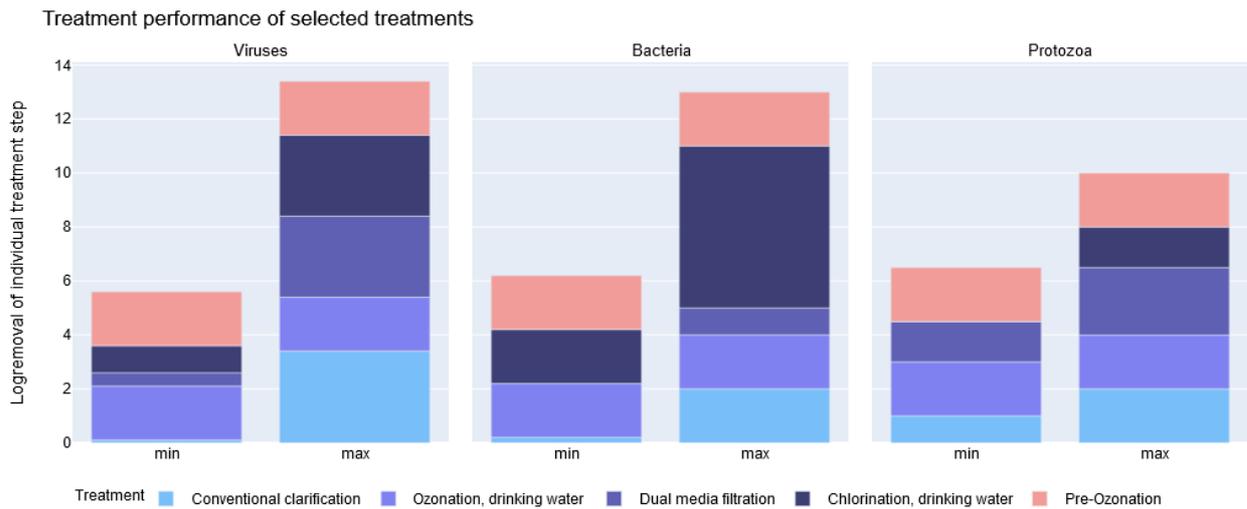
Figure 34 Overview of the assumed log-removal values of the future drinking water supply

In IMPETUS, treatment performance was modelled using literature-based LRV ranges due to a lack of local data in Manresa, leading to broader uncertainty in risk estimates. The assessment is preliminary and highlights the need for local validation. A conservative exposure scenario assumed 1L/day of unboiled tap water consumed year-round.

The future treatment system in Manresa reduces both risk and uncertainty, especially for chlorine-resistant pathogens (Figure 35). Both systems likely meet safety benchmarks, but the improved setup is more reliable. Monitoring is advised to confirm performance.
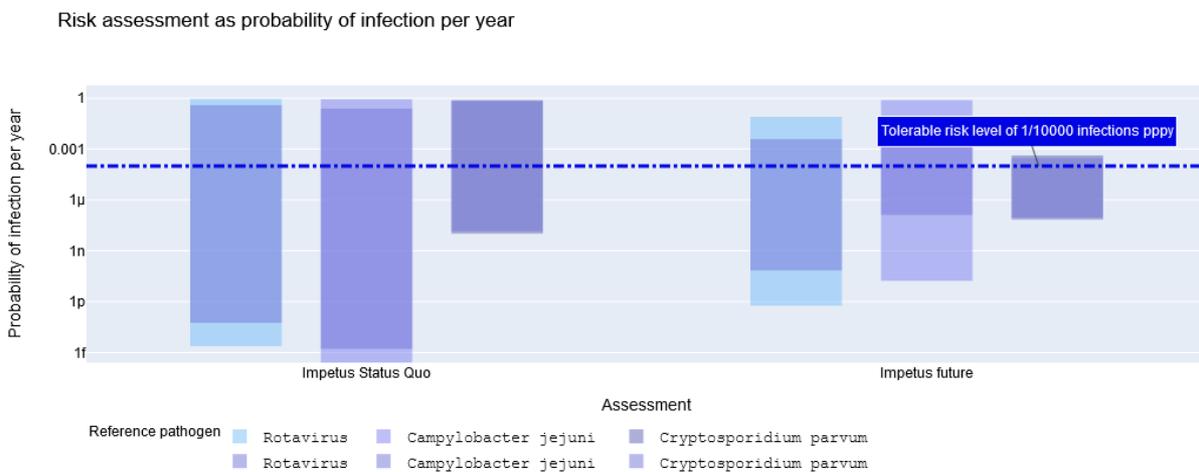
Figure 35. Comparison of the current and future drinking water supply against the background of the made assumption. Outer light shades areas refer to the calculated minimum and maximum infection probabilities while the inner dark shaded areas indicate the uncertainty related to the average annual risk

2.8.2 Impact

Short-term impact

The **IMPETUS project** has thoroughly assessed the vulnerability and resilience of current drinking water treatment systems along the Catalan coast to increasing algal blooms and water-borne diseases driven by climate change. By analysing operational data, historical performance, and pathogen behaviour under varying scenarios, the **IMPETUS project** has provided a detailed understanding of how current infrastructures respond under stress conditions, particularly during periods of algal bloom proliferation, extreme weather events, and seasonal water quality fluctuations.

The evaluation identified key weaknesses in existing systems and opportunities for quick risk mitigation. Additionally, the findings enable relevant stakeholders to make informed decisions about short-term investments, emergency preparedness, and resource allocation. This proactive strategy ultimately helps safeguard public health and paves the way for stronger, climate-resilient water management frameworks. Stakeholders were actively involved throughout the IMPETUS project: representatives from local administrations, utilities, and municipal management participated in workshops and consultation sessions during both the assessment and testing phases.

Long-term impact

Beyond the **IMPETUS project** horizon, the development of robust and adaptive management strategies is anticipated to play a pivotal role in strengthening pressures linked to climate change, urban expansion, and ecosystem degradation. These strategies are designed to go beyond conventional infrastructure upgrades, focusing instead on the integration of advanced, real-time monitoring technologies, modular and flexible treatment configurations, and predictive modelling tools that leverage long-term datasets and machine learning to forecast risk scenarios with greater precision.

Within this framework, IMPETUS has provided critical tools and insights for adaptive water management. Through the integration of real-time monitoring, modular treatment systems, and predictive analytics, the project's outcomes facilitate early risk detection, prompt interventions, and informed decision-making.

Such a comprehensive approach enables a transition from reactive to anticipatory water management, allowing for earlier intervention and more efficient allocation of resources during high-risks periods. By enhancing water systems' adaptability, these solutions provide a scalable model for sustainable water governance, contributing to technical innovation, policy formulation, and cross-sectoral coordination.

The IMPETUS project has developed valuable knowledge and data-driven solutions for improving the resilience and efficiency of drinking water treatment systems against climate-driven challenges, such as algal blooms and water-borne diseases, with strong potential for replication in Mediterranean coastal areas and other climate-vulnerable regions worldwide. The modular design of these technologies offers versatile applications across diverse aquatic environments, adaptable in size and designed to suit various operational needs, from small reservoirs to large water bodies, supporting broader climate adaptation and ecological resilience efforts.

2.8.3 Lessons Learned

Key Takeaways

- The implementation of continuous real-time monitoring systems has been a game-changer in detecting HABs early, enabling quicker and smarter management actions.
- The integration of predictive modelling further enhanced response efficiency by identifying high-risk periods with greater precision, thus optimizing resource allocation and reducing the overall costs associated with water quality monitoring.
- Solar-powered disinfection solutions have emerged as a promising, eco-friendly, and cost-effective approach to water treatment, especially ideal for remote areas or locations with limited infrastructure.

Challenges Encountered

- Occasional interruption or incompleteness of monitoring data, largely due to technical limitations of early-stage equipment. They were successfully addressed through the implementation of upgraded sensor networks and more resilient data platforms.

Future recommendations

- To enhance the effectiveness of water treatment across diverse environmental conditions, combining solar disinfection with supplementary methods such as ultraviolet or chemical

treatments is strongly recommended, especially in areas with low solar exposure or elevated turbidity.

- Strengthening system robustness through diversified treatment approaches, built-in redundancies, and ongoing advancements in monitoring technologies will support greater operational flexibility and long-term reliability.

Barriers to transferability

- Successful implementation in new regions may require robust historical datasets, including meteorological and water quality records, to calibrate and validate predictive models. Additionally, the performance of solar-based disinfection methods and floating photocatalysts depends heavily on environmental conditions such as sunlight intensity and water column depth.

2.8.4 Conclusion

The activities carried out under Task 4.8.2 have demonstrated the feasibility and added value of integrating real-time monitoring, predictive modelling, and innovative treatment technologies to enhance the resilience of drinking water systems against HABs and associated risks.

2.9 Solution 9: Assessing changes in the spatial distribution of species under global change scenarios (Task 4.9)

Sea level rise, more frequent and intense coastal storms, and other climate change-related factors are causing significant changes in coastal ecosystems. Climate change is leading to changes in the biodiversity of coastal areas, as habitats are degraded and species face challenges in adapting to changing environmental conditions. Coastal habitats such as wetlands and coastal dunes are on the front line of facing the impacts of climate change, and many already experience significant anthropogenic pressure, such as urbanisation, tourism and agriculture, making them even more vulnerable to the impacts of climate change.

The coast of Catalonia faces numerous challenges that threaten its rich biodiversity. The impacts of climate change affect the distribution, abundance, and survival of various species, leading to biodiversity loss, the spread of invasive alien species, and disruptions in important ecosystem services such as shoreline protection. This not only compromises the resilience of coastal inhabitants to climate change impacts, but also diminishes the region's genetic resources, reducing its potential for adaptation and innovation. Furthermore, declining biodiversity undermines the cultural heritage and recreational value of the area, ultimately affecting the livelihoods and well-being of local populations. Coastal wetlands such as the Ebro Delta, which provides habitat to more than 1,100 species, of which 109 are threatened (classified as Critically Endangered, Endangered or Vulnerable on the IUCN Red List of Threatened Species™), will face changes in habitat conditions (e.g., temperature, precipitation and sea level rise) due to climate change. Dunes are another key habitat within coastal ecosystems, which can play a key role in climate change adaptation, as they provide natural coastal defence for populations, infrastructure and species further inland. They are also important habitats in themselves, with more than 140 plant species occurring in Catalonian coastal dunes (Table 19 in Annex 6.6).

In order to enhance the long-term resilience of these coastal habitats and the species that rely on them, we must first understand the expected species responses to the effects of climate change. This is necessary to enable the appropriate prioritisation of conservation action and implementation of efficient adaptation strategies. We have undertaken analyses of potential future changes in spatial distributions for a selection of species occurring in coastal dunes (Catalonia) and marshlands (Ebro Delta) associated with global change. Although information and data on biodiversity in coastal environments are

increasingly more abundant and available, there exists a challenge to include biodiversity data in climate models and obtain concrete and reliable results on future biodiversity responses, which can be used to guide appropriate conservation and coastal planning. Biodiversity data is based on records of current presence, however, due to a lack of systematic data collection over an extended period of time, it is challenging to infer correlations with climatic and global change variables in order to assess how they have changed over time and the influencing factors.

The overall aim of Task 4.9 was to explore how likely species will change their distributions due to impacts associated with climate change, using innovative analytical frameworks. Taking advantage of the Impetus RKB and planning tools (WP2), potential changes in spatial distributions for different species occurring in coastal dunes and marshlands along the Catalonian coast were assessed by comparing projected future distributional changes with current distributions. To achieve this aim, the following steps were taken:

- Identify indicator species to analyse.
- Select, compile, and test explanatory and response variables.
- Run Species Distribution Models (SDMs).
- Make a balance of gains and losses of species in the two pilot sites (Ebro Delta and Catalonian coastal dunes).

2.9.1 Results

We analysed future changes in spatial distributions for a selection of species occurring in coastal dunes (Catalonia) and wetlands (Ebro Delta, Catalonia), as a result of a changing climate. Due to differences in the data availability and scale between different geographical areas, habitat types, and species groups, different methodologies were employed to analyse the distributions of species in the wetlands and coastal dunes. The methodology and results of the species analyses are therefore presented separately for each of the two study sites.

2.9.1.1 Wetland species (Ebro Delta)

2.9.1.1.1 Waterbird habitat availability

A Species Distribution Model (SDM) of waterbirds in the Ebro Delta was developed and run in order to predict potential changes in waterbird species distributions under various climate scenarios. While the coastal wetlands of the Ebro Delta provide an important habitat for a wide range of taxa (more than 1,100 species), we selected the waterbirds functional group as an indicator for the impacts of climate change, due to their high sensitivity to a range of climatic variables, their heavy reliance on coastal wetlands, and the relatively high availability of data for this group. We chose to use species within the Ardeidae family for inclusion in the SDM, as they were found to be the most abundant and representative group. These species, in decreasing order of occurrence, were: little egret (*Egretta garzetta*) (24.79 %), grey heron (*Ardea cinerea*) (21.80 %), great egret (*Ardea alba*) (15.90 %), cattle egret (*Bubulcus ibis*) (12.00 %), squacco heron (*Ardeola ralloides*) (8.30 %), purple heron (*Ardea purpurea*) (7.02 %), black-crowned night heron (*Nycticorax nycticorax*) (6.33 %), little bittern (*Ixobrychus minutus*) (3.54 %), Eurasian bittern (*Botaurus stellaris*) (0.18 %), and western reef heron (*Egretta gularis*) (0.14 %). The SDM was used to predict waterbird habitat availability under two climate change scenarios for the Mediterranean, the Intergovernmental Panel on Climate Change (IPCC) Representative Concentration Pathway (RCP) 4.5 (expected stabilisation of the greenhouse gas emissions) and the RCP 8.5 (expected continuous increase of the greenhouse gas emissions), across three distinct time periods: near-term (2021–2040), medium-term (2041–2060), and long-term (2081–2100) (Figure 36). The full methodology of the waterbird habitat suitability modelling procedure is outlined in De la Cruz and Numa (2024).

The SDM initially indicated a gradual increase in waterbird habitat availability in the Ebro Delta over the study periods, with temperature variations, increased cumulative precipitation and lower terrain

elevation identified as key factors influencing habitat suitability. However, upon incorporating land flood models due to sea level rise into the SDM, the available habitat area declined dramatically across all time periods for both climate scenarios. Given that sea level rise is generally a gradual, long-term process, the waterbirds habitat distribution is very similar between the two climate scenarios in both the near-term and medium-term, as a similar degree of sea level rise is expected between the two climate scenarios in the more near-future timeframes. In the long-term scenario, however, while drastic habitat losses are predicted for both climate scenarios, the situation is considerably different, with a predicted habitat loss of >50% based on RCP 4.5 and almost 70% based on RCP 8.5, by the year 2100 compared to the year 2020 (Table 20 in Annex **Error! Reference source not found.**. This suggests that taking measures to mitigate a high-emissions scenario could help to alleviate the impact of sea level rise on waterbirds species distributions in the Ebro Delta.

The model demonstrated the particular importance of rice fields as the only long-term remaining habitat for many waterbirds in the Ebro Delta in the face of climate change, as the vast majority of suitable habitat areas under the future scenarios were located in rice fields. This highlights the need for local capacity building for sustainable ecosystem management among local stakeholders, especially the agricultural community, to promote the long-term ecological resilience of these species and habitats. Thus, these results can inform the development of climate adaptation solutions and conservation planning in the region, and therefore be relevant to local and regional stakeholders and authorities, such as the Generalitat de Cataluña, the Ebro Delta Natural Park. We have already begun to address this, by building upon synergies with Task 4.2 (*Below-sea level multifunctional wetland to adapt to sea-level rise*) to identify adaptation measures to climate change that could benefit the development of nature-inspired solutions in rice fields, as a means of strengthening the long-term resilience of biodiversity in the Ebro Delta (see Deliverable 4.2 for further details on this solution).
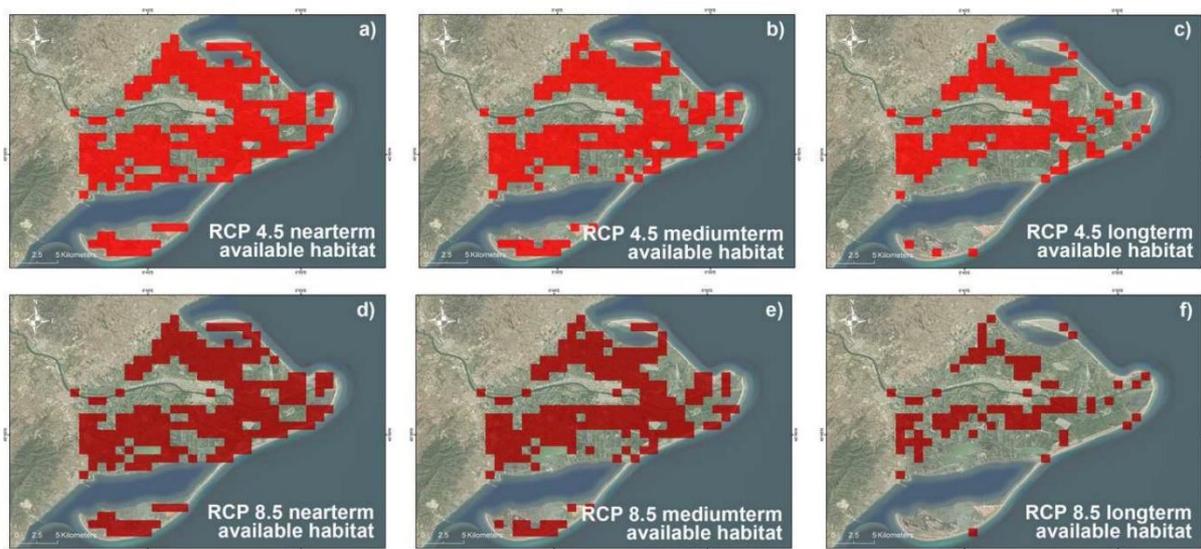
Figure 36 Projected optimal available habitat for the waterbirds functional group in the Ebro Delta under average conditions of maximum temperature, accumulated precipitation, and terrain elevation for climate change scenarios RCP 4.5 and 8.5 across the near-term (2021-2040), medium-term (2041-2060), and long-term (2081-2100). © De la Cruz and Numa (2024).

2.9.1.1.2   Species losses and gains in Ebro Delta

To address the data limitations and challenges associated with creating SDMs for all the species groups in a particular area, we developed an analytical framework based on global species databases to provide a practical and accessible first step for obtaining an overall picture of likely species distribution dynamics in a given site or region under climate change. This analytical framework applies scores to each species based on a set of criteria associated with their vulnerability to climate change, using data from the IUCN Red List of Threatened Species™ and other available biodiversity databases (Table 21 in Annex 6.6).

This analysis was piloted in the Ebro Delta in order to assess likely species losses and gains in the area under climate change. We found that of the 853 species present in the Ebro Delta (according to the Catalan Biodiversity Database[OBJ]), only 218 (25.55%) have been assessed on the IUCN Red List. No species of lichens, arthropods, bryophytes, or algae in the Ebro Delta have been assessed on the IUCN Red List, while only 178 vertebrates (55.45%), 3 mollusc species (33.33%), and 37 plants (12.3%) have been assessed. This further highlights the critical gaps in biodiversity data that exist and prevent these species from being included in climate change modelling and analyses.

After applying the scoring framework to the 218 species in the Ebro Delta assessed on the IUCN Red List, one species, the cinereous vulture (Aegypius monachus), was found to have a high probability of disappearing from the Ebro Delta due to the effects of climate change. Additionally, 30 species (13.76%), including three endemics: the Ebro barbel (Luciobarbus graellsii), the Ebro nase (Parachondrostoma miegii), and the Valencian toothcarp (Valencia hispanica), show a likelihood of local disappearance. 14 species (6.42%) are expected to remain neutral, experiencing neither significant gains nor losses. On the other hand, 85 species (39%) will likely benefit from the impacts of climate change in Ebro Delta, showing potential increases in range or population, and 88 species (40.36%) have a high probability of experiencing such gains. This analysis highlights that threatened species, including those unique to the Ebro Delta and the surrounding region, are the most vulnerable to the impacts of climate change. More details on this methodology and the results of the pilot analysis can be found on the IMPETUS marketplace.

2.9.1.2 Coastal dune species (Coast of Catalonia)

An assessment of the impacts of human-induced beach transformations on dune habitat biodiversity along the coast of Catalonia has also been undertaken. We initially encountered challenges related to the inclusion of biodiversity data within climate models, as the climate variables were at a larger scale than the local species data, and therefore, an SDM was not developed for the coastal dune species analysis. This led us to use different statistical techniques to explore other variables that could explain projected losses and gains of species in coastal dune habitats. Based on the existing literature, within the context of global environmental change, we hypothesised site-specific variables such as land-use factors and anthropogenic activities to be more influential to dune species distributions in the near-term than climatic variables, and therefore reframed this part of the task more holistically, focusing on *"global"* change, to encompass the overall burden of anthropogenic pressures to species in the region.

We used different statistical techniques to analyse the relationship between plant species occurrence and land-use factors in Catalonian coastal dunes. First, we performed a non-metric multidimensional scaling of 147 dune plant species within coastal dune habitats in three biogeographical zones in Catalonia (Girona, Barcelona and Tarragona) (Pintó et al., 2012), in order to create a visual representation that reflects the relationships between different species, communities, or habitats. See Table 19 in Annex 6.6 for a full list of the species included in this analysis. The results showed a variability of plant vegetation community structure across the three regions, which could reflect the degree of degradation of the dune ecosystems in each region (Figure 37). The assessed coastal dune habitats in Tarragona showed a clear distribution of vegetation communities, with no disturbed communities, with Girona dune habitats showed a distinct zoning of plant communities, some of which are disturbed. Dune habitats in Barcelona had a greater degree of variation in community structure, with a low degree of similarity between communities, and some disturbed communities.

TARRAGONA:
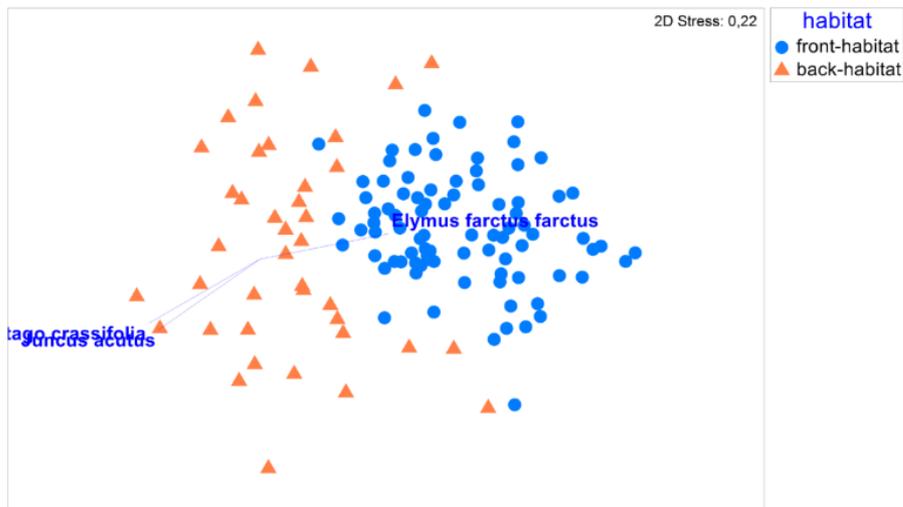
GIRONA:
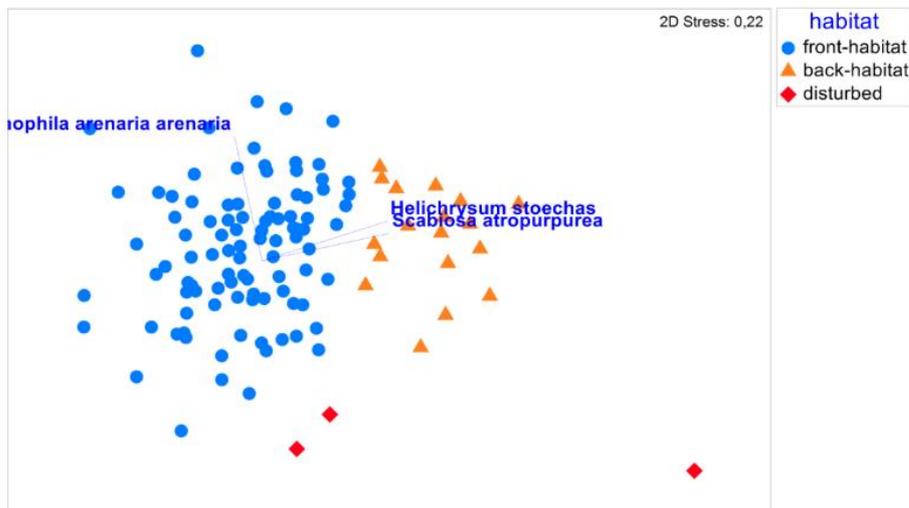
BARCELONA:
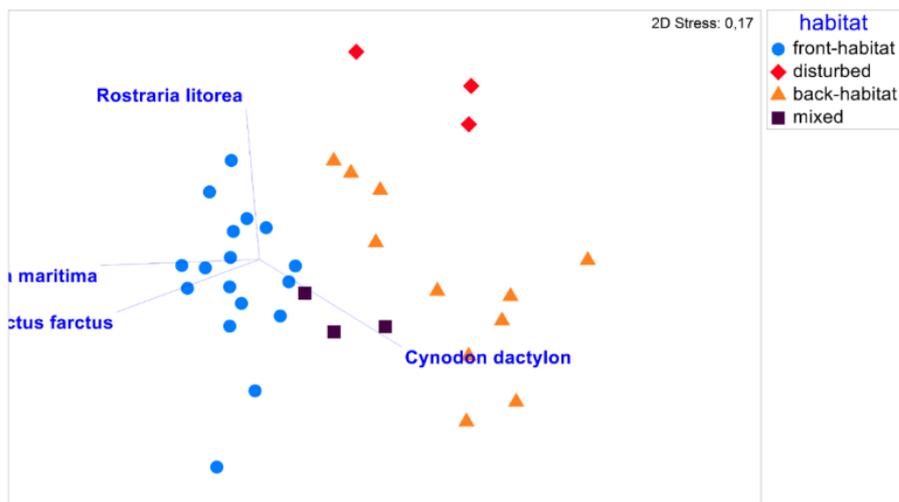
Figure 37 Non-metric multidimensional scaling showing variation in dune vegetation community structure across beaches in Tarragona, Girona and Barcelona.

To explore how these dune vegetation distribution patterns, correlate with land use factors, which were used as an indicator of human disturbance, we performed a canonical correspondence analysis (Ciccarelli, 2014) of the present species matrix with ten land cover categories: urban, communication routes, crops, grassland, scrubland, forests, forestry bare soil, lagoon and saltmarshes, freshwater and forests. However, none of these land-use factors explained a significant percentage of species variation, which suggests that dune size and other beach-specific factors related to the adaptive capacity of the ecosystem may have a greater influence on community structure and species dominance.

These results support the conclusion of similar research conducted in the region, particularly a study by Pintó et al. (2023), which found that the presence of dune-restricted species in Catalonian coastal dune systems was a function of dune size rather than proximity to human activity. This indicates the importance of dune beach size in determining the resilience of dune-restricted species in the future, particularly under growing anthropogenic pressure and the projected impacts of climate change in Catalonia, which include increased frequency and magnitude of coastal hazards, enhanced coastal erosion and sea level rise (Government of Catalonia, 2017). While our results found that current species distributions are not directly explained by land-use factors, dune habitat size can in turn be affected by anthropogenic activities such as dune management, spatial planning, and urbanisation, and therefore authorities responsible for these activities need to be aware of that. In the long-term, dune habitat size could also be affected by the impacts of climate change, as dune systems constrained by urban areas and infrastructure at the hinterland may be unable to migrate in response to sea level rise and coastal erosion. Our results suggest that this "coastal squeeze" effect could compromise the resilience of coastal dune vegetation, potentially leading to losses of dune-restricted plant species in smaller-sized beach-dune systems.

2.9.1.3   Publications and outreach activities

Various activities and communication materials have been produced in order to disseminate the results of our species analyses, including the following:

- A scientific publication detailing the methodology and results of the wetland species analysis, De la Cruz & Numa (2024), has been published in *Ecological Modelling*.
- An ArcGIS Story Map on coastal dune species vegetation in Catalonia and the importance of nature-based dune management has been published online.
- A workshop will be held in Amposta (Tarragona) in September 2025, where we will present and discuss the results of our species analysis to a wide range of stakeholders in the Ebro Delta. This workshop aims to bring together local and regional stakeholders and authorities to discuss challenges, opportunities, solutions and governance strategies for environmental change in the Ebro Delta. Approximately 20-30 stakeholders are expected to attend, including local (Natural Park, town councils), regional (Generalitat de Catalunya) and national authorities, project partners, experts, conservation practitioners and representatives from the various sectors found in the Ebro Delta.

2.9.2 Impact

Species distributional change:
The exploration of indicator species and assessment of their potential distribution changes contribute to a better understanding of the impacts of climate change on local biodiversity and ecosystems.
The results of the dune species analyses underscore the importance of dune-beach size in determining the distribution of plant communities in coastal dune systems in Catalonia. This highlights the need to consider habitat size and other beach-specific factors within conservation interventions and spatial planning, to support habitat provision for coastal dune vegetation species and maximise their resilience to environmental change in both the near- and long-term.

Knowledge Production and Dissemination:
The publication of the methodology and results of the wetland species analysis in *Ecological Modelling* (De la Cruz & Numa, 2024)[3], contributes to the enhancement of both local practical knowledge and global scientific understanding on the potential impacts of climate change on species distributions, which is an internationally important and urgent research topic.

Enhanced Biodiversity Management and Identification of Conservation Priorities:
An improved understanding of future changes in species distributions, and key influencing factors, can guide effective decision-making regarding conservation priorities and adaptation measures within the region. Information on predicted changes in species distributions can be used by conservation practitioners and technicians involved in spatial planning, conservation and protected area management at the local and regional level, to inform decision-making as well as the future development of potential nature-based and -inspired solutions within coastal Catalonia.
The waterbird SDM highlighted the importance of rice fields as the only current habitat that will remain in the long-term for many waterbirds in the wetlands of the Ebro Delta, in the face of climate change. This indicates the need to enhance local stakeholder capacity for sustainable ecosystem management, in order to promote the long-term resilience of these wetland species and habitats. There is therefore a need to harmonise agricultural land use with wider conservation and adaptation efforts.

Scalability of Nature-based and nature-inspired Solutions:
Building upon synergies with Tasks 4.2 and 4.3 (*Sand dune restoration and monitoring to prevent coastal erosion*), the results of the species distribution analyses can help to inform the development and upscaling of climate adaptation solutions currently under development in the Catalonian region. In particular, the findings of this task could be integrated into the plans for these solutions, given that tasks 4.2 and 4.3 both have considerable potential for promoting species conservation and restoration, and these tasks have already established relationships with stakeholders that are key to the wider scale implementation of conservation measures as well as the uptake of these solutions. In particular, the results can facilitate the efficient upscaling of nature-based and nature-inspired solutions such as these, allowing them to be implemented in a way that favours species adaptive responses and delivers biodiversity benefits on a wide scale (see Deliverable 4.2 for further details on the nature-based and nature-inspired solutions).

2.9.3 Lessons Learned

2.9.3.1 Challenges Encountered

The main challenges encountered were related to data fragmentation, unavailability, and incompatibility. We encountered several limitations related to variations in the types, scales and availability of data, highlighting the challenge of incorporating biodiversity into climate models. For the dune species analysis, the scale of the climate variables exceeded the scale of the biodiversity data – the latter was also fragmented, not standardised, nor available over long time periods. Thus, we had to redefine the task more broadly, within the context of "global" change. However, the canonical correspondence analysis of coastal dune plant species with land-cover categories was still inconclusive in explaining species variability in the study areas, meaning that potential explanatory factors (i.e. beach size) could only be inferred.

2.9.3.2 Future Recommendations

In response to data challenges related to incorporating coastal dune species data into climate models, we reframed the methodology of the dune species modelling in terms of "global" change. This, combined with the fact that the land use factors did not significantly explain plant species distributions, highlights the importance of maintaining a flexible, adaptive approach to species distribution modelling under climate change, allowing the methodology to be adapted in response to the available data and results generated. We also encourage performing preliminary tests to identify main explanatory variables and prevent potential setbacks related to data issues.

Our wetland species modelling generated clear and impactful results, demonstrating that SDMs are a powerful tool for predicting potential species distribution changes under climate scenarios. Sea level rise was used as an indicator for the impact of climate change, as it is the factor that best explains the impact on the waterbirds functional group. Given the significant impact of sea level rise on waterbird distributions, our results highlight the value of conducting future research to assess distributional changes to other species groups, especially those that may be sensitive to the impacts of sea level rise. However, additional explanatory variables, as well as other species indicator groups, need to be included in future analyses, to obtain a more comprehensive understanding of the distributional changes of biodiversity under climate change.

While the species losses and gains framework based on the IUCN Red List offers a useful starting point for assessing potential species responses under climate change, this methodology only represents a first step, and further species distribution modelling using local variables is necessary to ascertain the expected impacts of climate change in a given site and how exactly they might affect particular species groups, which is necessary for effective conservation planning. Moreover, the application of this framework to the Ebro Delta highlighted a notable imbalance in the assessment of different taxonomic groups on the IUCN Red List, further highlighting the need to increase the quality, consistency and availability of species data, particularly for more neglected species groups.

2.9.3.3 Barriers to Transferability

The analytical framework for assessing species losses and gains under climate change can be replicated in other sites using data from the IUCN Red List together with local biodiversity datasets, and therefore represents an accessible and low-cost method to obtain a broad-scale, initial overview of the status of species in a certain site and their potential losses and gains under climate change, however the accuracy of the results will be influenced by the available information on species presence at the local scale.

Similarly, the waterbirds habitat suitability modelling methodology has particularly significant potential for replication with other species and habitats, with SDMs an increasingly recognised tool for predicting species distributions under various future scenarios. However, there are limitations to the transferability of the results due to the local scale of our analysis. The wetland species modelling only included waterbirds, and potential losses and gains cannot be inferred for other functional groups. Moreover, the model was geographically restricted to the Ebro Delta, and biodiversity data limitations (such as data unavailability or fragmentation) could potentially affect the replicability of this methodology in other study areas and for other species groups. In order to apply these methodological approaches to other species and areas, it is necessary to address wider issues related to a lack of availability, standardisation, and fragmentation of biodiversity data in different habitat types and regions.

2.9.4 Conclusion

Our results demonstrate potential changes in species distributions in Catalonian coastal dunes and wetlands, and in the case of wetland waterbird species, we were able to identify the key factors influencing them in the face of climate change. This enables the appropriate prioritisation of conservation interventions and implementation of efficient adaptation strategies at a local and regional scale. Through the workshop in the Ebro Delta, as well as the publication of various communication materials, the results were shared with local and regional authorities (e.g., Natural Park, Generalitat de Catalunya) for their consideration and integration in relevant planning.

The pilot application of the loss and gains framework to species present in the Ebro Delta demonstrates that climate change is causing shifts in species ranges within specific ecosystems, resulting not only in species losses but also gains. We found endemic and threatened species to be most vulnerable to reductions in populations and/or distributions as a result of climate change. This potential decline in endemicity underscores a significant erosion of the region's unique biodiversity, and emphasises the importance of species distribution modelling and conservation planning to identify appropriate conservation measures and maximise the resilience of these species and their remaining habitats.

Numerous waterbird species in the Ebro Delta are likely to experience long-term habitat decline under both emissions scenarios (RCP 4.5 and 8.5) as a result of sea level rise. This emphasises the need for

strengthened conservation planning along with the implementation of nature-based and -inspired solutions, particularly in partnership with the agricultural community, to promote the resilience of coastal wetland habitats in the region. The wetland species portion of this task highlighted the value of SDMs as a predictive tool for assessing potential species distribution changes under climate scenarios. This methodology could be replicated for other species and habitats, in order to identify conservation priorities and maximise ecosystem resilience to climate change. Moreover, the difference between climate scenarios in terms of their impact on waterbird habitat availability in the long-term highlights the importance of climate change mitigation measures in addition to localised conservation actions.

The dune species analysis suggested the importance of dune habitat size in determining plant species distributions, highlighting the need to conduct further analysis and consider this as a key factor within the development of coastal adaptation solutions in Catalonia, in order to facilitate the natural dynamics of the dune system and maximise the resilience of dune floral biodiversity.

2.10 Solution 10: Solution Heat Awareness System (Task 4.10.1)

The Netherlands is increasingly experiencing high temperatures and prolonged heat waves, posing a growing public health challenge. Vulnerable groups, including the elderly, children, and individuals with pre-existing health conditions, are disproportionately affected. This is particularly relevant for the Province of Zeeland and Rijnmond region, where many heat-sensitive cities exist, such as Zierikzee. These areas face heightened risks due to ineffective urban planning, dense environments, and limited vegetation. Additionally, almost 26% of Zeeland's population is over 65 years old, a group at risk to adverse health effects, underlining the urgency for heat stress management tailored to local conditions.

The Netherlands has invested heavily in climate adaptation risks, such as flood adaptation, notably through the Delta Works and Delta Programme (Government of the Netherlands, 2024), which allocates €1.25 billion annually for nationwide flood safety measures. However, despite the growing impact of heat stress, legislation and policy in the Netherlands lack measures. No tools currently exist to accurately assess heat stress effects or evaluate adaptation strategies, highlighting the need for clear information to support decision-making.

This gap stems from technical challenges in quantifying heat stress, which depends on multiple interacting factors such as temperature, humidity, land use, and shading. All factors interact with each other in complex ways and must be measured or modelled with high resolution to fit policies on a local scale. Quantifying heat stress at the scale of cities or regions requires processing vast amounts of data from various sources such as satellite imagery, weather stations, and urban infrastructure databases. This remains a barrier for many authorities and limits the ability to dynamically assess the effectiveness of adaptation measures over time.

Research from Wageningen University (WUR) by Koopmans et al. (2020), now forms the basis for heat stress assessments in the Netherlands. This research uses empirical methods to calculate heat stress through the 'Physiological Equivalent Temperature (PET). This indicator, validated for the Netherlands, combines weather and environmental variables such as air temperature, humidity, and windspeed, to estimate the 'experienced' temperature on the human body. This offers a more realistic measure to heat stress than air temperature alone, better supporting heat adaptation planning and public health assessments. However, current assessments rely on static maps based on theoretical extreme days. While often used, they depend on various assumptions, limiting their ability to reflect real-time dynamics, localized variations, or future trends in heat stress. The proposed solution developed in IMPETUS helps to fill these gaps and assess local heat stress risks, identify "hot spots", and evaluate relevant climate adaptation measures.

Task objectives

- Develop a methodological framework able to identify indicators based on climate goals on increased air temperatures and heat stress for spatial planning in urban regions.
- Identify the pertinent indicators for heat stress in the demo-site, to effectively support policymakers in spatial planning and help achieve climate-resilient goals

- Develop an operational Decision Support System (DSS) which facilitates the interactive and on-the-fly computation and quantification of the heat stress for a given region using a Digital Twin 2D model supporting the identification of vulnerable locations.
- Incorporate digital templates, which can be used to visualize and quantify the effects of adaptation measures and climate scenarios, serving as guiding tools for stakeholders in adaptation pathways and discussions.
- Develop and establish the DSS as an Application Programming Interface (API) compatible tool allowing connectivity to other software packages to enhance societal, academic, and practical reach.

2.10.1 Results

2.10.1.1   Task outcomes

A comprehensive framework developed to identify key stakeholders on heat stress and define relevant climate indicators to support their climate ambitions.
The conceptual framework includes a standardized approach to identify relevant actors in climate risk issues. It focuses on aligning the ambitions of stakeholders, the Municipality of Schouwen-Duiveland or the Province of Zeeland in the case of heat stress, with the technical requirements of the task. By gathering input through individual and group assessments, a mapping of requirements is created. The framework guides the selection of practical indicators tailored to local contexts. In our task, we selected the PET heat indicator. The framework is broadly applicable and adaptable to other climate risks.

High-resolution heat stress maps constructed for the entire demo-site and the Netherlands.
High-resolution heat stress maps are developed for the entire demo-site (Province of Zeeland and the Rijnmond region) on a 1-meter resolution and expanded to cover all of the Netherlands (Figure 84 in Annex 6.7). These maps are based on the empirical PET indicator method developed by Wageningen University (Koopmans et al., 2020). The computation integrates data from various sources, capturing climatological, meteorological, and environmental factors. Derived products, such as the sky-view factor, are included in the analysis. The maps are constructed to fit a once-in-1,000-years extreme heat day. The maps are openly available and published via the Climate Effect Atlas (2025), commissioned by the Ministry of Infrastructure and Water Management. These maps now serve as the official Dutch heat stress assessments and the basis for policy development.

An integrated DSS developed for heat awareness, combining multiple new and existing technologies to identify vulnerable heat stress hotspots and support real-time assessments.

A DSS was developed (Figure 38) delivering accurate, interactive heat assessment for the demo-region by integrating stakeholder input (see section 2.10.1.2) with technical developments. The DSS supports dynamic identification of local heat stress hotspots. Static heat maps are transformed into dynamic, real-time tools by storing all climate data in the cloud-based data warehousing platform Lizard. This enables efficient management and easy access to large geospatial and temporal datasets, forming the foundation for the DSS.
The newly developed web-based spatial-temporal raster toolbox, Geoblocks, forms the technical backbone of the DSS. It supports cloud-based raster adjustments and on-the-fly computations, allowing dynamic updates while preserving original data integrity. Geoblocks enables rapid recalculation of heat stress indicators from multiple data sources within Lizard. By leveraging Geoblocks, scenario analyses and adaptation evaluations become faster and more efficient, providing immediate, reliable insights for climate adaptation planning without altering the underlying datasets.

Figure 38 Visual representation of the Decision Support System for heat awareness. The figure shows the quantified local heat stress per pixel on a 1 m resolution [PET; in degrees Celsius] within a 2D Digital Twin environment. The figure shows the city of Zierikzee in the Province of Zeeland. On the left side, different adaptation measures are presented, which can be implemented and exported.

The developed DSS supports interactive and rapid, cloud-based recalculation of heat stress maps through an accessible 2D Digital Twin environment.
The developed DSS enables rapid, cloud-based recalculation of heat stress maps. Leveraging the Lizard data-platform and the newly developed GeoBlocks technology, the system supports real-time, scenario-based visualizations. An overview of the interaction between all methods and techniques and their contribution to the DSS is presented in Figure 39.

Results were presented through a fully interactive 2D Digital Twin of the Province of Zeeland and Rijnmond region. A digital twin acts as a digital replica of the physical environment, capturing geographic, infrastructural, and environmental details in a two-dimensional format. Using a 2D Digital Twin supports an intuitive presentation of the data, enhancing understanding and decision-making. The results are fully interactive for users to allow full transparency.
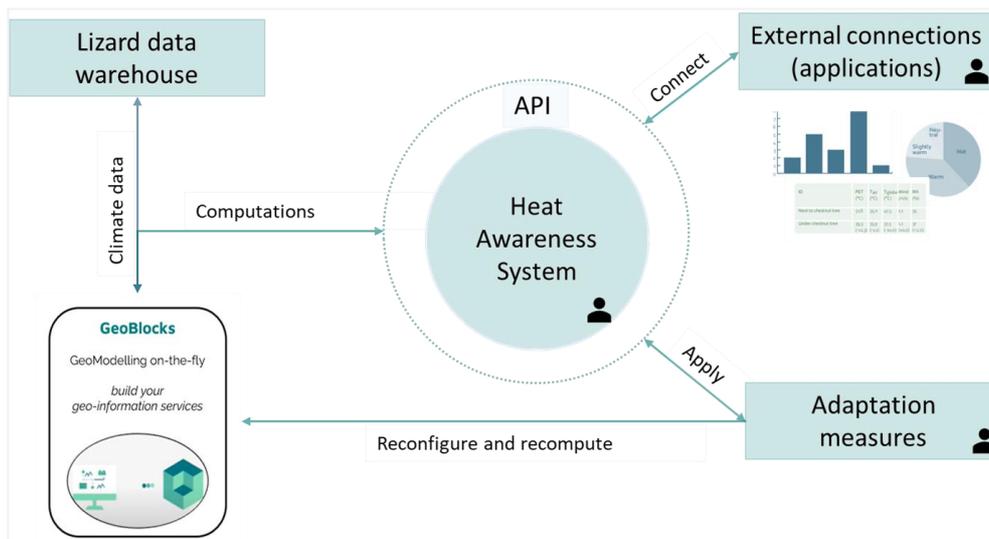
Figure 39. Overview of the workflow, methods and techniques used, combined and developed, and integrated into the heat awareness decision support system. External applications can connect and interact with the tool to provide additional analysis or further process the results. The icon (person) indicates where end-users can interact with the tool and highlights their active role in exploring heat stress information.

The developed DSS integrates community-defined adaptation measures, including standard measures and custom urban building plans.
The solution allows users to flexibly schematize adaptation measures against heat stress. The effect of vegetation can be assessed in three sizes (small, medium, and large). Five types of land surfaces (water, grass, vegetated, semi-paved, and concrete) can be simulated. Users can add their own buildings, ranging from 1 to 50 m in height, to model urban heat effects. Finally, custom spatial urban plans can be created by combining these elements, enabling tailored adaptation strategies for specific areas. Users can create, save, and share their spatial plans from different platforms and quantify the impacts of their spatial plans on the local heat stress. The DSS supports users in uploading their own official urban building plans through universal open data standards and in performing computations.

The developed DSS supports full API connectivity and exportability.
The solution supports full API (through REST API) compatibility, facilitating integration with other software platforms and enhancing flexibility and future development. It includes features for exporting scenario comparisons, enabling the evaluation of different adaptation measures. Additionally, the tool generates automated, report-ready statistical outputs. This provides intuitive insights and actionable results for both experts and non-experts. By allowing external connections, users can leverage the results for more advanced analysis.

2.10.1.2 Partnerships and collaboration

The task results were developed in close collaboration with key stakeholders, including municipalities as Schouwen-Duiveland, academic institutions (HZ University of Applied Sciences), and regional authorities (Province of Zeeland). This collaboration is central to the tasks' success and aligns with the objectives of Work Package 1 on stakeholder engagement. A key milestone has been the organization of multiple interactive co-design workshops between 2022 and 2024. In both individual and group settings, stakeholders contributed directly to defining indicators, prioritizing adaptation measures, and aligning the tool with policy needs. Early sessions emphasized the need for a robust heat stress indicator, confirming the choice of PET in the DSS. Detailed information on the co-creation process can be found in WP1 Deliverable D1.5.

A notable example is the second co-creation workshop held in October 2022 in Schouwen-Duiveland, involving the local municipality, the Province of Zeeland, and academics from the HZ University. During this session, the minimal functional requirements for the DSS are agreed upon, laying the foundation for the technical development phase. In recurring sessions, the progress is presented, new features are shown, and potential opportunities are discussed. By involving local authorities, experts, and end-users, this contributed to a solution that addresses real-world challenges.

The workshops provided clear feedback on shaping the tool's design. It aligns the responsiveness of the DSS and the required expertise level to the user's needs, a key element for its uptake and exploitability in the future. The input of participants feeds into an iterative co-creation and development process, improving the tool at each stage. Collaboration with UX/UI designers further strengthened the result: a tool that is technically robust and accessible to non-expert users, enabling broader adoption and transparent communication of climate risks.

A series of events was organized between 2024 and 2025 to demonstrate the tool's capabilities and gather feedback from additional end-users within and beyond the demo-site stakeholders. The sessions explored potential pilot cases and the application of the tool to address real-world heat risk challenges. One example is the showcase on January 16, 2025, in Utrecht, where experts from various municipal representatives discussed the tool's usability. Currently, multiple municipalities within and outside of the demo-site (such as the municipality of Leiden) are working with the DSS to address heat stress in their cities, and various adaptors have shown interest in using our solution in their future climate adaptation plans.

Additionally, the solution was showcased in multiple webinars, as 'Heatwave risk assessment tools - are they needed (European Commission & Covenant of Mayors, 2024), organized by the EU Missions for Climate Adaptation Platform (MIP4ADAPT) and the IMPETUS Climate Solutions Forum (SDSN Europe, 2024), to further spread awareness and increase the tools' outreach. or more information and details on the co-creation process, have a look at WP1 Deliverable.

2.10.2 Impact

2.10.2.1 Implications and potential impacts

The task results are characterized by their ability to translate technical climate data into accessible information. This supports stakeholders by facilitating dialogue with non-experts, offering clear, easy-to-understand insights into heat stress risks in real-life environments. With a broad network of quintuple helix stakeholders in the study, including municipalities, academic institutions, policymakers, and experts, it can help bridge the information gap between experts and non-experts. Hereby, the DSS has the potential to enable the resilience of communities across Europe to heat stress risks. A detailed analysis of the impact is included in the Theory of Change (ToC), can be found in WP1 Deliverable D1.5.

Within Work Package 4, Bundle 2 (Innovative Solutions), the integration of software development with expert knowledge leads to tools that effectively support climate adaptation. The tool is successfully tested in the demonstration region, allowing for local validation and improvements in its functionality. The framework ensures that the solutions align closely with stakeholders' climate goals, providing practical data for decision-making. Its adaptability extends beyond heat stress, offering potential applications for various climate risks, making an impact in both the short and long term.

The operational DSS provides policymakers with accurate heat risk information. Over time, this can support data-driven climate policies and can be rapidly deployed on a national scale, forming the foundation for wider climate adaptation strategies. The DSS also supports municipalities to better account for the needs of vulnerable populations. While these groups may not use the tool directly, they benefit indirectly through more inclusive planning. By highlighting high-risk, underserved areas, the system enables timely and targeted measures to protect those most affected by extreme heat.

2.10.2.2 Transferability, scalability, and adaptability

The DSS provided municipalities and decision-makers with an intuitive tool to dynamically evaluate climate resilience planning. The results are fully operational and universally transferable. The tool, its underlying software and technology are scalable, providing a flexible framework for heat analysis across Europe. The DSS is used by multiple cities in the Netherlands for testing new urban developments on heat stress risks, and is adaptable to other regions, indicators, and climate risks. It can be scaled to support risk analysis, incorporate local data, and assess scenarios to inform context-specific solutions. Long-term scalability and adaptability of the DSS will be achieved through ongoing testing in projects, result evaluation, and application in real-world use cases. By new insights, new functionalities will most likely be discovered to continue improving the DSS. Future efforts will support stakeholders through project-based or licensed applications, enabling continuous development and practical use.

Stakeholder engagement is a key factor in the tool's effectiveness. Active collaboration with municipalities and decision-makers strengthens the impact of adaptation strategies. Without their involvement, the practical application and effectiveness of the tool are significantly reduced. Engaging stakeholders early in the adaptation process is essential to address local needs and ensure successful implementation.

Additionally, the empirical foundation of the heat stress indicator is based on specific contextual conditions requiring adaptation for different urban environments, climate conditions, and data availability. Ensuring its applicability across diverse settings requires refinements in the empirical methodology and should be validated against local conditions.

2.10.3 Lessons Learned

2.10.3.1 Key takeaways

- High-quality data is the foundation for effective climate risk assessment tools. Ensuring that data accuracy and availability match the analysis is critical for successful implementation.
- Local knowledge from local stakeholders, partners, or experts is essential to ensure the solutions match specific needs and local goals for climate adaptation.

- Fine-tune technical developments by focusing on early engagement with both stakeholders and climate experts through iterative workshops to see the tool developments progress and improve the user experience of the final tool. Iterative development allows for frequent refinement, allowing clear feedback between developers and end-users. This enables developers to gain insights from real-world situations, while end-users observe their feedback being integrated into the tool.

- Promote training and capacity building to ensure stakeholders are up-to-date with the necessary knowledge and skills to effectively use the tool and apply it in practical scenarios.

2.10.3.2 Challenges

At the start of the project, no policy on heat stress existed in the Netherlands. Mostly, this is attributed to the novelty of the topic and a limited understanding of the impacts. This resulted in ambiguous and inconsistent climate goals, without clear limits or thresholds on quantified heat stress, making it hard to develop a supporting tool. To address this, we facilitate extensive collaboration among stakeholders, involving experts, scientific institutions, and engineers to develop a shared understanding of climate risks, establish clear climate objectives, and determine effective adaptation measures.

A further challenge is that different stakeholders may have varying needs and priorities, requiring a structured approach to align perspectives. Through working groups, stakeholder inputs are summarized, findings extrapolated, and common ground identified to develop unified strategies. Whilst this was successful, prolonged technical development phases, alternating with periods requiring significant stakeholder input without immediate results, led to stakeholder fatigue and decreased engagement. To mitigate this, we transitioned to less frequent but more targeted working groups, ensuring sustained involvement by clearly communicating the long-term benefits of participation.

The tool relies on high-resolution geospatial, climate, and environmental data, which benefits the demo-site. Yet limited data availability in other regions may limit broader application. The approach remains adaptable if aligned with available data quality, and collaboration with local institutions can help fill gaps and maintain accuracy. Similarly, not all adaptation measures are easily quantified, especially policy interventions or awareness campaigns. Measures tailored to the demo-site may require adjustments for use in regions with different priorities or conditions.

Finally, the tool's success depends on its acceptance and integration within the cultural and social context of each region. Differences in heat awareness, risk perception, and decision-making processes may influence how effectively stakeholders understand and act upon the tool's outcomes. Ensuring local relevance and engagement is essential for maximizing impact.

2.10.4 Conclusion

The task results established a strong framework to align heat stress solutions with the climate goals of key stakeholders. By technical innovations, high-resolution heat stress maps are developed (1x1 m), leveraging different climate data sources to provide precise, localized assessments of heat stress hotspots.

The developed solution (DSS) integrates a real-time heat stress analysis within a 2D Digital Twin model, allowing dynamic evaluation of adaptation measures such as land use, vegetation, and building modifications. Its cloud-based platform and API compatibility ensure scalability and easy integration with other systems, facilitating data-driven decision-making for policymakers and stakeholders. Hereby showing that technological innovations can play a key role in climate adaptation. An important factor herein is providing accessible and easy-to-understand information and visualization of climate risk.

By connecting municipalities, academics, and citizens, the developed solution promotes practical collaboration in identifying heat stress risks and assessing adaptation strategies, ultimately strengthening community-driven climate action. The software's flexibility allows it to be adapted for use in various regions, offering a scalable solution for heat stress assessment.

2.11 Solution 11: Solution Decision Support System for Flood Risk Management (Task 4.10.2)

The Netherlands faces increasing challenges in protecting its population from flooding due to heavier rainfall and rising sea levels. Flood risks are increasing across pluvial, fluvial, and coastal sources, particularly in the low-lying delta regions in the western parts of the country (Government of the Netherlands, 2024). The Atlantic demo-site, covering the Province of Zeeland and the Rijnmond region, is located in a major coastal delta, with a substantial portion of its land below sea level. Situated at the end of multiple large river tributaries such as the Scheldt, Rhine, and Meuse, and adjacent to the North Sea, the region is particularly vulnerable to flooding from coastal, pluvial, and fluvial sources. With major cities and Europe's largest harbour, it is critical to the Dutch economy.

Traditionally, flood management relies primarily on hard grey infrastructure such as dikes and barriers. Flood management in the demo-site, however, is shifting from these large-scale infrastructures, such as the Delta Works (Rijkswaterstaat, 2025), to a more integrated approach. This transition requires accurate information on current and future flood risks, along with methods to assess the effectiveness of adaptation measures. These insights are essential to support informed planning and implement effective strategies.

A major barrier to effective decision-making is the lack of tools for rapid, interactive local flood risk assessments on a local to regional scale. Current information is often derived and presented as complex data or static 2D maps, making it difficult for non-experts and policymakers to interpret the risks accurately and make informed choices on it. The absence of accessible, real-time tools that offer clear and actionable insights limits the ability to respond to evolving conditions and address the multifaceted nature of flood risks.

Additionally, current methods lack the ability to dynamically assess adaptation measures over time. Efficient handling of large datasets is needed to evaluate long-term impacts and support strategic planning. The DSS addresses these gaps by enabling interactive, scenario-based planning and presenting complex data in a clear and accessible format.

Task objectives

- Develop a methodological framework that identifies key flood information and relevant indicators based on current and future climate goals on fluvial and coastal flood risks relevant to spatial planning.
- Develop an interactive Decision Support System (DSS) for flood risk management in urban environments by coupling 3Di hydrodynamic software to a 3D Digital Twin model.
- Translate geospatial hydrodynamic simulation results into rapid, easy-to-understand, accessible and transparent 3D flood risk information presented in the Digital Twin environment by developing new visualization techniques allowing experts and non-experts to use the tool.
- Match the technical details of hydrodynamic simulations to the practical needs of stakeholders in spatial planning and crisis management by integrating post-processing and increasing dynamic insights in flood information over time by allowing interactive usage of the tool.
- Develop and establish the DSS as an Application Programming Interface (API) compatible tool allowing connectivity to other software packages to enhance societal, academic, and practical reach.

2.11.1 Results

2.11.1.1 Task outcomes

A comprehensive framework developed to identify key stakeholders on flood risks and define relevant climate indicators to support their climate ambitions.
The conceptual framework includes a standardized approach to identify relevant actors in climate risk issues It focusses on aligning the ambition of stakeholders, the Municipality of Rotterdam, water authorities, and the Province of Zuid-Holland, with the technical requirements of the task. By gathering input through individual and group assessments, a mapping of requirements is created. The framework

guides the selection of practical indicators tailored to local contexts. In our task, the framework guided the selection of practical flood risk indicators, as maximum water depth, which are further processed into flood arrival times and flow dynamics to provide actionable information for flood management. The framework is broadly applicable and adaptable to other climate risks.

High-resolution flood simulations performed for the demo-site
The task builds on the academically developed 3Di hydrodynamic software package (3Di Water Management, 2025), which enables fast, cloud-based scenario computations with active 1D–2D hydrodynamic interactions. This allows for integrated simulation of both surface water and 1D flow elements such as sewer systems. A key feature of 3Di is its sub-grid modelling, which delivers high-resolution, accurate results without requiring extremely fine grids. This ensures detailed flood dynamics can be explored with high computational efficiency. Using the 3Di software, high-resolution flood risk maps are developed at a 0.5-meter resolution for the demo-site. This approach relies on the cloud-based Lizard platform (Lizard, 2025) for model development and data processing.

An integrated DSS developed for flood risk management, combining multiple new and existing technologies to identify local flood risks and support real-time assessments.
An integrated DSS is developed, supporting flood risk management by quantifying current and future flood risks. In the development, multiple techniques are developed and combined. An overview of the interaction between all methods and their contribution to the DSS is presented in Figure 40.

The DSS builds on the foundation of the hydrodynamic software 3Di. In addition, a new innovative software package, OGC 3D-Tiles, has been developed. The software is capable of translating flood information and its dynamics into three dimensions. Unlike traditional flood risk simulations that derive and present data as 2D layers, this software enables all simulations to be visualized in 3D environments. For each computational cell, both flow dynamics and local water depth can be derived at high resolution (0.5 x 0.5 m). In doing so, it provides deeper insights by offering detailed 3D visualizations of water depths at any location after a flood event. The software conforms to all open data sharing standards such as the Open Geospatial Consortium (OGC) (2025), and is therefore universally readable.
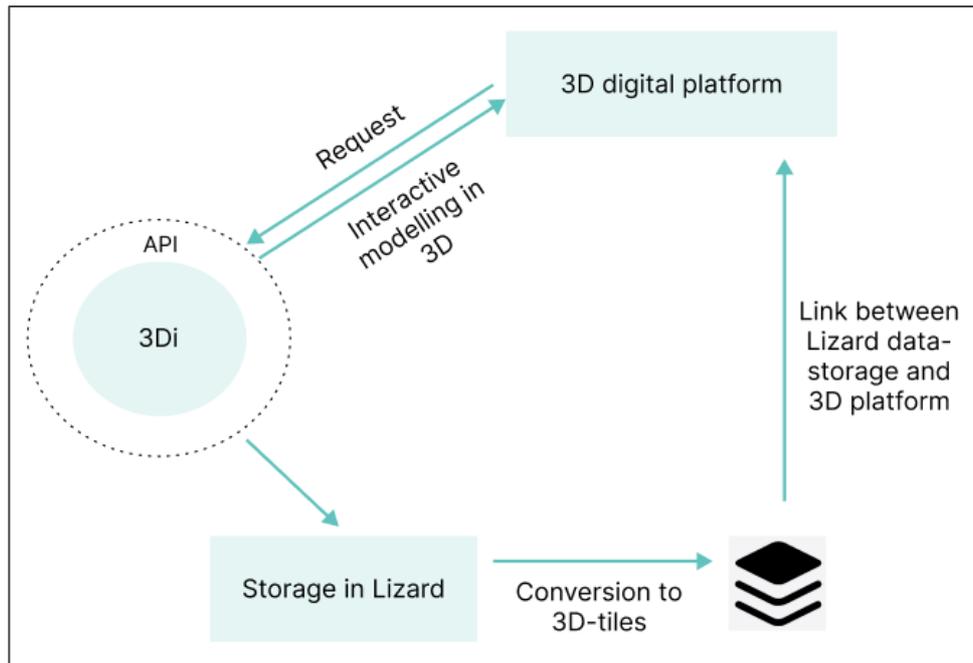
Figure 40 Overview of the workflow, methods, and technologies integrated into the Decision Support System (DSS) for flood risk management. The diagram illustrates how 3Di hydrodynamic modelling is connected with a 3D digital platform, enabling the conversion of simulation results into interactive 3D visualisations using OGC 3D Tiles.

A stable connection made between hydrodynamic models and a 3D Digital Twin environment.
A stable coupling is made between the 3Di hydrodynamic models and a 3D Digital Twin (Figure 41) through developed REST API functionalities. By this connection, the DSS enables realistic and interactive flood visualizations understandable for a wide range of stakeholders. The 3D Digital Twin acts as a 3D dynamic replica of the demo-site, integrating buildings, roads, and trees, and now also incorporates time-varying flood data. Integration with other software and digital twin platforms is also possible to ensure scalability for future applications.
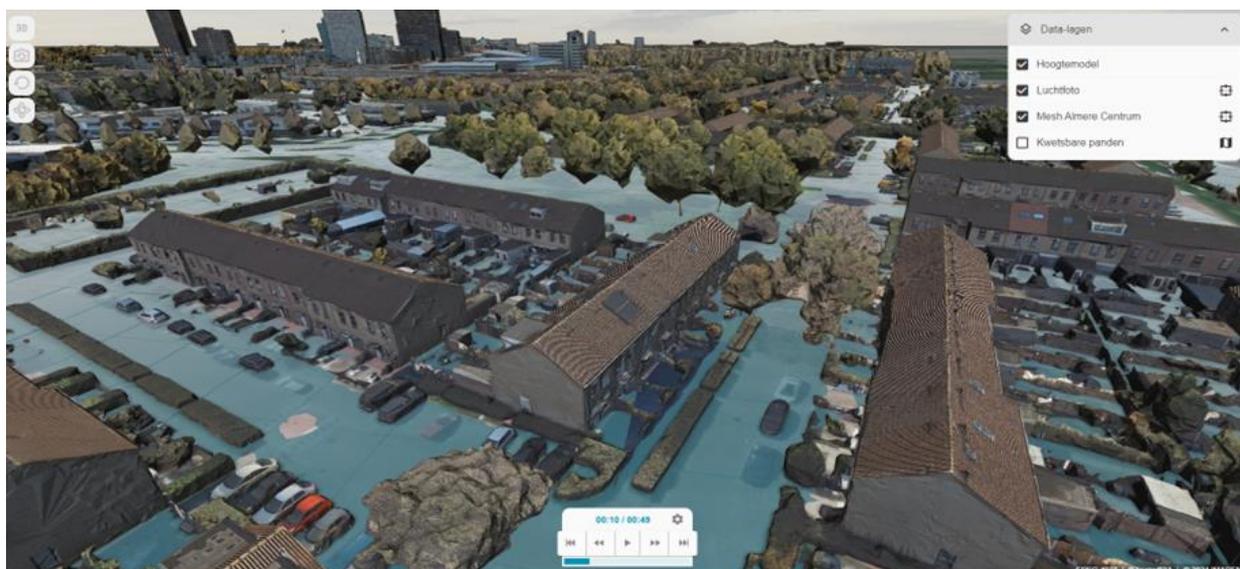
Figure 41 Visual representation of the Decision Support System for flood risk management. The image shows the visualisation of a flood event indicating the simulated water depth per pixel on a 0.5 by 0.5-m resolution within a 3D Digital Twin environment of an urban environment in the Netherlands (Municipality of Almere).

The developed DSS integrates community-defined adaptation measures, including different adaptation measures.
The DSS quantifies and visualizes the effectiveness of adaptation measures such as mobile flood barriers, pumps, and elevated areas, making flood risk data tangible and actionable. It enables rapid, cloud-based scenario analysis and recalculation for flexible evaluation of options. Through the interactive features of the 3Di software, users can schematize measures or spatial plans in the DSS and dynamically recompute flood risks. This enhances scenario analysis and supports informed decision-making.

The developed DSS supports full API connectivity and exportability.
The solution supports full API (through REST API) compatibility, facilitating integration with other software platforms and enhancing flexibility and future development. It enables dynamic scenario analysis, supports external connections to other platforms or software for advanced use, and presents results in an accessible format for both experts and non-experts.

2.11.1.2 Partnerships and collaboration

The task results were developed in close collaboration with the identified key stakeholders, including the municipality of Rotterdam and Dordrecht, water authorities, universities and flood risks experts. This collaboration is central to the success of the task and aligns with the objectives of Work Package 1 on stakeholder engagement. A key milestone is the organization of multiple productive co-design workshops and interactive sessions between 2022 and 2024. In both individual and group settings, stakeholders contributed directly to defining indicators, prioritizing adaptation measures, and aligning the tool with policy needs. Earlier sessions underscored the importance of translating complex flood information into clear information to support the stakeholders in their decision-making process. Detailed information on the co-creation process can be found in WP1 Deliverable D1.5.

A notable example is the second co-creation workshop held in October 2022 in Rotterdam, involving the municipalities of Rotterdam and Schouwen-Duiveland, flood risk experts, and the Province of Zuid-Holland (Annex 6.8). During this session, the minimal functional requirements for the DSS are agreed upon, laying the foundation for the technical development phase. In recurring sessions, the progress is presented, new features are shown, and potential opportunities are discussed. By involving local authorities, experts, and end-users, this contributed to a solution that addresses real-world challenges.

The workshops provide clear feedback on shaping the tool's design. It aligns the responsiveness of the DSS and the required expertise level to the user's needs. The input of participants feeds into an iterative development process, improving the tool at each stage. Collaboration with UX/UI designers further strengthens the result: a tool that is technically robust and accessible to non-expert users, enabling broader adoption and transparent communication of climate risks.

A series of events were organized between 2024 and 2025 to demonstrate the tool's capabilities and gather feedback from end-users within the demo-site and beyond. The sessions explored potential pilot cases and the application of the tool to address real-world flood risk challenges. One example is the showcase on January 15, 2025, in Rotterdam, where experts, digital twin providers, and municipal representatives discussed the tool's usability and signed a covenant to further explore digital twins for climate risk management. The sessions hosted attendants involved from the start of the project, as well as other relevant municipalities outside the demo-region, flood risk experts, and technology providers.

Additionally, the solution was showcased in multiple webinars, as 'Flood Resilience: Strategies and Solutions for a Safer Future (Futurium, 2025), organized by the EU Missions for Climate Adaptation Platform (MIP4ADAPT), and featured as a mission story (Climate-ADAPT, 2025) on the same platform. In the final phase of the project, collaboration with the Dutch National Flood Museum is made to organise an exhibition in the museum's knowledge centre, aiming to increase awareness and reach out to local communities.

2.11.2 Impact

2.11.2.1 Implications and impacts

The task results are characterized by their ability to translate technical climate data into accessible information. This supports stakeholders by facilitating dialogue with non-experts, offering clear, easy-to-understand insights into local flood risks in real-life environments. With a broad network of quintuple helix stakeholders in the study, including municipalities, experts, and policymakers, it can help bridge the information gap between experts and non-experts. Hereby, the DSS has the potential to enable the resilience of communities across Europe to flood risks. A detailed analysis of the impact is included in the Theory of Change (ToC), can be found in WP1 Deliverable D1.5.

Within Work Package 4, Bundle 2 (Innovative Solutions), the integration of software development with expert knowledge leads to tools that effectively support climate adaptation. The tool is successfully tested in the demonstration region, allowing for local validation and improvements in its functionality. The framework ensures that the solutions align closely with stakeholders' climate goals, providing practical data for decision-making. The adaptability of the DSS extends beyond flood risk management, offering potential to visualize various climate risks.

The operational DSS allows policymakers to visualize accurate, location specific flood risk information enabling data-driven urban planning and setting up effective adaptation strategies. Over time, it can support the development of long-term, climate-resilient flood management policies. By presenting complex flood data in an accessible way, the tool bridges the gap between experts and non-experts, fostering inclusive decision-making. While vulnerable communities may not use the system directly, they benefit from the identification of high-risk areas, enabling climate actions to be more targeted, inclusive, and equitable.

2.11.2.2 Transferability, scalability, and adaptability

The DSS provides municipalities and decision-makers with an intuitive and flexible tool for dynamic flood risk management. The software components, including OGC 3D tiles, hydrodynamic models, and other techniques, are globally scalable and provide a flexible framework to adapt to various practical use cases. Key components like 3Di are already widely used in global water management. The DSS is applicable in local to regional contexts, such as flood management, spatial planning, or stakeholder engagement, helping policymakers and urban planners assess current and future flood risks and apply targeted solutions.

For the system to be completely transferable internationally, data availability is essential. The system supports integration through an API that follows international open geospatial standards (OGC), allowing hydrodynamic results to connect with other applications. However, this requires local systems to also comply with these open data sharing standards. Similarly, a lack of data, for example, high-resolution elevation models or details on the built environment, can limit the accuracy and usability of the DSS. In regions with data availability, the tool may require additional information or the reliance on assumptions. Partnering with local research institutions can help bridge these gaps.

Just as important is early and active involvement from local stakeholders, as municipalities, NGOs, and decision-makers. Their input ensures the tool addresses real needs and improves its usability in practical planning and decision-making. Without their engagement, the impact of the system is likely to be limited.

Long-term scalability and adaptability of the DSS will be achieved through ongoing testing, result evaluation, and application in real-world use cases. As part of the N&S software, it will be continuously developed beyond the project. Future efforts will support stakeholders through project-based or licensed applications, enabling continuous development and practical use.

2.11.3 Lessons Learned

2.11.3.1 Key takeaways

- High-quality data is the foundation for effective climate risk assessment tools. Ensuring data accuracy and availability is critical for successful implementation.

- Local knowledge from local stakeholders, partners, or experts is essential to ensure solutions match specific needs for climate adaptation, making them more practical and impactful.

- Fine-tune technical developments by focusing on early engagement with both stakeholders and climate experts through iterative workshops to see the tool developments progress and improve the user experience of the final tool. Iterative development allows for frequent refinement, allowing clear feedback between developers and end-users. This enables developers to gain insights from real-world situations, while end-users observe their feedback being integrated into the tool.

- Promote training and capacity building to ensure stakeholders are up-to-date with the necessary knowledge and skills to effectively use the tool and apply it in practical scenarios.

2.11.3.2 Challenges

Developing the DSS presents several technical challenges, particularly integrating high-intensity software components into a cohesive system. Ensuring effective data exchange and computational efficiency required continuous optimization. An iterative development approach, supported by expert validation and improved processing workflows, enhanced system performance and usability.

Different stakeholders have varying needs and priorities, requiring a structured approach to align perspectives. Through working groups, inputs were summarized, findings extrapolated, and common ground identified. While effective, long technical development phases, alternating with periods requiring significant stakeholder input without immediate results, caused stakeholder fatigue. To address this, we shifted to more targeted sessions, clearly communicating long-term benefits.

The tool's reliance on high-resolution geospatial data benefits the demo-site, where this data is freely available, but limits broader application where data is less available. Specific adjustments are needed to align the DSS with local data quality and to match different contexts. Likewise, not all adaptation measures, particularly policy interventions or awareness campaigns, are easily quantified or directly relevant in other situations. Measures implemented for the demo-site are tailored to local conditions and may not be directly transferable to other regions, requiring local tailoring.

Finally, the DSS is contingent on local technological infrastructure, particularly the availability of a host 3D Digital Twin. While hydrodynamic simulations are globally scalable and can still be run interactively without this environment, the lack of visualization limits the tool's impact. This reduces stakeholder engagement and weakens its effectiveness in encouraging broad participation and action.

2.11.4 Conclusion

The task results established a strong framework to identify key stakeholders and define relevant indicators for flood management. By aligning the development process of the innovative solution to the climate goals of stakeholders, the results are ensured to be relevant and make a practical impact.

The developed solution (DSS) integrates detailed hydrodynamic flood simulations within a 3D Digital Twin, enabling rapid and adaptive real-time analysis of current and future flood risks as well as the effectiveness of adaptation measures such as flood barriers, pumps, or elevated zones. Its cloud-based platform and API compatibility ensure scalability and integration with other systems, supporting data-driven decision-making for policymakers and stakeholders. By presenting complex flood risk information in a clear and intuitive way, the tool bridges the gap between experts and non-experts. This highlights the critical role of technological innovation in climate adaptation, where accessible and understandable risk visualization is key.

By connecting municipalities, academics, and citizens, the developed solution promotes practical collaboration in identifying flood stress risks and assessing adaptation strategies, ultimately strengthening community-driven climate action. The collaboration and iterative development with stakeholders are key to meeting practical needs, leading to a more widely accepted solution.

2.12 Solution 12: Multi-layer integrated flood risk management, Decision Support and Early Warning System for civil protection (Task 4.10.3)

The Zemgale region, situated within Latvia's Central Lowland, is characterized by its exceptionally flat terrain and dense river network, including the Lielupe and Daugava rivers, which makes it particularly vulnerable to recurrent flooding. Seasonal snowmelt, heavy rainfall, and ice-jam events regularly contribute to high water levels, creating significant risks for settlements and agricultural land. The extensive economic losses caused by floods underscore the need for a reliable Early Warning System (henceforth - EWS). Such a system provides the capacity to combine real-time hydrological monitoring with advanced flood modelling and spatial data analysis, thereby supporting timely decision-making, proactive risk management, and the protection of people, infrastructure, and economic activities in the region.

An initial Warning system in Jelgava City, relied primarily on river sensors to measure water levels and a simple notification mechanism to alert residents. While this approach proved valuable at the local level, its functionality was limited in scope and lacked predictive capacity. To extend coverage across the entire Zemgale region, elements of the Jelgava system, such as its notification functions and parts of its code, were reused as a foundation. A new system covering Zemgale region was subsequently developed within IMPETUS project, integrating hydrological modelling with GIS-based flood risk analysis and HEC-RAS simulations. This enhanced system moves beyond reactive monitoring, offering predictive capabilities that enable authorities and residents to anticipate flood events, thus ensuring more effective preparedness and civil protection measures across the broader region.

Therefore, the developed Early warning system for flood risks for Zemgale region in Latvia (Boreal demo site) is designed to perform two functions simultaneously – to predict floods and to notify residents with a property in flood risk area and registered in the system. Notification is also sent to municipality's civil protection specialists and other municipal institutions, which are responsible for dealing with flood consequences. The solution uses the HEC-RAS program, which models floods based on multiple data.

EWS consists of two interconnected parts: flood modelling component – a specialized modelling environment (HEC-RAS) that uses terrain data, river geometry, and hydrological forecasts (e.g. water level, flow rate) to simulate potential flood extents; and warning and visualization platform – a web-based tool that processes the generated flood maps and integrates them with additional data layers.

To predict floods in Zemgale region, a 2D flood model was developed using GIS, real-time data from the Latvian Environment Geology and Meteorology Center, as well as digitised and open-source data, enabling automated daily flood risk updates. Key activities included: identifying potential flood modelling areas in Zemgale region, assessing available regional data, preparing GIS data for flood modelling in HEC-RAS river analysis system, developing 1D geometry for the Lielupe river basin to enhance high accuracy digital terrain model with river bed information, developing 2D flood model geometry for the region, acquiring and calculating necessary hydrological data, preparation of transformation tables for inputs to 2D flood model.

Warning and visualization platform is built using a two-layer architecture style that includes separate frontend (user interface) and backend (data processing and business logic) layers.

This architecture consists of data processing and application servers. The data processing server collects information from two primary sources: data.gov.lv and the HEC-RAS server. This includes cadastre data, address data, and HEC-RAS data, which are loaded, analysed, and then stored in a database management system. Once processed, the data are passed to the graphical data service, which handles data visualization. Users can access the visualized data through a web interface using HTTP/HTTPS protocols. At the application server layer, users interact with the system via a web application.

The average full circle operation of the system from modelling to preparedness to send notification is around 7-8 hours. The calculations and modelling process requires 4-6 hours (depends on data and HEC-RAS performance statistics) and visualization process is another part - the system need to take the flood map from the HEC-RAS and transfer it on the "real" map with cadastre data to analyse - if there are any properties in the affected area. The warning and visualization platform is processing and visualizing the flood model for 1-2 hours on average.

The model developed within IMPETUS project runs on the following HEC-RAS performance statistics:
1. A calculation step of 5 minutes, which provides sufficient time resolution for accurate representation of flood dynamics.
2. Spatial resolution – 4-meter raster, which allows for detailed analysis of the distribution of water flow in the urban environment.
3. Calculation duration – for 9 days, simulating the development and course of floods over a sufficient period to cover possible peaks and areas of impact.

The primary challenge at the start of the project was to configure a river basin model capable of reliably predicting flood risks. As the development progressed, an additional challenge emerged—automating the entire workflow. By the end of the project, this was successfully achieved, enabling seamless integration from the delivery of forecast data into the HEC-RAS program to the processing and loading of flood modelling results into the system, ultimately generating a list of affected areas requiring notification.

In summary, the main task objective is to ensure the possibility to evaluate flooding risks prior to the event and to provide public institutions and citizens with the necessary information to select appropriate measures for effective protection of people, health, environment, and economic activities. The result's impact is relevant for the demo site, because the area of Zemgale region is one of the most threatened areas of the Lielupe river basin in terms of flooding of the territory due to the flat terrain of the basin and the peculiarities of the river's hydrographic network. The regional GIS-based system in Zemgale is enhanced with water level analytics to create a decision support and early warning system for flood risk management and civil protection. The solution enhances regional adaptation capacity by improving flood preparedness and civil protection decision-making in Zemgale region.

2.12.1 Results

Task outcome: improved and expanded flood risk early warning system.

Newly developed Early warning system in case of flood risks provides functionality for the management of civil risks and protection events, identification of risk areas, properties, and addresses, as well as the notification of users previously registered for warning messages in the Zemgale Planning Region, information will also be received by specialists involved in preventing/mitigating consequences.

Outreach
The system covers a territory that, over the past five years, has been home to an average of about 93,000 households, or roughly 225,000 residents. Since the system has only recently been completed, it has not yet been tested during a real flood event; to date, it has only been validated through simulations to assess its functionality and performance.

The previous system was used by Jelgava municipality for the Jelgava city territory, it's area is 60 km² out of 10,7 thousand km² of Zemgale Planning Region's area and 55,000 residents on average over the past five years, that is only 0,6% of territory that is currently covered by new system and around 24,4% of residents.
Thus, the new system expanded its influence both territorially and in terms of the number of residents who fall under the influence of the system. Jelgava city municipality was the only local authority with

access to previous system; however, it is planned that six municipalities would work with that, but during the project it is operated only by Jelgava city municipality.

Enhanced flood prediction model

The system provides effective flood modelling and early warning based on various data sources and technologies. Initially, various geographic data are entered, such as terrain information, river geometry, and Latvian Geospatial Information Agency LiDAR data, which are processed using ArcGIS or manually. In addition, the hydrological forecast data of the Latvian Environment, Geology, and Meteorology Center, including water level and flow, are obtained.

These data are used to build and run the HEC-RAS model, where the RAS Mapper tool helps generate and visualize flood risks. Based on the input data, the HEC-RAS model performs flood simulations that are calibrated both automatically and manually. As a result, maps of flooded areas and water levels are created and automatically displayed in the system.

Two river basin models were targeted the Lielupe River basin (Figure 42) and the Daugava River basin (Figure 43), to cover the Zemgale Planning Region territory.
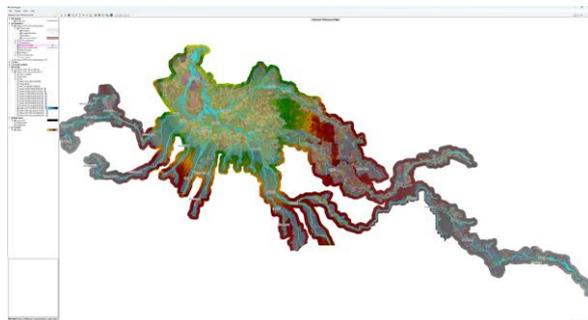
Figure 42 Lielupe River's basin
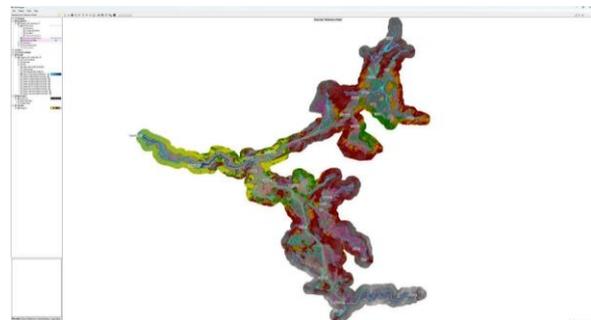
Figure 43 Daugava River's basin

Notification function

There is an exchange of data between the HEC-RAS model and the Early Warning System, which also includes the transfer of cartographic data and water level maps.

Based on collected data and pre-defined conditions, the system provides early warning functionality.

When the HEC-RAS model is integrated into EWS map, if predicted water levels exceed predefined thresholds, this triggers the identification of specific properties, addresses, and areas within the flooded zone, activating alerts in the system so that registered users and relevant institutions are notified in advance about the potential risk.

Example of some triggered properties in Jelgava city by model of HEC-RAS (Figure 44):
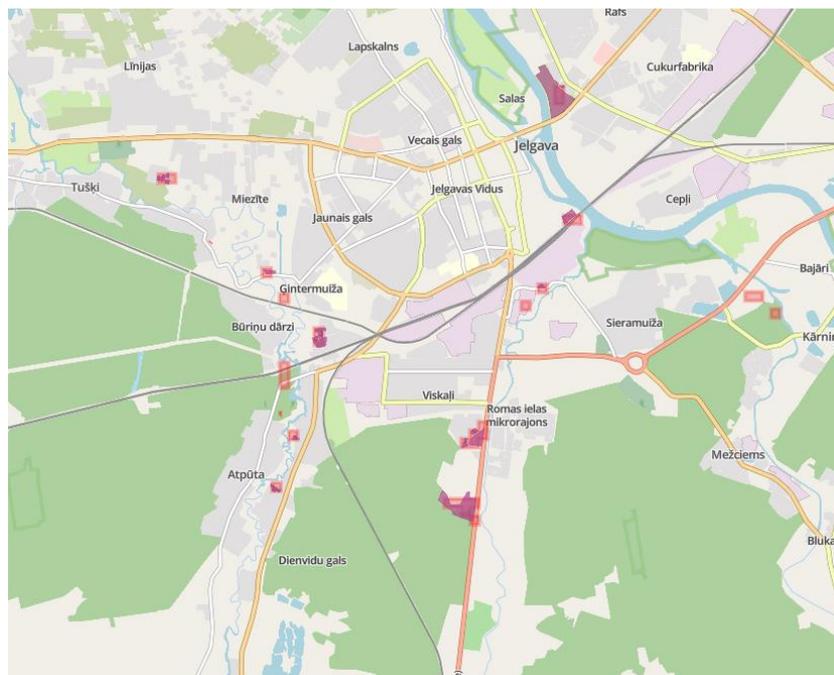
Figure 44 HEC-RAS modelling results on EWS map (red marked properties are potentially to be notified).

Collaboration

The outcome was achieved due to collaboration between project partners Jelgava Digital Center responsible for the development of the system and its functionality and Zemgale Planning Region being the part that is responsible for the HEC-RAS flood prediction model. Cooperation with Latvian Environment Geology and Meteorology Center was established for receiving, publicly available input data for the model. Baltic Environmental Forum had a role of coordination and moderation of discussions with stakeholders.

During the development of the system, experts from Jelgava Digital Center were engaged in the development of the technical specification for EWS. End-users, as civil protection specialists and dispatchers, who had previous experience working with the initial Warning system were actively engaged to ensure the tool's interface met real operational needs. Their input helped to align system functions with day-to-day emergency management practices, while an external audit of processes was also conducted to evaluate existing workflows and suggest more efficient approaches. In addition, these users were given the opportunity to provide feedback on the "how-to" handbook, ensuring that documentation was practical, user-friendly, and directly applicable to their tasks. The outcome of this engagement was a more intuitive and effective interface, tailored to the real work context of civil protection specialists.

Outreach and communication materials are planned to follow the system's full deployment, including public information campaigns.

2.12.2 Impact

In recent years, when experiencing a crisis related to flooding, citizens are increasingly willing to engage in measures related to civil protection that could alert them to dangerous situations.

By upgrading the early warning system, we are providing local authorities and residents with essential information to respond swiftly to climate-related challenges. This system will ensure timely emergency notifications in the Zemgale region, boosting public safety and improving collaboration among all stakeholders.

The solution provides several **benefits** contributing to the IMPETUS substantial impacts at the DS#6:

- By applying HEC-RAS flood model for Zemgale region there are upgraded monitoring data at place in the EWS which are easily accessible to users. Availability of flood risk prognosis by HEC-RAS is helpful for potentially reduced property damage for citizens and municipalities. However, these benefits are currently difficult to quantify due to the lack of metrics for evaluating citizen engagement and avoided damage. In the short term, residents will be better prepared to take preventive measures, reducing property damage, such as the 7-million-euro loss during the recent Jelgava floods in 07/2024. Over time, the system will encourage greater awareness and proactive action against floods and climate change, fostering stronger municipal cooperation for more effective disaster management In addition, impact is the reduction of potential contamination that could be provided in preparation for the predicted flood, for example, a company working with chemicals, or if the flood takes over areas where pollution accumulates or which are already known to be polluted or potentially polluted places.
- By reduced lag-time and enhanced exchange of operative information from the model to users, potentially affected municipalities can have more time for preparation to take emergency actions against flooding risks. Timely taken preventive measures would help to reduce municipal property damage of approximately 5-million-euro loss during the recent Jelgava floods in 07/2024.

The **main challenge** is associated – with the forecast accuracy. Deficiency in predicting, e.g., false alarms or missed events could undermine public trust in the Early Warning System and reduce citizen use of it. The main factors affecting forecast accuracy were identified as limitations in available meteorological data, uncertainties in terrain and riverbed modelling, and the system's current reliance on forecasted rather than observed ground saturation and rainfall-runoff conditions. Additionally, the flat terrain of the Lielupe basin and the complexity of its hydrographic network make precise modelling challenging, while technical aspects such as data processing speed and calibration of the HEC-RAS model also influence reliability.

Potential for further improvement in the system includes expanding the system nationwide and enhancing the flood model to predict risks in areas susceptible to rain-induced flooding, even those distant from rivers. However, further research is required to assess the technical requirements (e.g., server capacity, data flow scalability) for extending the HEC-RAS solution to a national scale.

The main **key performance indicators**
Output indicators:
1. The Enhanced Early Warning System for Jelgava City is in operation (planned – 1, achieved – 1).
2. Elaborated Early Warning System with AI driven prediction in Zemgale region is in operation (planned – 1, achieved – 1 with hydraulic modelling software HEC-RAS)
3. Elaborated Digital twin and advanced tools for climate adaptation are in use (was not elaborated)
4. Municipalities having obtained and using the elaborated system (planned >2, achieved – 1, further negotiations on-going)
5. A handbook for know-how to stakeholders is developed and available (planned – 1, achieved – 1)

Outcome indicators:
6. Methods applied for enhanced preparedness to flood risk management for integrated and coordinated national and regional multi-layer Early Warning System related to flooding (planned – 6, achieved – 6, hydrological modelling, flood risk prediction, early warning, GIS based area maps, flood maps, automated data flow)
7. Training for municipalities to use information from the handbook thus increasing knowledge of local authorities to prevent and avert flooding risks and disasters (planned – 3, achievement in progress)

8. Inhabitants are provided with early warning information on flood risks (% of inhabitants residing in flood risk areas) (planned – 100%, achieved - 100% because early warning information is available at: https://apzinosana.lv)

Impact indicator
9. Enhanced public safety at flood risk events in Zemgale region due to elaborated Early Warning System (Yes, because the system is operational)

2.12.3 Lessons Learned

In Latvia, there are no similar examples in the implementation of such detailed, down to the land unit (land plot, which is defined as property in the cadastre), warning algorithms. The high level of detail in the system affects how precisely floods can be mapped and predicted over an area, and it also makes it more challenging to create accurate forecasts that the warning system relies on. The system also involves a complex hierarchy of user roles and permissions, partly shaped by national civil protection regulations.

Challenges/ key takeaways:
Some aspects of the flood model require ongoing refinement:

*   On the input side, this means improving the quality and density of measurements (better riverbed surveys, more flow and water-level sensors). Separately, model calibration is needed — i.e., adjusting physical parameters such as channel roughness, inflow hydrographs and boundary conditions so simulated results match observations. In addition, numerical settings (time step, spatial resolution and simulation duration) should be tuned to balance modelling precision and computational cost, since finer resolution and smaller time steps increase accuracy but also require more processing time.
*   During implementation of the task, it was found that HEC-RAS performs efficiently on a dedicated physical server with sufficient processing power and memory. It is not optimized for cloud-based or virtualized computing environments and does not fully utilize virtual cores or parallel processing in virtual machines. Although, this does not prevent the system from functioning effectively in practice, but it highlights that faster performance can be achieved with appropriate hardware. Due to these limitations, the software is better suited for research and scientific modelling, where processing time is less critical, rather than for real-time or rapid flood scenario modelling.
*   The future challenge, once the project is over, is to engage more citizens in its use, as currently, notifications are sent to those who have pre-registered in the system. At this stage, we cannot provide a reliable estimate of user numbers or define a specific target for engagement, as uptake will depend on many external factors — including public awareness, willingness to engage etc. Therefore, rather than making numerical projections, the focus will be on ensuring the system is accessible, well-communicated, and capable of operating with as many users there will be as awareness grows.

Areas of improvement: The system's flood model simulates flooding based on forecast data only in areas near water bodies with known terrain. To predict pluvial (rainfall) flooding, which also becomes a challenge due to climate change, is necessary to develop another modelling system. It could be achieved and will enhance accuracy and expand coverage, for example, by incorporating factors like underground rainwater sewage system and related open systems like ditches, pumping stations, their operation capacities, etc., and expected water flow into the modelling would be necessary.

Future recommendations

*   In the long term, there is a plan to expand the system to notify people not only in the event of floods, but also during other disasters, such as fires. Additionally, the results from flood

- modelling could be used to enhance floodplain maps, helping to regulate areas where development should be restricted.
- The solution can be applied to any area that is at risk of flooding, but it requires a hydrological model that reflects the real-time situation and forecasts.
- The system works only if it is based on a ready-made HEC-RAS model based on several data: hydrological observations (monitoring) and forecasts from the forecast model; 2D modelling area, etc.
- As a result, the work of local government employees, who previously notified residents of floods by physically visiting affected areas, will now be streamlined through system notifications. The primary benefit, however, is for residents, who will be informed of floods in advance and can take preventive measures.

2.12.4 Conclusion

The Early Warning System for flood risks integrates data, GIS-based analysis, and the HEC-RAS flood modelling tool to predict and notify stakeholders about potential flooding. The system automates flood risk assessments using 2D flood modelling, leveraging data from the Latvian Environment Geology and Meteorology Centre and other sources. It enhances civil protection efforts in the flood-prone Zemgale region by offering real-time analytics, interactive mapping, and automated notifications. The system strengthens preparedness by providing timely warnings, allowing public institutions and residents to take preventive measures to safeguard people, infrastructure, and economic activities.

Key outcomes include an operational EWS for Jelgava City and municipalities of Zemgale Planning Region, increased public awareness, and provided ground for better stakeholder collaboration in disaster management, because it is possible to exchange information about the threat more promptly. The EWS improves collaboration by providing a shared platform where stakeholders can access real-time flood data, alerts, and maps, allowing coordinated decision-making and response. Key stakeholders include civil protection specialists, other municipal emergency services and institutions, and registered residents; by centralizing information and standardizing notifications, the system ensures everyone can act promptly and in a coordinated manner during flood events. Despite its effectiveness, challenges remain, such as ensuring forecast accuracy, expanding coverage beyond river-based flooding, and increasing public engagement. Future improvements involve incorporating additional environmental factors like soil saturation and expanding the system to address pluvial floods. The system's scalability allows for broader implementation in other flood-prone areas, streamlining emergency response and reducing potential damage.

2.13 Solution 13: Regional Digital Twin for climate adaptation and green business development (Task 4.10.4)

Attica faces significant environmental challenges, including water scarcity, frequent droughts, saltwater intrusion into aquifers, declining water quality, and increasing competition between agricultural, domestic, and industrial water demands. The region's high vulnerability to climate change is compounded by rapid urbanization, land-use pressures, and socioeconomic inequalities, which can limit adaptive capacity.

In this complex setting, there is an urgent need for sustainable, integrated solutions that address water management, land use, ecosystem preservation, and community resilience. A **Digital Twin platform** can serve as a powerful enabler by real-time monitoring of key environmental indicators, integration of diverse data sources, ensuring a holistic view of the system, optimization of resource allocation by identifying the most effective and efficient interventions under varying climate and demand conditions as well as stakeholder engagement and transparency through interactive visualization tools that help policymakers, residents, and businesses understand challenges and evaluate solutions collaboratively.
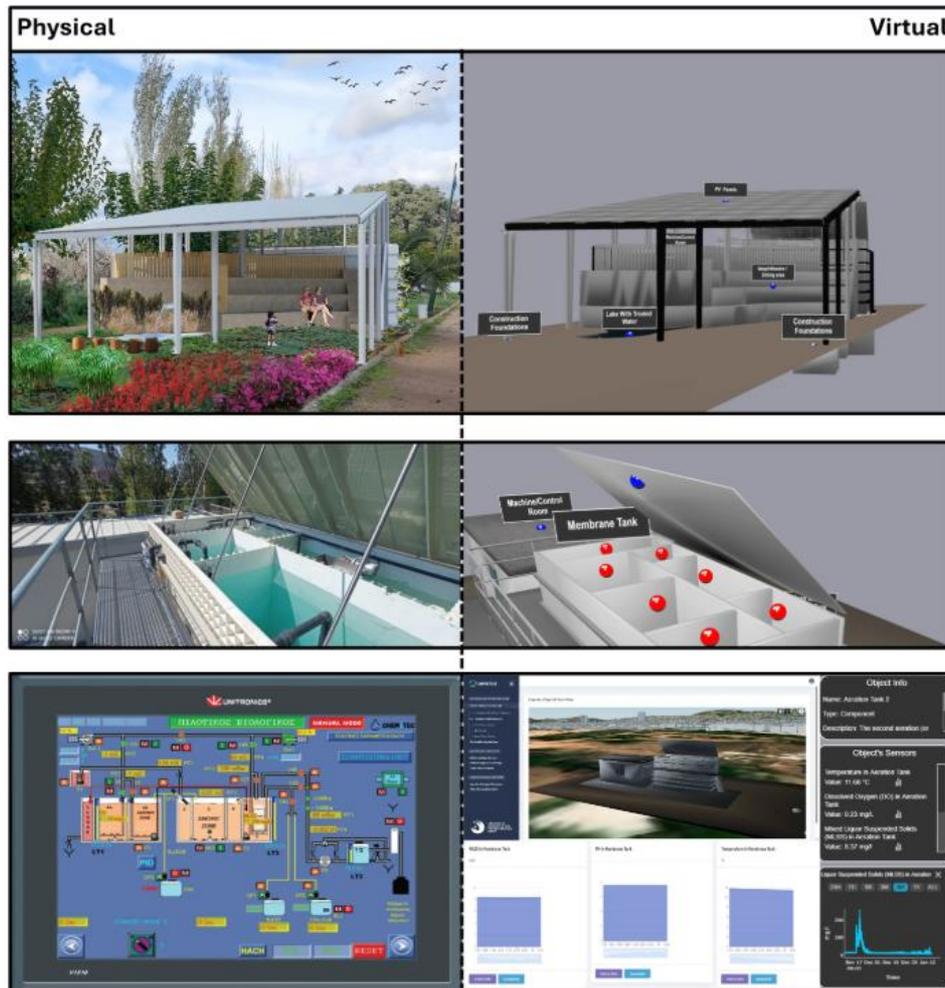
Figure 45 Visualisation of physical systems to digital replicas in real time

By creating a dynamic, data-driven representation of Attica's environmental and socio-economic systems, the digital twin platform enables informed, evidence-based decisions, supporting long-term resilience and adaptive planning in the face of climate-related challenges.

The Digital Twin of the Attica Region is a dynamic, virtual representation of real-world applications and water-related distributed solutions, such as localised sewer mining interventions or Controlled Environmental Agriculture solutions, and geospatial services such as reforestation services and heatmaps.

The platform monitors and visualizes digital replicas of physical systems in **real time**, enabling analysis and **optimization of solution performance** in real-world environments, supporting the planning for climate challenges (Figure 45).

It also brings stakeholders together and **engages key actors**, like experts, end users, and decision-makers, to share knowledge, develop green business ideas, and build a more climate-resilient future.

2.13.1 Results

The Attica Digital Twin showcases distributed interventions such as sewer mining at Markopoulo Urban Gardens and the Athens Plant Nursery, as well as smart farming (Controlled Environmental Agriculture – CEA) in Spata that optimize the efficient use of water, energy, and materials (Figure 46), which are operational within the framework of the project related to the respective tasks (T4.5.3 and T4.20).
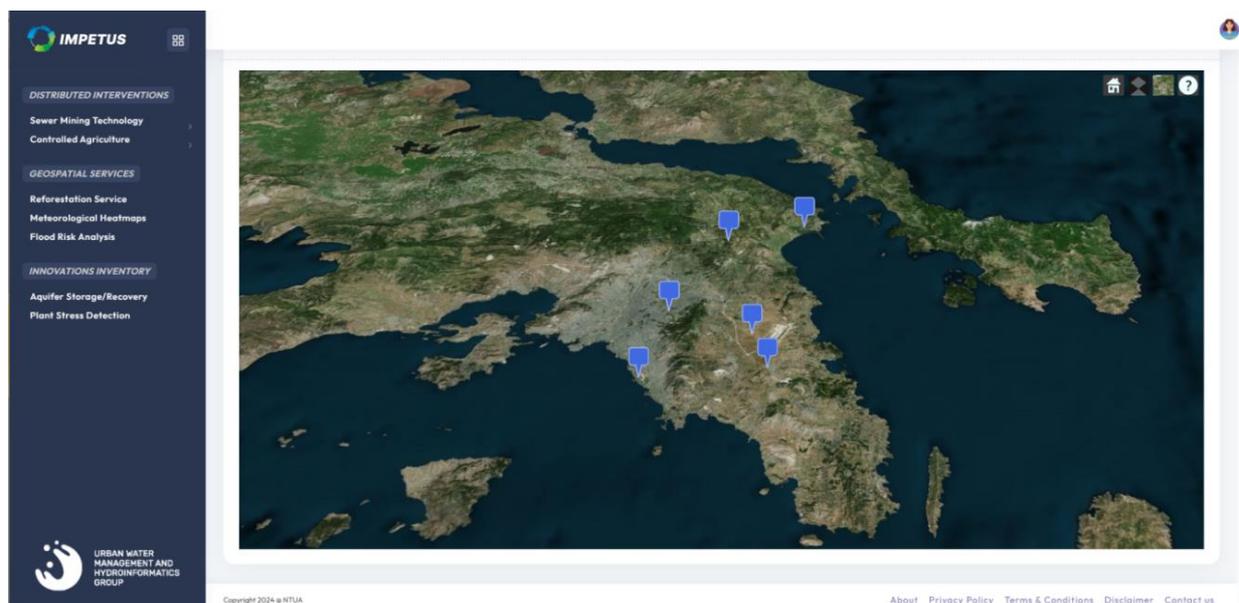
Figure 46 Attica Digital Twin map highlighting distributed climate adaptation interventions

The platform also offers a range of tools and geospatial services like:

- ✓ **Reforestation services** for identifying areas of biodiversity loss and defining restoration measures (Figure 47); which are implemented within the scope of the project (Task 4.4)
- ✓ **Heatmaps** that consolidate near real time data gathered from plethora of diverse sources, like meteorological stations, APIs, satellites and radars, etc., and convert it into a standardised format based from the FIWARE's Smart Data Models initiative. These heatmaps are described as potential applications and are therefore beyond the scope of the current project.
- ✓ **Flood risk analysis tools** designed to provide immersive and insightful flood risk assessments, that are intented to be implemented beyond the scope of this project;

to enable analysis of climate challenges and facilitate decision making.

The cutting-edge platform aspires to become a central hub for exploring new and innovative environmental solutions already implemented across the region.

Coupled with other NTUA advanced hydro informatics tools and services (such as Risknought, CPRISK-ABM, Nessie, and other products), our Digital Twin technology can extend its capabilities to address challenging water problems, from remote monitoring and control of decentralized water systems to enhancing the cyber-physical security of water infrastructure to operational flood risk assessment and management.

From the end-user's perspective, the **Digital Twin** is a straightforward and intuitive tool, as it serves as a one-stop shop for identifying innovative distributed solutions already implemented across the Region or to be materialized after the scope of the project. The core concept is that users only need a web browser and an internet connection to access the Portal's features and capabilities, while substantial computational resources operate in the background to ensure a seamless and engaging experience.

In detail, the Attica DT is a **web-based interactive dashboard** that combines real-time data, dynamic mapping, immersive 3D visualisations (Figure 48), and advanced simulation tools to provide users with intuitive insights into climate and environmental challenges. One of its standout features is the use of immersive 3D scenes, leveraging **advanced mapping technologies** (e.g. Cesium), which allow users to visualise real-world landscapes and infrastructure in a highly interactive way.
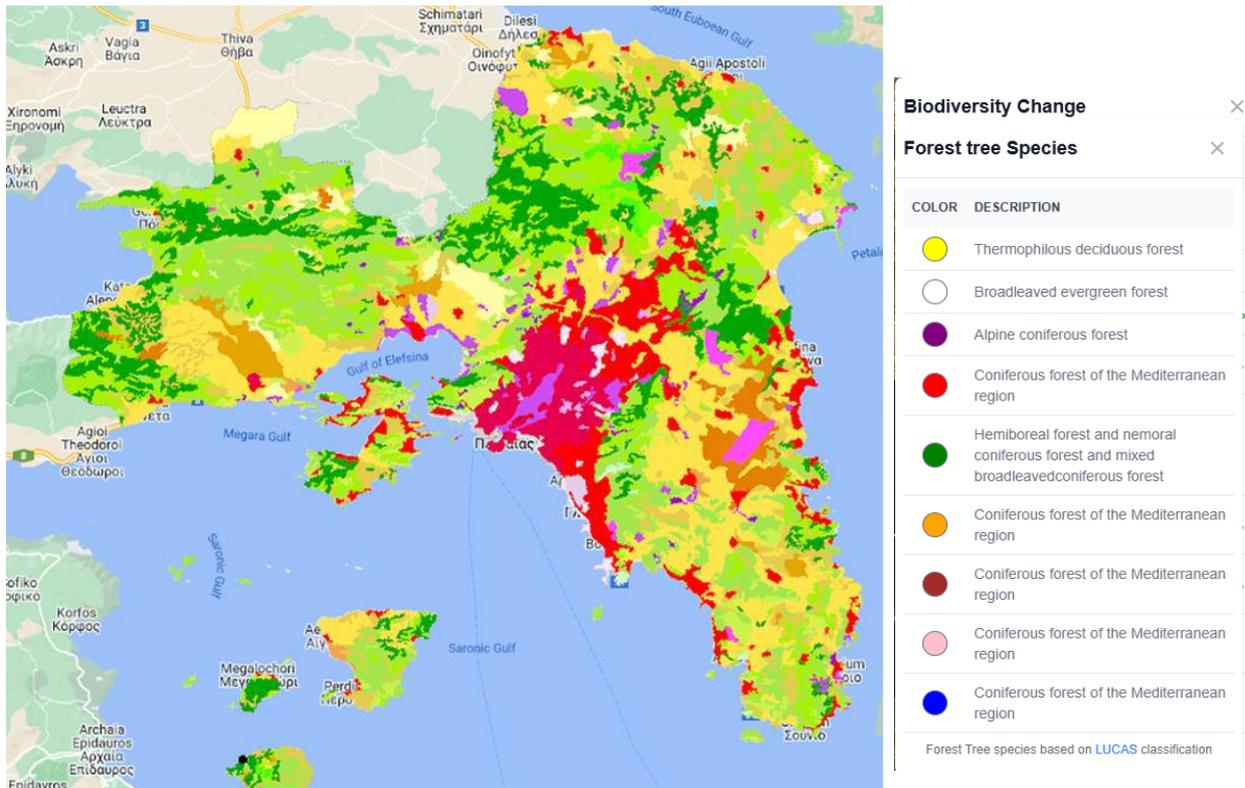
Figure 47 Geospatial map depicting reforestation services for the identification of biodiversity loss and restoration measures
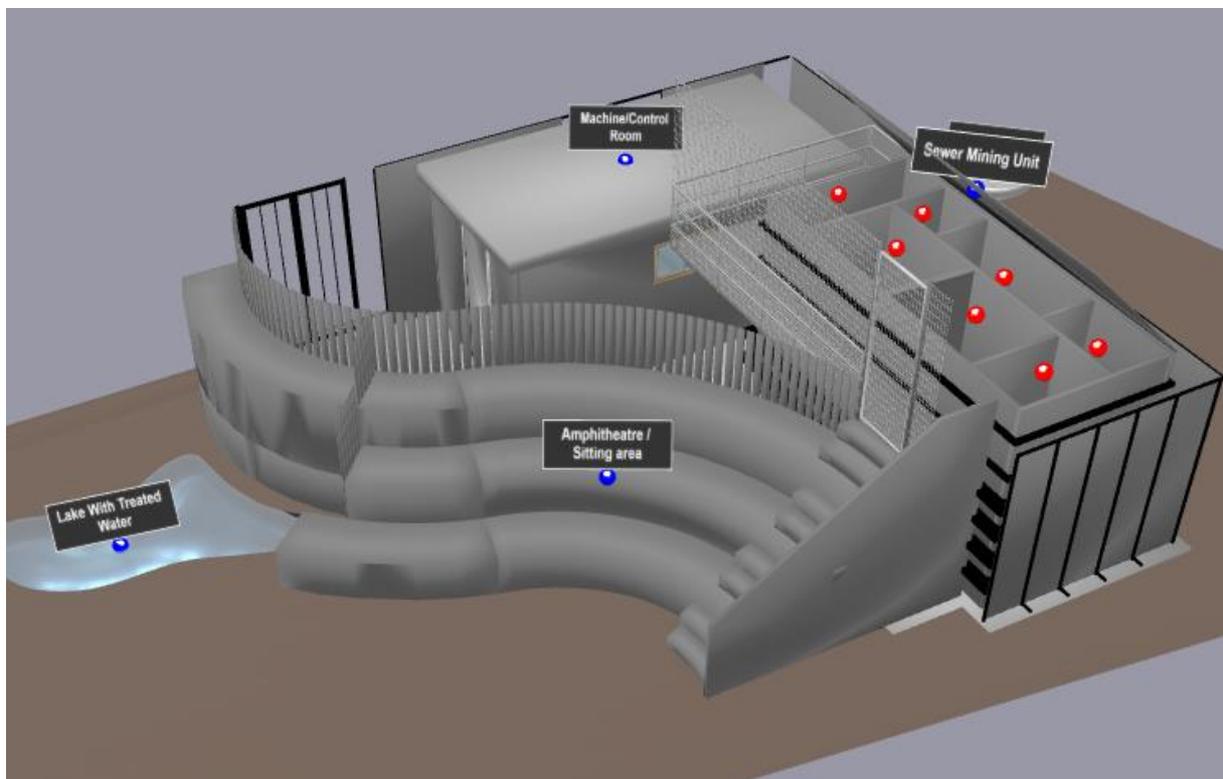
Figure 48 Dynamic mapping and immersive 3D visualisation of the Sewer Mining configuration in Markopoulo

Advanced technologies are also intended to be used so as to allow authorized users, without requiring IT or programming expertise, **to interactively create and render detailed 3D models** and immersive scenes directly in the browser (Babylon.js). This helps users explore complex environments, such as landscapes, infrastructure, and simulated climate scenarios, in a highly interactive way. It also allows policy makers, stakeholders, and the public to intuitively understand spatial relationships, risks, and potential impacts, turning complex environmental data into clear and engaging visual stories that support better decision-making.

The integration of the Attica DT with a powerful **data management system**, named Nessie, enables real-time retrieval and visualisation of environmental data on the virtual model. Nessie seamlessly collects and harmonises large volumes of high-resolution data from IoT devices such as smart sensors, runs advanced analytics (including forecasts and anomaly detection) and delivers selected and aggregated results via APIs directly to the Attica DT dashboard (Figure 49). Historical data are also available to view.

Figure 49 shows an example dashboard displaying real-time data and some daily analytics. Users can customize the dashboard, choosing what to see and what to hide. Users may also create new dashboards, in order to group certain data in one page for easier and quicker view.

Utilising FIWARE standards, the DT seamlessly integrates data from diverse sources, ensuring easy data exchange for interested parties and policymakers. Smart Data Models enhance interoperability, especially for inherently disconnected data sources.
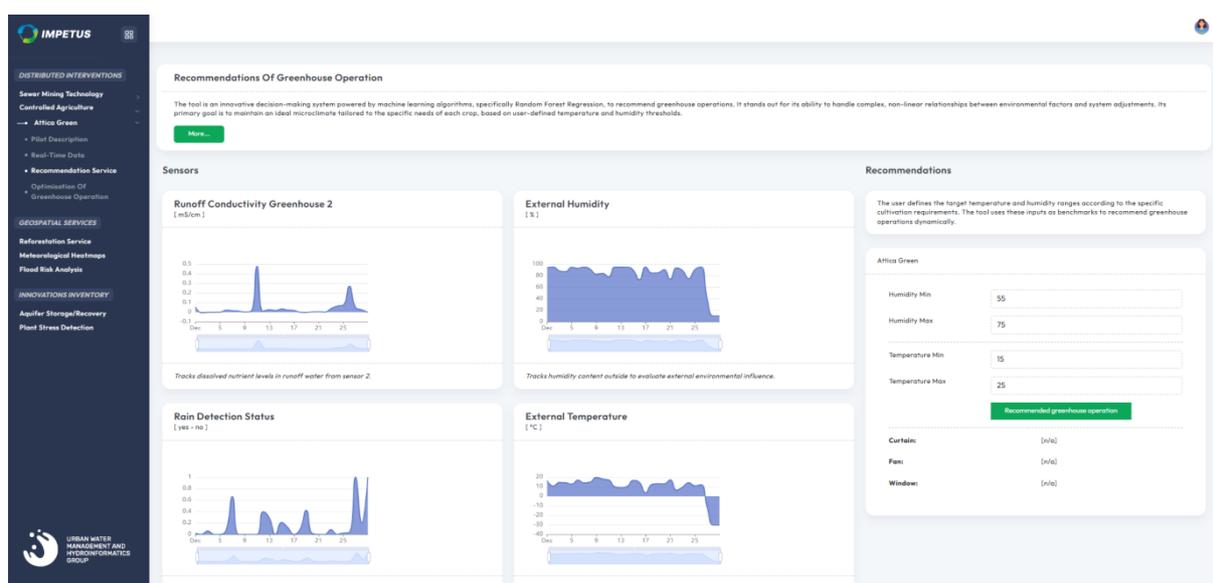
Figure 49 A comprehensive view of real time and historical data for the hydroponic greenhouse along with an innovative, decision-making recommendation tool for resource optimisation

Utilising **FIWARE standards**, the DT seamlessly integrates data from diverse sources, ensuring easy data exchange for interested parties and policymakers. Smart Data Models enhance interoperability, especially for inherently disconnected data sources.

With regard to the **flexibility and transferability** of the platform, this is designed so that it can be easily expanded and adapted to incorporate new data sources, technologies, and evolving system requirements, including integration with third parties' developments.

Applications range from remote monitoring and control of decentralized water systems, to strengthening the cyber-physical security of water infrastructure, and supporting operational flood risk assessment and management. A DT of a specific infrastructure, for example a sewer mining facility, serves as a prototype digital system that can be readily adapted to similar applications. This is possible because the core principle—real-time monitoring and visualization of physical systems through digital replicas—remains

the same. Such digital representations enable performance analysis and optimization in real-world conditions, supporting better planning and resilience against climate-related challenges. The flexibility of this system makes it an indispensable asset for promoting sustainable, data-driven decision-making across the Attica Region.

In particular, the following matters have been addressed:

- ✓ **Modular and extensible architecture**: The DT is built in a flexible way to grow and evolve. It is an adaptable platform that integrates diverse initiatives, tools, and solutions from multiple users.
- ✓ **Interoperability and standards compliance**: Built on scalable and state-of-the-art standards, the platform supports integration with heterogeneous data sources, emerging technologies, and third-party systems, ensuring adaptability to evolving operational, environmental, and policy needs.
- ✓ **Future-proof design for continuous evolution**: Its architecture enables dynamic expansion and customization, positioning the DT as a robust enabler of data-driven, sustainable decision-making and cross-sector collaboration across regional and institutional boundaries.
- ✓ **Web-based, interoperable visualization** interface that enables stakeholders to monitor, adapt, and scale system functionalities across different geographic and operational contexts, facilitating regional replication and customization.
- ✓ **Policy-aligned scalability and institutional integration** to align with evolving regulatory, legal, and governance frameworks, supporting its adoption into national and regional planning processes. This institutional compatibility enhances long-term viability and unlocks access to strategic funding opportunities, and programmatic support, and cooperation initiatives, thereby ensuring sustainable deployment, broader impact, and resilience in the face of evolving environmental and socio-economic challenges.

2.13.2 Impact

The Digital Twin Platform has the potential for both significant **short-term** and **long-term** impact across environmental, technological, and societal dimensions.

With regard to the **direct impacts**, these could be summarised in the following issues:

1. Operational optimization and decision support
- ✓ Real-time monitoring and simulation allows for a quick identification of inefficiencies, unexpected events, or risks (e.g., wastewater leakage, air blower defect, flood risk). This impact is relevant in the sewer mining application in Markopoulo.
- ✓ Enables **data-driven decision-making**, improving day-to-day management of the water systems, infrastructure, and emergency response. This impact is relevant to the CEA solution in Spata.

2. Stakeholder collaboration
- ✓ By creating a shared, visual representation of systems, it **facilitates collaboration** between the regional authorities, municipalities, utility operators, engineers, and policy-makers. Builds trust and accelerates **alignment between actors**, reducing fragmentation and ensuring that responsibilities in planning and implementation processes are shared and harmonized rather than siloed. In the context of sewer mining, this serves as a concrete proof-of-concept in real-world settings, demonstrating how diverse operational, regulatory, and technical challenges can be collectively addressed and resolved.

3. Capacity building and engagement
- ✓ Makes complex water and climate data more accessible and interpretable. This is a next step when more climate data are integrated in the platform.
- ✓ **Engages non-technical users and the public**, fostering broader understanding and awareness of water-related challenges and solutions. The sewer mining solution through the

Digital Twin system empowers communities to participate in decision-making, strengthens trust in institutional processes, and supports a culture of shared responsibility in addressing climate and water resilience.

4. Prototype testing and scenario analysis

- ✓ Allows simulation of different climate or infrastructure scenarios without physical risk or cost, providing a valuable foundation for future applications and large-scale deployment.
- ✓ Supports **pilots and early-stage innovation** (e.g., sewer mining technology, nature-based solutions, smart irrigation, etc.) by visualizing outcomes before deployment.

With regard to the **long-term impacts as a future potential**, these could be summarised in the following issues:

1. Increase climate resilience and improve adaptation

- ✓ Supports **long-term climate adaptation planning** through predictive modeling and improve performance systems.
- ✓ Enables **evidence-based urban and regional planning**, helping communities build resilience to droughts, water scarcity, floods, and shifting water patterns.

2. Green innovation ecosystem

- ✓ Provides a foundation for **new green business models**, products, and services that emerge from digital twin insights (e.g., precision water management tools).
- ✓ Acts as a **platform for continuous innovation**, where solutions evolve with real-world feedback and environmental changes.

3. Policy and regulation shaping

- ✓ Offers **scientific evidence and impact simulations** that can inform national or local environmental policies, water governance, and EU Green Deal targets.
- ✓ Helps measure and report on **sustainability KPIs and climate targets**.

4. Scalability & Replicability

- ✓ A well-functioning platform can be **replicated and extended across regions or sectors** (e.g., agriculture, energy, coastal management).
- ✓ Becomes part of a **larger digital public infrastructure**, contributing to smart cities and regions.

2.13.3 Lessons Learned

The Lessons Learned from your Digital Twin Platform initiative can be summarised below:

Key Takeaways

- ✓ The platform's true strength lies not just in visualization, but in **dynamic integration of data, predictive analytics, and stakeholder engagement**. This holistic approach consolidates key data and insights, transforming them into collaborative action.
- ✓ Early and continuous involvement of **end users, domain experts, and decision-makers** to maintain optimal system conditions and promote sustainable practices, significantly improve platform relevance, usability, and long-term adoption.
- ✓ Access to real time system data enhanced **situational awareness**, allowing teams to shift from reactive to **proactive strategies** in managing water-related risks. This is relevant to the CEA solution with regard to the efficient irrigation practices as well as in the Reforestation and Biodiversity Monitoring Tool, where, by leveraging advanced data analytics, digital tools, satellite images, knowledge and information from relevant stakeholders and end-users, forest restoration planning and decision-making at various governance levels is enhanced. Bridging engineering, environmental science, and digital technologies led to **cross-disciplinary innovation** that would not have emerged within silos, ensuring the long-term viability of solutions and strengthening the region's capacity to adapt to climate change.

Challenges Encountered

- ✓ Accessing and **integrating heterogeneous data sources**/formats (mainly data from sensors and data from sampling and analysis) and different technologies into a unified digital platform presented technical and administrative challenges.
- ✓ Advanced 3D visualization of physical infrastructure and systems, providing intuitive, high-resolution models that enhance understanding and engagement for end users presented some technical challenges as the end user perspective needed to be integrated.
- ✓ Bridging the communication gap between system developers, domain experts, and policymakers by offering a common digital environment for collaboration and informed decision-making was an important challenge to overcome.
- ✓ Incorporation of end-user perspectives in the design process to ensure usability, accessibility, and relevance, was a key challenge so as to result in a more user-centric and functional interface.

Future Recommendations

- ✓ Begin with a **focused pilot use case** to prove value quickly, then gradually expand to full system integration, through the use of a regional master plan on such interventions, e.g. water reuse master plan.
- ✓ Design platforms with **modular architecture** to adapt to different environmental, regulatory, and technological settings, which was already in the original concept of the Digital Twin and the experience gained can further support the adaptable environment even further.
- ✓ Ensure **co-creation sessions, user training, and expectations management** are included from the start—not as afterthoughts, which is both an immediate recommendation but also needs further development and funding to be effective and impactful.
- ✓ Establish clear **data ownership, privacy, and interoperability protocols** early to avoid legal and operational roadblocks later.
- ✓ **Generalise** the platform to enable seamless application across different projects, which is an element to be adopted in future projects and initiatives.
- ✓ Expand **user roles** and permissions allowing each user a personalized view of the DT platform, according to their needs, which is useful for future different needs of stakeholders.
  Add a **conversational agent** that will allow users to interact with the platform in natural language. This agent will support various use cases, such as: a) allowing administrators to check the current status of infrastructures and explore simulation results and b) enabling other stakeholders to zoom in and focus on specific infrastructure of interest.

Barriers to Transferability

- ✓ Many regions, such as the Attica area lack **sufficient or reliable environmental data**, which can limit the accuracy or usefulness of digital twins.
- ✓ Variability in **organizational digital maturity** or willingness to adopt new tech may hinder implementation, which is also the case for the Attica region.
- ✓ In some areas, **poor connectivity, outdated hardware, or lack of sensor networks** can limit real-time capability, which was not so much the case of the Attica region, but is a common barrier in other areas.
- ✓ Differences in **data sharing regulations or environmental policies** may require project redesign when applied in other areas, which is also the case in the Attica region.
- ✓ Resistance to change, lack of trust in digital solutions, or different decision-making cultures may impede platform adoption, which is also relevant to the experience that was gained in the Attica region.

2.13.4 Conclusion

The development of the Attica Digital Twin Platform has demonstrated the transformative potential of digital technologies in addressing complex water-related and climate challenges. By integrating real-time data, geospatial intelligence, and interactive modeling, the platform provides powerful tools for monitoring, analysis, and scenario planning. It has improved operational efficiency through visualisation instruments, enabled proactive decision-making, and supported climate adaptation strategies, while also fostering collaboration among diverse stakeholders, including experts, end users, and policy-makers.

Through this initiative, critical insights can be gained into the importance of early stakeholder engagement, flexible system design, and robust data governance. While challenges such as data interoperability, variable digital readiness, and institutional complexity were encountered, they were mitigated through adaptive approaches and continuous learning. Moving forward, the platform offers a scalable and replicable model that can support sustainable infrastructure planning and resilient communities, provided local contexts are carefully considered and cross-sector collaboration is maintained.

2.14 Solution 14: Climate proofing of the city centre and of its urban water infrastructure against sea level rise (Task 4.11)

Adapting communities to sea level rise and storm floods is a complex issue in a city like Tromsø situated on an island (Figure 50). The slow-moving changes of sea level rise also risk not receiving enough attention. The focus of policy and planning is on the here and now and the more immediate future. Climate adaptation literature highlights the challenges that lie in sea level rise-adaptation due to the long-term perspective of a rising sea, and the uncertainty of future predictions and the effectiveness of adaptation measures (Campos et al. 2016). The key question is how to make infrastructural and adaptation decisions today that will not hinder effective and cost-efficient future adaptation (Lawrence et al 2018). The timing of implementation measures is essential. Too early could mean unnecessary costs if new and improved measures are introduced later. But responding too late could lead to damage to existing infrastructure. Flexible approaches are called for (Metzger et al, 2021). **The objectives for task 4.11 are:**

- Identify relevant measures for sea-level protection and engage stakeholders in discussing potential directions for climate adaptation.
- Identify relevant public spaces along the seafront influenced by sea level rise and employ Virtual Reality (VR) visualizations as a technical solution providing a better understanding of the need for climate adaptation, also engaging stakeholders in testing the VR technology at a public meeting.
- Developing a Digital Twin of Tromsø city centre.

The solution focuses on climate-proofing of the city center. The coastline of the city center has, to a large degree, been modified from its natural state through infrastructural development on artificial fillings out into the sea (land reclamation), exacerbating future challenges with sea level rise. Adding to the future challenges of a rising sea level, Tromsø is expected to face higher temperatures, leading to increased precipitation and stormwater, also increasing the risk of flooding (Rød et al 2024). Stormwater management has therefore become a more immediate and urgent issue than long-term sea level rise. When adapting to sea level rise, future risks of increased floods also need to be taken into account, as they both affect the lowest-lying areas.

Figure 50: Flooding event (storm surge) in Tromsø city, 2011.

The main outputs are:

A city-scale DT of Tromsø. The DT has the capacity to analyse huge sets of data of relevance to climate change adaptation. The DT of Tromsø is a digital representation or virtual replica of the city, giving a wide set of stakeholders a better understanding of long-term changes through realistic simulations. It is also a tool for long-term planning for adaptation that provides improved insights for decision-making.

- VR visualizations of future sea level rise/storm flood in the city center of Tromsø in order to enhance public awareness and engagement. VR tools hold promise to raise CC awareness. (Meijers et al. 2023)
- A handbook for how Tromsø municipality can create a citizen jury (CJ) with local inhabitants focused on climate adaptation. The handbook provides the local government with information on a tool which aims at engaging the local community in a more in-depth way than many other participation methods do (Campos, 2016). The aim is thus to contribute to long-term adaptation with the local community on board. This contributes to the quintuple helix ambitions of IMPETUS.

The three outputs thus provide tools which can help to visualize and plan for long-term climate adaptation and simultaneously aim at inviting more stakeholder groups into understanding the issue and contribute to the adaptation process.

2.14.1 Results

A first result is VR-visualizations demonstrating future predictions of how sea level rise can affect the city centre of Tromsø used for public engagement, produced by SWECO. More specifically the outcome is 3D-images of Tromsø city centre during a storm surge with a 200-year recurrence interval in the year 2100's sea level (Figure 51). The views of the storm surge event can both be shown with and without a barrier keeping the water out. The barrier is a see-through glass wall along the sea front and is used to demonstrate what a potential climate adaptation measure could look like. However, it functioned as a starting point for imagining what an adaptation measure can look like and the need for, and design of, adaptation measures in the city centre.

A second result is a 3D-model to visualize storm surge events including adaptation measures also developed by SWECO.
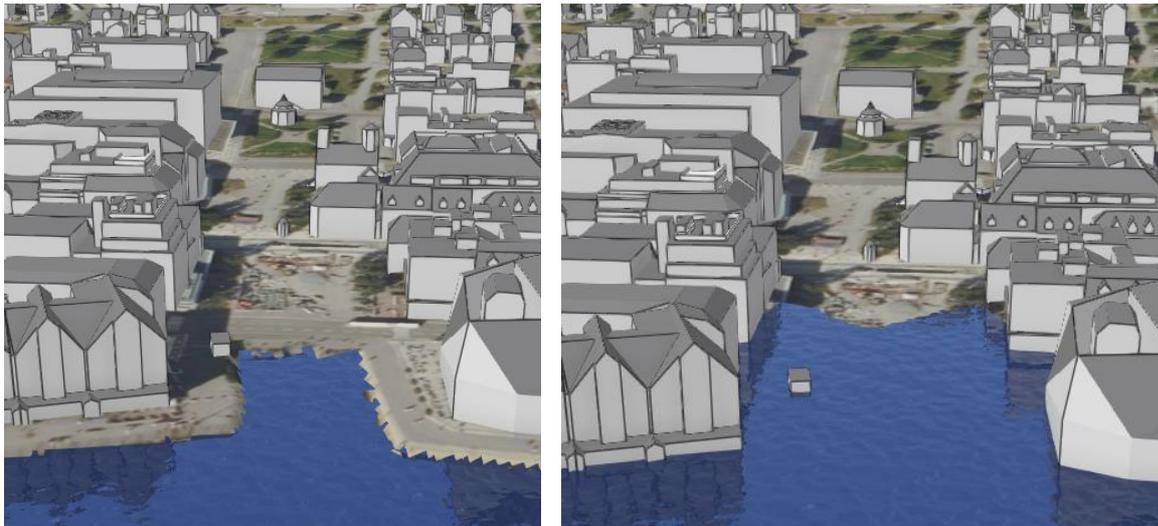
Figure 51 Modelling of sea level in main square (Torghuken, Stortorget) Left: Sea level at present. Right: 200 year interval storm surge, year 2100

The VR-visualizations have been tested on stakeholders in three different settings during the spring of 2023:

- In a workshop with 15 municipal employees working on issues related to climate adaptation
- In a meeting with the two mayor candidates ahead of the local election in 2023 (Figure 53). The meeting was documented by the local newspaper Nordlys resulting in articles about the issue and the IMPETUS-project both online and in the printed newspaper (Figure 54).
- In a local public arena for architecture and design with the general public, with 31 persons attending.

The VR-visualizations using the Tromsø case have also been presented by SWECO at the World Water Congress in Toronto in August 2024. In the process of finishing the Digital Twin it is explored if the VR-visualizations can be added as a functionality in the Twin. The work with VR-visualizations was also developed further through a master's thesis which was co-supervised in collaboration between UiT and SWECO, focusing on VR as a risk communication tool towards three groups of stakeholders: citizens, city developers and municipal planners. Main findings from the thesis summary: "Citizens are most impacted in terms of their perception and understanding as they sense little control over the risk. The local business owners have diverse responses, some of these are located at the seafront, but show relatively little concern. Municipal planners are the least impacted, as they have prior established and solid understanding of the risk." (Kuipers 2024).

The tird result is the developemnt of a fully operational Digital Twin of Tromsø city centre. This work has been led by Troms and Finmark Fylkeskommune, and the DT was co-created with UiT, Geodata AS consultancy, with input from stakeholders. The main stakeholders has been planners and climate service officers in Tromsø municipality. The stakeholders have been given input on what type of data they wanted the DT to anayse, on the design of the landing side of the DT and its functionality. Two physical workshops with approximately 15 persons attending was organized, in addition 2 digital workshops, 1 with 12 and the last one with 31 participants has been arranged. This last one was open for other municipalities in the county in addition to Tromsø.

The DT is a publicly available planning tool based on ArcGIS online-technology (IMPETUS). The tool is addressing future climate change challenges related to sea level rise, storm surges, and floodings. https://impetus.tromsfylke.no/

Considerable effort has been made on data assimilation and implementation in the DT. It consists of a complete 3D terrain model of Tromsø city with digitalized 3D buildings and infrastructure. Coupled to

this model is data on sea-level change, storm surges and surface water, following the newest iteration of the IPCC report and downscaled climate models for the region. Analyses highlighting the affected areas of sea-level and storm surges has been developed, which gives the user valuable insight on which specific areas the storm surge can cause damage. The models also contain information on avalanche risk zones, as more frequent and intense precipitation is expected to affect the region. The DT has been modified with input from the stakeholders throughout the project in several workshops, both in terms of its user-friendliness, data input and exploring the possibility to show visualizations of potential adaptation measures in it.

Relevant stakeholders, working on issues related to climate adaptation in Tromsø municipality has been invited to meetings and workshops to give input on how the DT can be of good use for them. Three workshop sessions have been held:

- *Workshop 1, November 2023*: Introducing the DT as a concept to stakeholders (mainly from Tromsø municipality). Receiving feedback from stakeholders on relevant functions, map layers, and analyses to include in a DT.
- *Workshop 2, May 2024*: Digital workshop presenting a prototype version of the DT to stakeholders from Tromsø municipality. Receiving feedback from stakeholders on their impression of the tool, what works well, less well, and what is missing.
- *Workshop 3, December 2024*: Joint digital workshop presenting the Digital Twin and Marine Spatial Planning tool (developed in task 4.19) with relevant stakeholders, mainly from municipalities in the Troms region. Focus for the DT was both on making a broad range of stakeholders aware of the tool and how it can be used/replicated after the project ends, and to get feedback on the final stage of development.

The stakeholders suggested a number of datasets to be integrated in the DT, for instance infrastructure, buildings, nature-based solutions, climate and weather data, simulations of extreme weather events, storm surge and more. They also provided input on the user interface. Most of these inputs has been integrated into the DT that now consists of a huge set of data layers (Figure 52).

Figure 52: The Digital Twin of Tromsø city with an analysis of Tromsø inner port in the city centre showing the sea level rise of the year 2050 together with a storm flood event with a 200-year recurrency level, and the municipal land use plan. See IMPETUS for legend and scale.

As previously mentioned, sea level rise is a complex process of change. It is challenging to get engagement and action around the topic as the changes happen relatively slowly. Therefore, it is easy to prioritise other, more urgent needs. In line with the VR-visualizations (and DT) focus on communicating long term risk, a complementary tool focusing on understanding long-term changes and getting engagement around adaptation in a more method-focused and less technical way was developed. In collaboration with the municipality, the involvement of the public in the adaptation decision-making process was proposed through the establishment of a citizen jury. Although the actual setup of the jury is not yet implemented, a handbook was developed for the municipality of Tromsø to support implementation at a later stage. The handbook is based on a literature review on the Citizen jury-methodology, presenting a thorough review of aspects to consider when planning and carrying out a citizen jury as well as the rationale behind it. As an appendix, the handbook provides more hands-on suggestions on the process of setting up a CJ with a specific topic related to flooding in Tromsø city. Here, the VR-visualizations and DT are added as tools that can be included in the process, connecting the results of the project activities. The handbook is written in Norwegian and exclusive to the municipality of Tromsø. The handbook is available on the website and has been handed over to Tromsø municipality.

2.14.2 Impact

As outputs, public engagement through VR-visualizations, development of the DT, and guidelines for developing a Citizen jury have all been carried out during the project phase. The VR methodology has been taken further through Master's theses and perceived a positive attitude towards using such an approach again from central stakeholders such as Tromsø Municipality. The DT is fully operational and available to city planners in Tromsø municipality and the general public. An effect of it being publicly available for all to use is that it leads to a wider understanding of the need for climate adaptation in the city centre of Tromsø among different types of stakeholders. The tool is developed in such a way that technical personnel can add information to it after the project ends. The DT can therefore have long-term effects of being a useful planning and communication tool. An outcome of the guidelines for developing a Citizen jury is that they will be available for the municipality of Tromsø. This outcome lays the groundwork for a new form of public engagement in the municipality. However, the actual impact of the guidelines will depend on whether the municipality chooses to test the engagement format in practice, something that lies beyond the scope of the project. Stakeholders at the demonstration site have been provided with various tools designed to support a shared understanding of the risks and opportunities involved in moving from words to collective action on climate adaptation.

Figure 53: One of the mayoral candidates in the 2023 local elections tests the VR visualisations of future sea levels.

HAVNIVÅSTIGNING   TROMSØ SENTRUM   OVERVANNSHÅNDTERING

Her sjokkeres Anne-Berit og Gunnar: – Skremmende å se

Figure 54: The Mayor of Tromsø Municipality trying VR visualising Tromsø city centre in a severe flooding scenario. The title reads "[name of mayoral candidates] are shocked:-Frightening to watch"

The response from stakeholders when demonstrating the DT prototype/pilot has been mixed. Some feedback among others are expectations to it as a useful tool and that it should have included more explicit functionalities for concrete adaptation measures. The usability of the tool is also difficult to estimate before it is taken into use. If the Digital Twin becomes a well-used tool by a large group of local stakeholders it can both impact the general awareness of the need for local climate adaptation in a positive way, as well as being a tool for adaptive planning. This can lead to more informed decision making, and consequently provide possibilities for a better adapted city centre. A future challenge is the long-term funding for updating the tool with new climate change predictions and changes to the built environment. If not updated, it will become less relevant for stakeholders. Recent responses from the Norwegian Mapping Authority hold promise for the DT to be generalized, but it is too early to conclude.

The task has emphasised co-creation with local stakeholders, the need for providing tools which better communicate climate risks and how local inhabitants can be engaged in new ways into adaptation processes through the handbook on CJ.

The DT is publicly available online (https://test-impetus.tromsfylke.no/). It is also available through the Resilience Knowledge Booster (RKB), and there will be information about it on the Multi-sided/IMPETUS-platform. The DT can be used by a wide set of stakeholders in the local context:

- As a planning tool for Tromsø municipality both internally and externally towards the public, private developers and politicians.
- By private developers, to give them a better understanding of how relevant climate risk could affect the region and possibly their projects in the future.
- As a decision-making tool by politicians.
- The public can use the tool to get more informed on climate change. It can also be used by government representatives at regional and national level.

Guidelines on the process of developing the DT is shared through the RKB. The tool is developed through ArcGIS-online. The map-services are however specific for Norway and the Arctic Demo site. Funding, knowledge, data availability and time are all limitations to transferability of the DT. The planned guidelines can help to overcome knowledge limitations.

2.14.3 Lessons Learned

A key takeaway of the task is to try to overcome barriers between knowledge and ideas by working with tools that are accessible to all. Another key takeaway from the work is the need to communicate and create engagement around the need for adaptation to, and between, different stakeholder groups to improve the conditions for action on adaptation issues.

- The focus area of the task changed over time both as a consequence of the iterative process of learning more about the issue and the local context during the project. The changes have also contributed to lessons learned.
- The stakeholder involvement of the DT creates better conditions for the DT to be useful for end-users. This can however also represent challenges in meeting stakeholder needs regarding technology, time and budget. The DT-can be further developed by the stakeholders. Focus on clearer definitions and expectations from the start regarding functionalities and limitations of the Digital Twin and possible specific data sets.
- The concept of a DT and its result was not enough well-spread among all partners. Specifically, the delay in the development of the Twin led to a decision of asking SWECO to develop the VR-visualizations to ensure that some visualizations of future climate change would be available for stakeholder engagement.
- The VR-visualizations has proved its importance in terms of climate communication. The communication aspect has also been an important aspect when working with sea level rise as a climate change issue as it is situated so far into the future which is a challenge in gathering a momentum and sense of urgency. The VR-tool thus provided a new type of visualization in the local context of the predicted future changes which can be seen as an important first step for stakeholders to see before specific adaptation measures is relevant to discuss. The VR-visualizations is dependent both on the VR-equipment (VR-glasses, program for developing visualizations etc.) and the technical skills of developing the visualizations. Apart from this, the transferability of using VR as a tool in risk communication can be understood as high. An important aspect if replicating the approach is to consider the purpose of showing specific visuals for specific stakeholder groups.
- The Citizen jury-handbook is written in Norwegian and is to some degree framed to be of use for Tromsø municipality specifically, there are thus limitations in the transferability of the handbook as such. There are however no limitations in transferability in terms of the concept of a methodology handbook, providing knowledge on how to develop an engagement method to stakeholder that has not yet tested the specific method. As the project started, there was no plan on carrying out a Citizen jury-handbook. It however, over time, became clear that there were challenges in getting engagement around rising sea levels due to their slow-moving character. The idea of making a handbook on how to create a Citizen jury for Tromsø municipality was then developed to ensure an outcome of the process, providing the municipality with easily accessible information, if the opportunity to develop a Citizen jury would emerge in the future. A lesson learned from the handbook-process is thus to be open to continuously changes in your approach to adapt to the local context, barriers and needs.

2.14.4 Conclusion

The task has taken a comprehensive approach on starting the process of climate proofing Tromsø's city centre. Climate adaptation is often related to large and expensive changes to the physical environment, and to the current way of operating. By developing a Digital Twin of Tromsø, VR-visualizations for climate communication and a handbook on how to engage inhabitants in Citizen juries. The task has helped in providing the local community with more tools and knowledge about the need for adaptation, nudging stakeholders to include an adaptive perspective in the future development of the city centre. A lesson learned for future projects is to be aware of the difficulty in engaging many stakeholder groups into complex processes of change. Climate adaptation is a cross-sectoral collaborative issue with many potential solutions to move forward.

2.15 Solution 15: Early-warning systems for geological and avalanche risk sites (Task 4.12)

There are several types of rapid mass movements, including landslides, rock falls, snow avalanches, and slushflows. Task 4.12 investigated two types of rapid mass movements, large-scale mountain rock slides and slushflows.

Landslides incorporate a broad range of material and have different movement types. This study focuses on large-scale mountain rockslides that threaten Arctic communities through direct landslide impacts or secondary consequences such as landslide-triggered tsunamis. The current early-warning system in place in Ullsfjorden is operated by national authorities (Norwegian water and energy resources directorate-NVE stakeholders) and is functional, but this study has worked to improve the understanding of links between local weather patterns and slope movements that precipitate early warning alarms. These links are to form the basis of predictions on slope behaviour under climate change.

Slushflows are a type of rapid mass movement characterized by the sudden release and flow of water-saturated snow and ice, and which may entrain debris. With the expectation that winters will become wetter and warmer under a changing climate, as stated in the IPCC report (Cissé et al., 2022), the formation of slushflows is expected to increase in the coming years in regions that retain a seasonal snowpack (Hestnes and Jaedicke, 2018). While forecasting of snow avalanches is a well-established practice to protect people and infrastructure, the understanding of slushflows is limited, and forecasting systems are not yet available. In addition, they often occur in areas not traditionally thought of as avalanche terrain, without warning. Several large slushflows have occurred in the coastal mountainous regions of Norway in recent years, leading to property damage and road closures (Figure 55). The objective of this work was to broaden the understanding of slushflows, as well as to improve forecasting and hazard zoning.

Figure 55 Two slushflow events that occurred in northern Norway in spring 2023. Both events covered/damaged important roads from ice and rock debris.

2.15.1 Results

The work has been executed in stages:
1. Field reconnaissance and identification of a relevant study site;
2. Capture of slope movements: placement of ground-based radar (GBR) and acquisition of commercial and free satellite radar data (InSAR) in the study area;
3. Characterisation of the study area: geological mapping and analysis of the mountain;
4. Weather data acquisition and interrogation for the study area;
5. Determine weather impacts on slope movements: correlation of movement data from processed radar, and weather data;
6. Slope stability implications with climate change: infer long-term trends of mountain slope behaviour given modelled climate change (rainfall, temperature) for the DS.
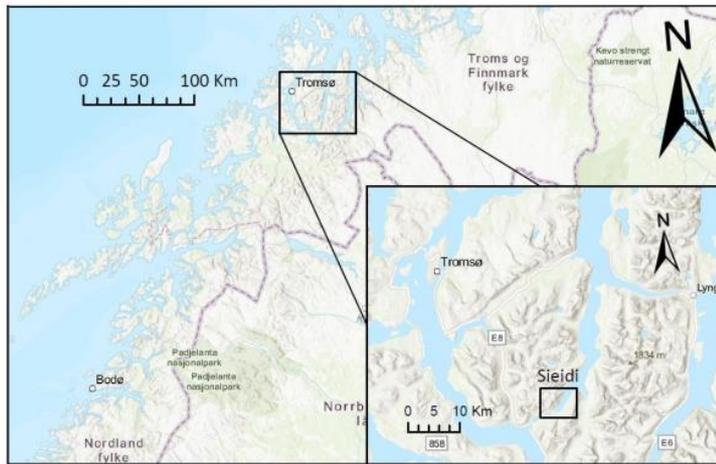
Figure 56 Map of northern Norway showing location of Seidi field site (Figure from Kaltenrieder (2024).
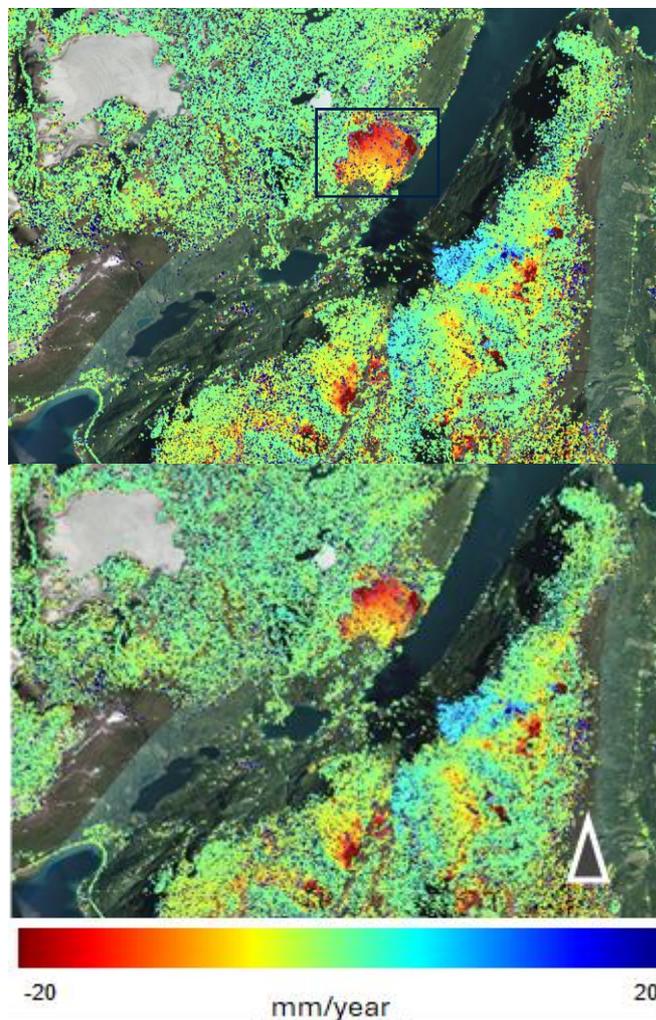
Figure 57 Site selection of the Seidi rockslide from satellite InSAR movement data. The slope of interest (black rectangle) shows a high degree of deformation relative to the surrounding areas. Dark red patches indicate surface movements of up to 70 mm/year. https://insar.ngu.no/.

The initial site choice determined the Seidi (Figure 56) rockslide to be the best. It shows a high degree of displacement and well-contained surface movement boundaries (Figure 57). In addition, the rockslide

sits above Ullsfjorden, a fjord with a populated shoreline within the impact zone of a landslide-triggered tsunami. GBR is a tool that captures high-frequency slope movements. This is preferable to satellite InSAR, which captures radar movements of the ground surface at a (best case) 6-day recurrence interval, so it misses movements between these days. The GBR was placed in position on the opposite shoreline (Figure 58) and programmed to capture slope movements hourly. The data was stored locally and collected fortnightly over the snow-free period of 2022. Simultaneously, satellite InSAR from the free Copernicus programme was acquired (pre-processed, available through InSAR Norway: https://www.copernicus.eu/en) and purchased from the TerraSAR-X satellite programme (raw, processed by us) for Seidi. Geological characterisation of Seidi was completed in 2023.

Figure 58 Installation of the GBR (inside white dome) at Seidi rockslide. Image from NORCE, Norwegian Research Centre.

Unfortunately, a roadblock was met at this point, as the landowner of the property used for GBR placement in 2022 refused to allow placement of the same platform in 2023. As the study was dependant on multiple snow-free seasons of GBR data-acquisition to achieve meaningful results, the study needed to be revised. At this point, the study was expanded to include four other monitored rockslides (Figure 59) in the region with long-term data records (2017-2025). Movements captured by InSAR corner reflectors (permanent structures installed on the rockslides, which give accurate InSAR measurements) allow us to compare seasonal trends across different sites (Figure 60). Annual displacement patterns vary for each site (Figure 60). In two cases, the slide accelerates in spring and decelerates in autumn. This is particularly prominent for one site, which shows extreme acceleration events after snowmelt in years where the winter snow mass has been greater than usual. In the other two cases, the rockslides have somewhat continuous movements throughout the year, seemingly not affected by seasonal changes in groundwater or temperature. These differences can be explained by the maturity of the slide: slides that are well-developed move as a cohesive mass throughout the year, while slides that are earlier on in their development show stronger seasonal patterns.

Figure 59 Two of the rockslides are considered in this study. Left panel: The Jettan rockslide, which poses a tsunami risk to villages on the Lyngen fjord. Right panel: The Gamanjunni-3 rockslide, which

poses a risk to settlements in the valley below. Right-hand image courtesy of the Geological Survey of Norway (NGU).

GBR data were also examined for the rockslide Gamanjunni-3, a high-risk rockslide and rock glacier system in a valley north of Seidi (Figure 59, right panel). The rockslide is considered high risk to life in the Norwegian early-warning system framework, as it is fast-moving and shows signs of active deformation, such as frequent small rockfall events and localised collapses of rocky material. The rockslide exhibits relatively consistent movement throughout the year. The analysis aimed to link small acceleration events to rainfall or temperature anomalies, as these are known to cause rockslide movements at other sites around the world. However, no conclusive link between rainfall/temperature and acceleration events at this site could be established. What is clear is that the rockslide has small acceleration events in early spring every year (<10 mm of total movement), while the rock glacier tends to move later in the season and decelerate in the autumn when temperatures fall below 0 °C again.
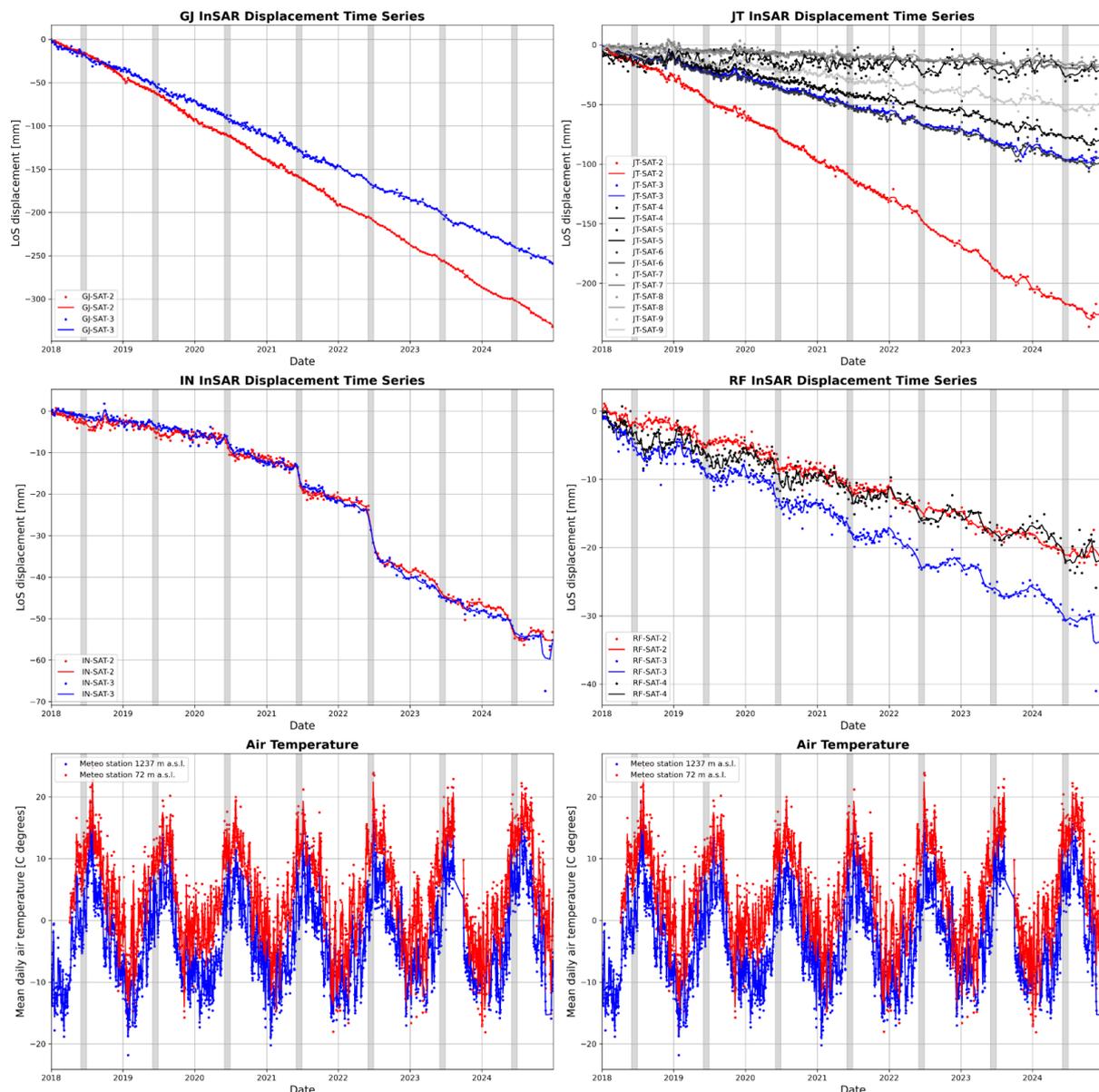
Figure 60. Results of the displacement and temperature series data for four rockslide sites in northern Norway, between 2018 and early 2025. The typical month of peak acceleration for rockslides following spring snowmelt is in June and highlighted in grey bars. Los is refering to mm displacement relativ to the satellite in the Line of Sight. Gamanjunni (GJ), Jettan (JT) the seasonal trend is small and for Inder Nordnes (IN) and Revdalsfjellet (RF) a clear seaonal acceleration can be seen following snowmelt. Red and Blue colors indicate satellite orbit orientation.

2.15.1.1 Slushflow/avalanche results

Slushflows are a type of rapid mass movement characterized by the sudden release and flow of snow and ice and may carry debris (Figure 61). To broaden the understanding and acceptance of slushflows as an important hazard type, the following actions have been undertaken:

- Interrogation of the national avalanche dataset to determine the quantity and quality of slushflow investigations;
- Development of a new slushflow classification system;
- Development of a methodology for site-specific forecasting for those areas at high exposure risk to slushflows;
- Development of a methodology for semi-automatic generation of regional hazard indication maps for slushflows.

Figure 61 A slushflow deposit blocking the main access route to northern Kvaløya (an island near Tromsø). This occurred during rainstorms in December 2024. Image courtesy of Kaia Krogh, Tromsø Fylkeskommune.

2.15.1.1.1 Interrogation of the national dataset

Slushflows are reported in the national mass movement database. There were 1051 unique slushflow events in Norway recorded in the database as of spring 2023 (with first recorded event from 1951). The quality varies based on user input, and each event is assigned a quality grade from A-D, with A being the best (known date, time and position of the slushflow) and D with little to no information. 701 of the registered slushflow events were tagged as quality D. There tends to be more events recorded in southern Norway compared to the north (Figure 62), likely due to the bias of inhabited areas. There are also more events recorded in coastal regions. This is probably because the coasts have a maritime climate, wetter than the continental and leading to more slush-triggering events. Most events are recorded within 0-25 m above sea level, indicating that the locations reported are not the release area of the event. Events are also recorded on low slope angles.
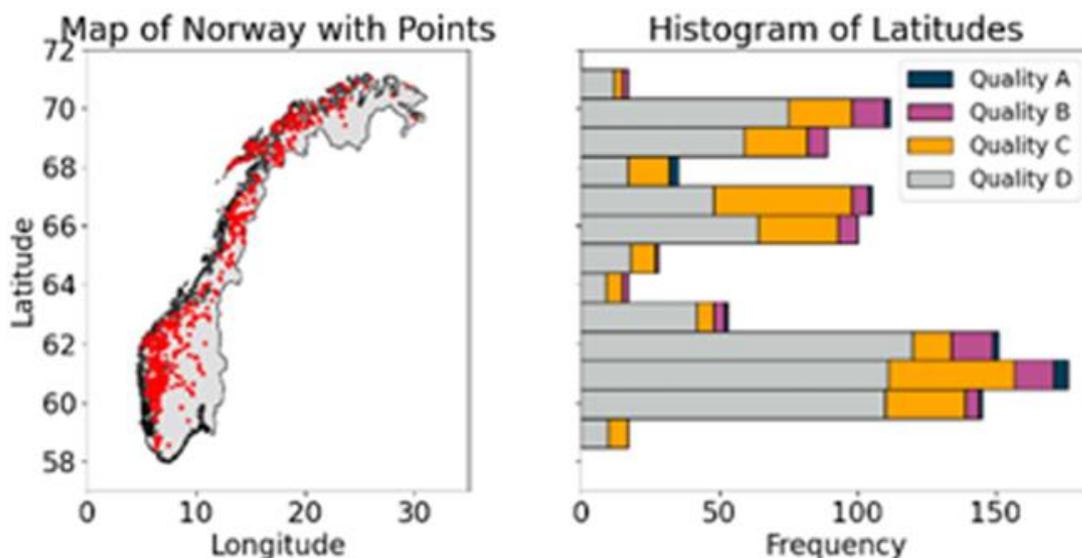
Figure 62 Registered slushflow events in the Norwegian national landslide/avalanche database. Left panel: location of 1051 recorded slushflow events. Right panel: Quality designation per latitudinal degree for each registered slushflow in the database.

Data quantity and quality are one of the major issues that slushflow research faces. Slushflow deposits are not always easy to recognise. The debris caused by a slushflow is often misclassified as from a debris flow or wet snow avalanche because they can be initiated by wet snow avalanches, which transition to a slushflow and/or could transition from a slushflow to a debris flow. There has not been a standardised method to record events in Norway. Different parties record events in different ways and at different locations. To advance research on slushflow formation the static variables that have a spatial relevance to slushflow formation (slope, elevation, curvature, hydraulic sinks, and uphill potential) must be analysed. Therefore, the most relevant data to accurately record slushflows is the release location and the location of the furthest runout.

Despite the issues with data quality from the database, these data can still be used to research some aspects of slushflow formation. The quality of the data has also been improving since 2017, almost half the events were quality levels A or B, of a sufficient quality to use for investigations on the dynamic variables that affect slushflow formation. However, currently there are only 90 events that meet these data quality standards, which is too few to use some sophisticated machine learning methods. Each year, there are about 10-20 quality events that are added to the database at a high-quality grade, and annually, some older events are upgraded to A and B grades. For temporal studies, more than 900 additional events with quality grades C and D could be potentially used.

2.15.1.1.2 Development of a new slushflow classification system

Slushflows have been well defined as a sub-category of mass flows classified by the composition of the mass. However, they have not been systematically broken down into sub-categories that describe the formation, type of movement, size, and quantity of entrained material. These sub-categories are needed because the types of slushflow, the terrain from which they initiate, and the triggering mechanism can differ greatly.

A classification system is proposed that includes traits from snow avalanche classification, such as size and release mechanisms, and builds on these to incorporate other unique traits such as water availability and indications of debris materials. Recent events meeting the scientific criteria for slushflow definition were examined to identify characteristics and apply the new classification system.

Three slushflows that occurred in 2023 show the diversity of behavior that slushflows can display. In the Norwegian database, two of the three of these events were registered as a slushflow, but all three of them meet the definition of slushflow put forward in the scientific literature. To increase the effectiveness of risk reduction measures, a robust classification system is needed to group similar

events, with set criteria for event description (Figure 63). The next steps to this work are to develop a classification system based on the composition, release type, water content, terrain, and size of slushflows.

Size: 1-5

Composition: snow, water, ice, rock, soil, vegetation

Amount of Liquid water: limited vs unlimited

Release type: surface vs subsurface

Terrain: Steep vs flat

Figure 63 The categories presented in the new classification system for slushflows.

2.15.1.1.3 Methodology for site-specific forecasting

A method was developed for assessing the slushflow potential at a given site, particularly for locations with increased exposure, such as road workers present for several hours or days during high slushflow seasons. The method involves a workflow or guideline for using drones to inspect the terrain and snowpack in the area surrounding those at risk. By using drones and answering the questions in the workflow, users can determine whether signs of imminent slushflow activity are developing.

2.15.1.1.4 Methodology for regional hazard indication mapping

A workflow and method were developed for mapping slushflow hazards across large spatial regions. To limit complexity and the potential hazard area, the analysis focused on a specific subset of slushflows, those initiated by overtopping waves of water bodies such as lakes or bogs. By replicating the runout of an observed event in Vestland County, Norway, it was demonstrated that the open-source model Flow-Py can adequately simulate the slushflow runout from an avalanche-impacted lake (Figure 64). This best-fit parameterization was projected across a large test region in southern Norway and Troms County to simulate runout from possible initiation points and produce a hazard indication map (Figure 65). The developed algorithm functions effectively for the simulation of large regions, in this case, a 100 × 100 km DEM tile, which was processed within minutes. While the parameterization study is limited to a single observed event, this work advances the method for slushflow hazard indication mapping, enabling future event records to refine the outputs and allowing application to a variety of different initiation conditions.
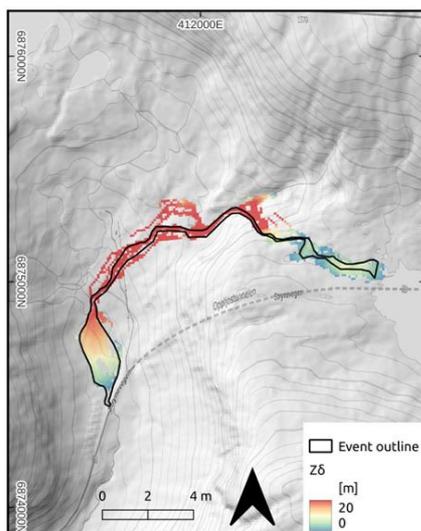

Figure 64 *Slushflow runout map. The black outline shows real slushflow runout as mapped by observers in the field. Coloured cells represent modelled output from Flow-Py. Results show a good*
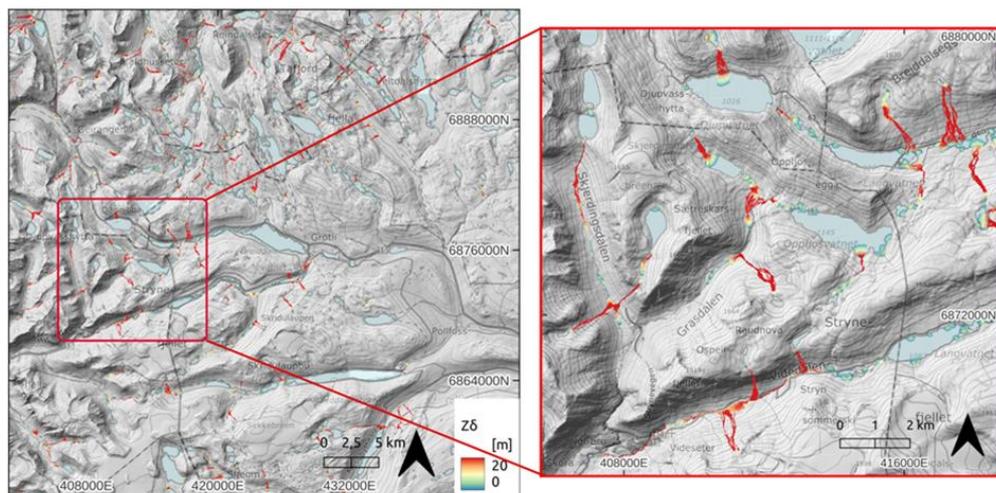
match between actual and modelled data.

Figure 65 A portion of the 100x100 km generated regional hazard indication map, which shows potential slushflow locations and runout areas.

2.15.2 Impact

2.15.2.1 Impact of landslide results

The objective of this work was to improve the early warning system for landslides triggered by unstable rock slopes in Norway by analysing the variability of slope movements and linking them to climatic and geological controls.

The results, to be published in two academic papers in 2025 and 2026, show mixed success. While no link could be established between intra-seasonal weather patterns and specific movement events, seasonal trends over years could be compared across different rockslide sites. This work was performed in collaboration with Geological Survey of Norway (NGU), who have responsibility for risk mapping of rockslides in Norway, and NVE, who manage the early warning system for rockslides. These stakeholders are aware of the results and the implementation of these results in their work going forward. The understanding of the seasonal trends at the four chosen rockslide sites, and that the patterns all differ, gives valuable information on the way in which each site responds to extreme climate variables (or in some cases, no response). This will allow a more focused approach to risk management in terms of risk prioritisation.

The work, which is unique in its data input type, has scalability potential to all monitored sites in Norway within the larger database. This would give a great amount of information in terms of climatic and geological controls on rockslides through comparison across many sites, vastly improving the understanding of this problem type and improving the risk management of them. This work is specific to slow-moving rockslides, which pose a tsunami or landslide impact risk to people in exposure areas. It may not be applied to other landslide types that have a more sudden onset, such as debris flows. To more broadly apply the workflow and methods, new monitoring systems for site-specific problems would need to be accessed.

2.15.2.2 Impact of slushflow results

The objective of this work was to broaden the understanding of slushflows and to improve forecasting and hazard zoning. These objectives were met through several unique activities:

- Slushflow data study to determine quality of records and gaps. This work can be seen in D'Amboise et al, 2023.
- Development of a new slushflow classification system. The need for this work was highlighted in the previous task, and it will be published in an academic journal in 2025-6. The work was presented at the National Geohazards Day in Norway and met with great interest. In addition, the motivation behind the work was published in D'Amboise et al, 2024. Uptake of the ideas has

- Methodology developed for site-specific forecasting for those at high exposure risk to slushflows. This workflow is done and will be published in a poster format and presented to stakeholders at the Norwegian snow and avalanche conference (Skredkonferansen) in Opdal, Norway (10.30.2025-11.2.2025).
- A methodology developed for semi-automatic generation of regional hazard indication maps for slushflows. This work, to be submitted for publication in 2025, will be the first of its kind to present a method for automatically generating regional hazard indication maps for slushflows. Co-authors include stakeholders (Norwegian geotechnical institute NGI) in national bodies (NVE) whose responsibility it is to generate official regional hazard maps. These maps so far do not exist, and our published methodology and algorithm will make significant headway into a system for the generation of such.

Through these four activities, the objectives set out have been successfully achieved. The safety of people from slushflows has been improved through the increased recognition of slushflows as a problem in the DS and actions being taken by NVE as a direct result of this work. Forecasting and hazard zoning for slushflows have also been enhanced, with specific results already integrated, and further results to be integrated, into national workflow systems. The scalability of this work is high, with the potential to improve slushflow hazard assessment and forecasting in all problem areas (mountainous and Arctic regions), such as the European Alps or the Himalaya. The proposed methodologies are widely adaptable to other settings and to other slushflow or mass movement types.

2.15.3 Lessons Learned

Rockslides in the DS region respond in different ways to climatic variables, and these can be determined by comparing seasonal displacement patterns across different sites. Most sites respond to groundwater input from snowmelt, but this is dependent on their geological maturity. With increasing precipitation and intensity in the DS predicted from climate change, the sites most responsive to groundwater changes will need to be prioritized for risk management.

Slushflows are a poorly understood and documented mass movement type. The importance of slushflows in the DS has been highlighted through this work, and new systems for forecasting and hazard mapping have been proposed. Close collaboration with stakeholders has resulted in work output that has been and will be directly used in national systems operated by the NVE.

In particular, the landslide work faced acquisition challenges when the landowner of the established GBR installation site revoked permission for land use. This was overcome by adapting the study site and data type. Fortunately, the main stakeholders of the work, NVE, granted access to other data sources. Although thorough planning was conducted in the early stages of the project, the importance of securing landowner permission for multiple consecutive years was overlooked, with the focus placed only on permission for the current season.
Future projects of similar type should include thorough forward planning in terms of data acquisition for the duration of the project.

In both the landslide and slushflow work, there is potential for adaptation to a wider range of settings and other mass movement types. Hazard and risk assessments will benefit from the results of this work; however, the presented workflows are specific to the mass movement types, geological characteristics, regional context, and climate setting of the study area. If results are to be upscaled to larger regions, particularly in different climatic settings, caution must be exercised to ensure the success of future studies.

2.15.4 Conclusion

Early warning and forecasting systems for two important mass movement types in the DS, rockslides and slushflows, have been improved through analysis of long-term monitoring data and through publications and reports on new systems and methodologies established during the project. The impact has been significant, with both the recognition of these problems increasing in the DS and the direct

uptake of results by the stakeholders responsible for forecasting in the region. The project demonstrated that thorough planning leads to the most successful field-based outcomes and that close cooperation with stakeholders is the most effective way to ensure results are relevant, impactful, and useful.

3 Conclusions

Bundle 2 brings together a diverse set of technologies implemented under very different climatic, hydrological and socio-economic conditions across the seven IMPETUS demo sites. Despite these differences, the solutions share common ambitions: strengthening regional resilience, improving the evidence base for adaptation, and providing practical tools that help authorities, utilities and local actors navigate climate-related pressures. Across the 15 tasks, several themes emerge clearly.

First, the bundle has demonstrated that decentralised and flexible water solutions can substantially increase local water availability and reduce dependence on conventional freshwater sources. The hybrid decentralised reuse system (Task 4.5.1) and the Sewer Mining unit (Task 4.5.2) both showed that meaningful volumes of reclaimed water can be produced reliably even under highly variable loads. These pilots also revealed the central role of operational simplicity, regulatory clarity and stakeholder acceptance in scaling such systems. They highlight the need for targeted communication, streamlined permitting and incentive structures that support decentralised water reuse in water-scarce regions.

Second, the modelling solutions developed within the bundle have strengthened the analytical foundation for climate-resilient water management. Sediment transport modelling (Task 4.6), the interactive regional water-balance tool (Task 4.7.1), the WEFE nexus DSS (Task 4.7.2), and the Water–Energy Simulation Model (Task 4.5.3) all confirm that regions benefit substantially when complex data can be translated into accessible, decision-ready information. These tools have helped identify future stress points, test adaptation measures and anticipate the consequences of climate scenarios. A recurring lesson is the importance of early stakeholder engagement: models become far more relevant when they incorporate the insights and needs of local planners, utilities and impacted communities.

Third, the bundle illustrates how digitalisation can enhance climate adaptation when tools are designed to integrate data from multiple sectors. The Attica Digital Twin (Task 4.10.4), the flood and heat awareness DSS tools (Tasks 4.10.1 and 4.10.2), and the integrated flood risk and early-warning system (Task 4.10.3) demonstrate the added value of interoperability and open standards. These solutions create new opportunities for cross-department coordination, more transparent communication of risks and better integration of climate considerations into land-use, water, infrastructure and emergency planning. Their modular design also enables future expansion and alignment with regional and national digital infrastructures.

Fourth, the solutions focusing on water quality, bathing water safety and pathogen risks highlight how climate change affects public health. The assessment of stormwater impacts on bathing water (Task 4.8.1) and the pathogen-risk analyses for drinking water (Task 4.8.2) show that extreme events can create short, intense periods of heightened vulnerability. These tasks underscore the need for more responsive monitoring approaches and for utilities to incorporate climate-linked health risks into planning and investment strategies.

Across the tasks, several lessons recur. Stakeholder involvement is essential, not only for co-design but also for long-term uptake. Many solutions, particularly those involving modelling and digital platforms (Tasks 4.7.1, 4.7.2, 4.10.1-4.10.4), highlight that early and continuous engagement with municipalities, utilities, civil protection agencies, and end users improves relevance, usability, and acceptance. Another cross-cutting lesson is the importance of data availability and quality. Whether for modelling, digital twins, or pathogen assessments (Tasks 4.5.3, 4.7.1-4.7.2, 4.10.1-4.10.4, 4.8.2), regional datasets often require harmonisation and updating before tools can reach their full potential. Finally, many tasks underline that regulatory clarity is key: decentralised reuse solutions (Tasks 4.5.1 and 4.5.2), digital

governance tools (4.10.4), and early-warning technologies (Tasks 4.10.3 and 4.12) all depend on supportive institutional and administrative frameworks.

In terms of overall impact, Bundle 2 contributes substantially to regional climate resilience across Europe. It offers tested and replicable solutions that support drought management (4.5.1, 4.5.2), water reuse (4.5.1, 4.5.2), flood and heat risk reduction (4.10.1-4.10.3), early warning for geological hazards (4.12), ecosystem conservation (4.9), and digital climate governance (4.10.4). Many of the solutions provide direct operational benefits to the demo sites, while others generate transferable knowledge that can inform regional or national adaptation strategies. The collective output demonstrates that technological innovation, when designed with end users and embedded in regional workflows, can strengthen both short-term preparedness and long-term planning capacity.

The bundle also interacted closely with other Work Packages throughout the project. Several modelling and digital tools, particularly the water-balance model (4.7.1), the WEFE DSS (4.7.2), and the Digital Twin and DSS developments (4.10.1-4.10.4), provided scenario outputs, indicators, and visualisations that fed directly into WP2's Resilience Knowledge Boosters, supporting regional dialogue and decision processes. Tools such as the Sewer Mining system (4.5.2) and the Water-Energy Simulation Model (4.5.3) contributed to WP1 by engaging local stakeholders, informing co-creation activities, and supporting the participatory elements of the demo site work. A substantial number of tasks played a role in WP5, where their spatial data, risk layers, and scenario analyses informed adaptation pathways and governance discussions; these include tasks (4.5.2, 4.5.3, 4.7.1, 4.7.2, 4.10.1-4.10.4). In addition, several outputs, such as the modelling frameworks and the decentralised water solutions (4.5.1, 4.5.2, 4.5.3), also informed WP6, where scaling and transferability across European regions were assessed. Together, these links ensured that the technological work in Bundle 2 contributed not only to WP4's objectives but also to the wider strategic and cross-regional ambitions of IMPETUS.

The following table (Table 8) summarises the individual impacts, scalability potential, and transferability of each solution in Bundle 2, bringing together the key insights from all tasks and offering a consolidated overview of their contribution to climate resilience across the IMPETUS regions.

Table 8: General overview of the impact, transferability, and scalability of the tasks.

Task	Impact	Transferability	Scalability
4.5.1 Decentralized hybrid fit-for-use water reclamation systems for increasing water availability	• 20% increase in water availability through compliant reclaimed water production. • Reduced dependence on conventional water sources in touristic and coastal areas. • Environmental and economic benefits for tourism infrastructures (reuse, self-sufficiency).	• Transferability depends on local regulations and treatment requirements. • Adoption requires simplified permits, incentives, and stakeholder awareness. • Wider use constrained by technical, social, regulatory, and spatial barriers.	• Modular design supports scaling to small or large applications. • System performs robustly under seasonal load variations. • Scaling requires supportive regulation, standardized monitoring, and training.
4.5.2 Sewer Mining for multi-sector climate proofing	• Provides autonomous, decentralised resource recovery in water-scarce cities. • Reduces pressure on wastewater systems and saves potable water. • Supports climate proofing by converting wastewater into a reliable local supply.	• Transferable as a compact, small-footprint technology for dense urban areas. • Requires early stakeholder engagement to build acceptance. • Transfer depends on navigating time-consuming permit procedures.	• Technology is flexible, expandable, and scalable for wider urban use. • PV integration enables scalable reductions in grid dependency. • Scalability affected by space-cost trade-offs for PV and other components.
4.5.3 Water-Energy simulation and optimisation model for wastewater systems	• Quantifies system resilience under multiple climate and population scenarios. • Supports long-term energy optimisation in wastewater operations • Enhances circular economy planning by assessing reuse options (e.g., sewer mining).	• Transferable to regions needing scenario-based wastewater planning. • Applicable where climate-proof operational decision-making is required. • Useful for areas planning integrated water-energy optimisation.	• Scalable through integration with the regional Digital Twin and Master Plan. • Model structure supports expansion to larger or more complex wastewater systems. • Simulation framework enables scalable evaluation of multiple future scenarios.

Task	Impact	Transferability	Scalability
4.6 Sediment transport through irrigation networks	• Improves understanding of sediment transport in irrigation canals. • Supports optimisation of water distribution and irrigation efficiency. • Helps reduce maintenance needs through better sediment management.	• Applicable to other regions with open-channel irrigation networks. • Transferable where sediment-induced inefficiencies are a key issue. • Useful for irrigation districts across similar hydraulic contexts.	• Model-based approach enables scaling across larger canal systems. • Scalable to varied sediment loads and flow conditions. • Can be extended to broader irrigation management strategies.
4.7.1 Interactive multi-agent regional water balance model	• Improves understanding of regional water availability under climate change. • Supports decision-making through scenario exploration and visualisation. • Facilitates stakeholder engagement by simplifying complex water dynamics.	• Applicable to regions needing integrated regional water balance analysis. • Transferable where stakeholder-oriented modelling is required. • Useful for territories facing climate-driven water stress.	• Scalable to larger areas via modular model design. • Model can integrate additional agents and variables over time. • Scales with data availability for more detailed regional simulations.
4.7.2 Decision Support System integrating multiple information layers for the sustainable and integrated management of regional water resources	• Converts complex climate data into clear, accessible information, helping stakeholders communicate more easily with non-experts. • Offers locally validated insights that align with stakeholder climate goals and can also be applied to other climate risks beyond water management. • Improves planning for vulnerable populations by highlighting high-risk areas and enabling more inclusive adaptation measures.	• Can be adopted widely, as the DSS and its underlying software are already used in multiple European cities. • Works in diverse regions, provided that essential local datasets (e.g., elevation, built environment) are available. • Benefits from early involvement of local stakeholders, which increases usability and real-world uptake.	• Expands easily to larger regions or new climate indicators, thanks to its flexible framework. • Grows with new data inputs, allowing users to incorporate local datasets or run additional scenarios as needed. • Evolves over time, as ongoing testing and user feedback continuously improve the DSS.

Task	Impact	Transferability	Scalability
4.8.1 Bathing water quality management under stormwater impacts	• Improves understanding of storm-driven contamination, helping operators anticipate high-risk periods. • Supports more targeted monitoring, enabling quicker identification of water quality issues. • Strengthens public health protection by highlighting conditions linked to contamination spikes.	• Fits other bathing sites that face stormwater-driven quality declines. • Can be applied where rainfall-contamination relationships are similar. • Works in regions aiming to refine bathing water alerts.	• Scales to broader monitoring networks, given its reliance on standard indicators. • Adaptable to additional sites with comparable data. • Expandable as more rainfall or quality datasets become available.
4.8.2 Pathogen monitoring and drinking water resilience under extreme events	• Clarifies how extreme weather affects pathogen presence, improving risk awareness. • Helps water managers understand vulnerability, especially under heavy rainfall or snowmelt. • Contributes to safer drinking water strategies by identifying climate-sensitive risk periods.	• Applies to other regions where climate events influence pathogen risks. • Useful for any utilities aiming to anticipate climate-related contamination threats. • Adaptable wherever rainfall, temperature, and quality data are available.	• Expandable to more sites as utilities adopt climate-related monitoring. • Scales with additional indicators, allowing broader pathogen assessments. • Grows naturally with improved event-based datasets.
4.9 Assessing changes in the spatial distribution of species under global change scenarios	• Highlights how climate change may shift species distributions, revealing potential contraction or expansion zones. • Identifies species at higher extinction or decline risk, supporting conservation priorities. • Links projected shifts to concrete adaptation needs, including NbS to strengthen ecosystem resilience.	• Applicable in other regions with sufficient ecological and climate data. • Useful for areas facing similar coastal or wetland pressures • Adapts easily to new taxa where monitoring datasets are available.	• Scales to larger species groups thanks to its modelling framework. • Supports expansion to wider regions when climate projections are accessible. • Can integrate more scenarios for deeper long-term assessments.
4.10.1 Heat Awareness System	• Builds a clearer picture of local heat-stress hotspots, supporting targeted adaptation.	• Applicable to other regions needing heat-risk mapping with local datasets.	• Scales to national or regional levels thanks to its flexible data framework.

Task	Impact	Transferability	Scalability
	• Improves stakeholder understanding of heat risks by aligning technical indicators with local needs. • Strengthens decision-making through accessible, high-resolution heat maps and tools.	• Useful in areas where participatory approaches guide indicator selection. • Adapts well to different climate risks beyond heat stress.	• Easily extended with new indicators or additional datasets. • Grows with cloud-based infrastructure, enabling larger analyses over time.
4.10.2 Decision Support System for Flood Risk Management	• Reveals local flood hotspots, helping authorities target adaptation actions. • Improves understanding of urban flood dynamics through high-resolution modelling. • Supports climate-proof planning by combining hydrodynamic results with 3D visualisation.	• Applicable to other cities with detailed elevation and land-use data. • Relevant where urban flooding is increasing due to climate change. • Can be adapted to different hydrodynamic models if local tools exist.	• Scales well to larger areas when computational resources allow. • Supports additional scenarios as more climate data becomes available. • Expandable to more detailed 3D environments when local mapping improves.
4.10.3 Integrated Flood Risk Management & Early Warning System	• Combines multiple technologies to give a fuller picture of flood risks. • Strengthens early-warning capacities by integrating forecasting and visualisation. • Improves coordination between emergency services and planners.	• Usable in other regions that rely on multi-source flood information. • Adaptable to different warning protocols, provided data feeds exist. • Works where authorities seek to modernise civil-protection tools.	• Scales with additional data streams, enabling richer situational awareness. • Expandable across jurisdictions, supporting regional-level flood management. • Flexible enough to incorporate new risk modules over time.
4.10.4 Regional Digital Twin for climate adaptation and green business development	• Creates an integrated view of climate risks, combining many regional datasets. • Improves regional decision-making through interactive maps and analytics.	• Adaptable to other regions that can supply similar data layers. • Useful for administrations modernising their digital governance tools. • Can be replicated where open-data policies support integration.	• Scales to national-level datasets when broader coverage is required. • Supports additional sectors as new modules are added. • Grows with new sensing and monitoring technologies.

Task	Impact	Transferability	Scalability
	• Supports investment and planning by highlighting opportunities for climate-resilient development.		
4.11 Climate proofing of the city centre and urban water infrastructure against sea level rise	• Shows how sea-level rise will affect key urban areas, informing local planning. • Raises public awareness through accessible VR visualisations. • Supports adaptation decisions by illustrating future flooding scenarios.	• Applicable to coastal cities facing sea-level rise. • Works where VR is suitable for communicating climate risks. • Can be used by planners and schools to raise awareness.	• Scales to larger urban areas, given enough elevation and flooding data. • Allows the inclusion of more scenarios as projections evolve. • Expandable to additional VR environments for wider audiences.
4.12 Early-warning systems for geological and avalanche risk sites	• Clarifies how climate change affects slushflow and rockslide behaviour, improving situational awareness. • Provides high-resolution monitoring, enabling early detection of hazardous movements. • Strengthens risk mitigation by combining field data with modelling.	• Relevant for other mountainous regions with similar hazards. • Adaptable where satellite and ground-based monitoring exist. • Useful for civil-protection agencies seeking climate-aware early warning.	• Scales to additional slopes if monitoring infrastructure is extended. • Expandable to regional hazard maps, combining many sites. • Integrates further climate scenarios as new data becomes available.

4 Outlook and Recommendations

The solutions implemented in Bundle 2 show how diverse technological approaches, from decentralised reuse systems to advanced modelling, digital twins, and early-warning tools, can support regional climate resilience in very different contexts. Across the tasks, a few clear patterns emerge: the need for reliable data, close cooperation with authorities and end-users, attention to system complexity, and the importance of embedding tools into existing planning and operational workflows. The lessons documented in D4.3 point toward several practical recommendations for future development, adaptation planning, and scaling.

Technical Recommendations

1. Improve data availability and interoperability: Many tasks highlight challenges related to fragmented, incompatible, or sparse datasets, whether in biodiversity modelling (4.9), pathogen risk assessment (4.8.2), hydrological modelling (4.7.1), or digital twin integration (4.10.4). Ensuring long-term data access and compatibility through standard formats, harmonised sources, and clear data stewardship will be essential for strengthening model performance and allowing different tools to interact effectively.

2. Enhance monitoring networks and sensor infrastructure: Sensor-based tasks, such as drinking-water pathogen assessment (4.8.2) and flood/early-warning systems (4.10.2–4.10.3), show that consistent and spatially distributed monitoring is central to reliable risk assessment. Some partners note that systematic installation and maintenance of sensors and hydrological monitoring networks would substantially increase tool accuracy and long-term usefulness.

3. Prioritise modular, adaptable tool design: The digital twin (4.10.4), WEFE DSS (4.7.2), and flood DSS (4.10.2) all demonstrate the value of modular architecture: it allows tools to be adjusted to different regulatory and environmental settings and supports scaling to other regions. Building light, configurable modules can make future deployments more efficient and reduce the technical barrier for new users.

4. Strengthen empirical foundations and contextual adaptation: Several tools, such as the bathing water analysis (4.8.1) and heat stress DSS (4.10.1), depend on local empirical relationships. Future versions should incorporate validation in multiple contexts and refine indicators to ensure their relevance under different climatic and socio-environmental conditions.

Operational Recommendations

1. Integrate tools into routine governance and decision-making: Tasks such as the Berlin water-balance model (4.7.1) and East Attica Water–Energy Simulation Model (4.5.3) show how effective solutions become when they align with existing planning processes. Embedding modelling and DSS tools into standard procedures, rather than treating them as stand-alone pilots, will improve uptake and sustainability.

2. Plan for long-term maintenance and operational simplicity: Across decentralised reuse systems (4.5.1, 4.5.2) and early-warning technologies (4.10.3, 4.12), operational sustainability hinges on manageable maintenance requirements and user-friendly control procedures. Ensuring that technical setups remain simple, well-documented, and supported by clear responsibilities will help avoid downtime and ensure reliable operation.

3. Address uncertainties transparently and define responsibilities: Hydrological and modelling tasks emphasise the challenge of communicating uncertainty to planners and the need for legal clarity on how model outputs feed into decisions (4.7.1). Developing guidelines for interpreting uncertainties and assigning responsibility for decisions informed by model outputs will help authorities use tools with confidence.

4. Strengthen administrative capacity for participation in EU projects: Some tasks report that local administrations face administrative burdens and limited staff availability, which slowed cooperation (4.7.1). Future initiatives should consider creating dedicated support roles or coordination units inside authorities to streamline participation and reduce bottlenecks.

Collaboration & Partnership Recommendations

1. Engage stakeholders early and continuously: Almost every task emphasises this point. Whether it is municipalities using the heat DSS (4.10.1), utility companies co-developing water models (4.7.1), or civil protection agencies testing flood early-warning systems (4.10.3), early involvement improves data quality, makes outputs more relevant, and increases long-term adoption.

2. Improve communication workflows between developers, domain experts, and authorities: Several tasks underline that coordination structures and communication workflows took longer to establish than expected (4.7.1, 4.10.4). Once established, they worked well, but future projects should allocate time early on to set up these communication channels and clarify expectations.

3. Support shared learning across demo sites and work packages: D4.3 shows multiple examples of tools feeding into WP2 (RKB), WP1 (co-creation), WP5 (pathways) and WP6 (boosting impact). Continued cross-WP exchange on data needs, modelling practices, or DSS integration will help ensure that solutions benefit more regions and become more robust.

4. Clarify data ownership and interoperability protocols early: Digital twin developers stress the importance of establishing clear rules for data sharing, privacy, and interoperability from the outset (4.10.4). These frameworks are essential for smooth collaboration and for extending the platform to other sectors or regions.

Outlook

The technologies demonstrated in D4.3 offer a solid foundation for long-term climate adaptation. Many solutions are already in operational use and have strong interest from regional authorities, utilities, and civil protection agencies. Future progress will depend on strengthening data pipelines, deepening stakeholder involvement, and ensuring that digital tools and models are integrated into the daily routines of regional administrations.

The lessons documented in the Report point clearly toward a next phase: moving from demonstration to wider rollout, supported by robust monitoring, clear governance frameworks, and continued collaboration across sectors. If these recommendations are carried forward, the solutions developed in Bundle 2 can continue to evolve and provide lasting value to regions facing increasingly complex climate challenges.

5 Literature

3Di Water Management. (2025). 3Di hydrodynamic simulation software for water management. Nelen & Schuurmans. https://3diwatermanagement.com/

Abuzir, S., Gren, L., Domini, M., Bertanza, G., Davidsson, Å., & Kjerstadius, H. (2025). Performance of a full-scale anaerobic UASB digester treating blackwater from an urban city district in Helsingborg, Sweden. Cleaner Water, 4, 100082.

Addison-Atkinson, W., Chen, A. S., Memon, F. A., & Chang, T.-J. (2022). Modelling urban sewer flooding and quantitative microbial risk assessment: A critical review. Journal of Flood Risk Management, 15(4), e12844.

Beniston, M., & Stoffel, M. (2014). Assessing the impacts of climatic change on mountain water resources. Science of the Total Environment, 493, 1129–1137. https://doi.org/10.1016/j.scitotenv.2013.11.122

Borja, R., Sánchez, E., & Weiland, P. (1996). Influence of ammonia concentration on thermophilic anaerobic digestion of cattle manure in upflow anaerobic sludge blanket (UASB) reactors. Process Biochemistry, 31(5).

Campos, I., et al. (2016). Participation, scenarios and pathways in long-term planning for climate change adaptation. Planning Theory & Practice, 17(4), 537–556. Routledge.

Ciccarelli, D. (2014). Mediterranean coastal sand dune vegetation: Influence of natural and anthropogenic factors. Environmental Management, 54, 194–204. https://doi.org/10.1007/s00267-014-0290-2

Cissé, G., McLeman, R., Adams, H., Aldunce, P., Bowen, K., Campbell-Lendrum, D., Clayton, S., Ebi, K. L., Hess, J., & Huang, C. (2022). Health, wellbeing, and the changing structure of communities.

Climate Effect Atlas. (2025). *Climate Effect Atlas Netherlands.* Netherlands Environmental Assessment Agency (PBL), Deltares, Rijkswaterstaat & Wageningen University. https://www.klimaateffectatlas.nl/en

Climate-ADAPT. (2025). *Coupling high-resolution flood modelling – Mission Story 34.* European Environment Agency (EEA). https://climate-adapt.eea.europa.eu/en/mission/solutions/mission-stories/coupling-high-resolution-flood-modelling-story34

D'Amboise, C. J. L., Hansen, V. E., Hendrikx, J., & Vick, L. M. (2023). Motivation and the initial steps for a data science investigation on slushflows in Northern Norway. Proceedings of the International Snow Science Workshop, Bend, Oregon, USA.

D'Amboise, C. J. L., Edvardsen Hansen, V. E., & Vick, L. M. (2024). Motivation for slushflow classification. Proceedings of the International Snow Science Workshop (ISSW).

Dembski, F., et al. (2020). Urban digital twins for smart cities and citizens: The case study of Herrenberg, Germany. Sustainability, 12, 2307.

De la Cruz, A., & Numa, C. (2024). Habitat availability decline for waterbirds in a sensitive wetland: Climate change impact on the Ebro Delta. Ecological Modelling, 498, 110896. https://doi.org/10.1016/j.ecolmodel.2024.110896.

Delta Commissioner. (2024). Delta Programme 2025: Towards a new balance in the living environment – Room to live with water – Outlines. Ministry of Infrastructure and Water Management. https://english.deltaprogramma.nl/documents/publications/2024/09/17/dp-2025-outlines

Drogkoula, M., Kokkinos, K., & Samaras, N. (2023). A comprehensive survey of machine learning methodologies with emphasis in water resources management. Applied Sciences, 13(22), 12147. https://doi.org/10.3390/app132212147

European Commission. (2024). Flood resilience strategies and solutions for a safer future – Event organised by MIP4Adapt. https://futurium.ec.europa.eu/en/eu-mission-adaptation-community/events/flood-resilience-strategies-and-solutions-safer-future-event-organised-mip4adapt

European Commission & Covenant of Mayors. (2024, June 18). Joint event with REACHOUT: Heatwave risk. https://eu-mayors.ec.europa.eu/en/Joint-Event-with-REACHOUT-Heatwave-risk

European Environment Agency (EEA). (2025). Coupling high-resolution flood modelling – Mission story 34. https://climate-adapt.eea.europa.eu/en/mission/solutions/mission-stories/coupling-high-resolution-flood-modelling-story34

Federigi, I., et al. (2019). The application of quantitative microbial risk assessment to natural recreational waters: A review. Marine Pollution Bulletin, 144, 334–350.

Filatova, D., Picardo, M., Núñez, O., & Farré, M. (2020). Analysis, levels and seasonal variation of cyanotoxins in freshwater ecosystems. Trends in Environmental Analytical Chemistry, 26, e00091.

Fortier, C., & Mailhot, A. (2014). Climate change impact on combined sewer overflows. Journal of Water Resources Planning and Management, 141, 04014073. https://doi.org/10.1061/(ASCE)WR.1943-5452.0000468

Futurium. (2025, May 21). Flood resilience strategies and solutions for a safer future (event organised by MIP4Adapt). European Commission. https://futurium.ec.europa.eu/en/eu-mission-adaptation-community/events/flood-resilience-strategies-and-solutions-safer-future-event-organised-mip4adapt

Gao, M., Zhang, L., & Liu, Y. (2020). High-loading food waste and blackwater anaerobic co-digestion: Maximizing bioenergy recovery. Chemical Engineering Journal, 394, 124911.

Generalitat de Catalunya. (2025, July 9). Un estudi del Servei Meteorològic de Catalunya (Meteocat) confirma que les sequeres han empitjorat els darrers anys. https://govern.cat/salapremsa/notes-premsa/724822

Giorgi, F., Raffaele, F., & Coppola, E. (2019). The response of precipitation characteristics to global warming from climate projections. Earth System Dynamics, 10, 73–89. https://doi.org/10.5194/esd-10-73-2019

Government of Catalonia & Institute of Catalan Studies. (2017). Climate change in Catalonia: Executive summary of the Third Report on Climate Change in Catalonia. Barcelona: Government of Catalonia and Institute of Catalan Studies. Available at https://cads.gencat.cat

Government of the Netherlands. (2024). Delta Programme 2025: Outlines. Ministry of Infrastructure and Water Management. https://english.deltaprogramma.nl/documents/publications/2024/09/17/dp-2025-outlines

Healy, R. W. (2010). Estimating groundwater recharge. Cambridge University Press.

Healy, R. W., & Cook, P. G. (2002). Using groundwater levels to estimate recharge. Hydrogeology Journal, 10(1), 91–109.

Hestnes, E., & Jaedicke, C. (2018). Global warming reduces the consequences of snow-related hazards. Proceedings of the International Snow Science Workshop (ISSW), Austria.

Karakurt, S., Schmid, L., Hübner, U., & Drewes, J. E. (2019). Dynamics of wastewater effluent contributions in streams and impacts on drinking-water supply via riverbank filtration in Germany – A national reconnaissance. Environmental Science & Technology, 53(11), 6154–6161.

Koopmans, S., Heusinkveld, B. G., & Steeneveld, G. J. (2020). A standardized Physical Equivalent Temperature urban heat map at 1-m spatial resolution to facilitate climate stress tests in the Netherlands. Building and Environment, 181, Article 106984. https://doi.org/10.1016/j.buildenv.2020.106984

Koopmans, S., Heusinkveld, B. G., & Steeneveld, G. J. (2020). A standardized physical equivalent temperature urban heat map at 1 m spatial resolution to facilitate climate stress tests in the Netherlands. Building and Environment, 181, 106984. https://doi.org/10.1016/j.buildenv.2020.106984

Kossieris, P., Tsoukalas, I., Makropoulos, C., & Savic, D. (2019). Simulating marginal and dependence behaviour of water demand processes at any fine time scale. Water, 11(5), 885. https://doi.org/10.3390/w11050885

Kuipers, W. (2024). VR in risk communication [Master's thesis, UiT The Arctic University of Norway].

Lawrence, J., et al. (2018). National guidance for adapting to coastal hazards and sea-level rise: Anticipation change, when and how to change pathway. Environmental Science & Policy, 82, 100–107.

Lehmann, J., Coumou, D., & Frieler, K. (2015). Increased record-breaking precipitation events under global warming. Climatic Change, 132, 501–515.

Lizard. (2025). Lizard geospatial platform for water and climate data. Nelen & Schuurmans. https://lizard.net/

Meijers, M. H. C., et al. (2023). Experiencing climate change virtually: The effects of virtual reality on climate-change-related cognitions, emotions, and behavior. Environmental Communication, 17(6), 581–601. Routledge.

Metzger, M. J., et al. (2021). The flexibility gamble: Challenges for mainstreaming flexible approaches to climate-change adaptation. Journal of Environmental Policy & Planning. Routledge.

Nochta, T., et al. (2021). A socio-technical perspective on urban analytics: The case of city-scale digital twins. Journal of Urban Technology, 28(1-2), 263–287.

Open Geospatial Consortium (OGC) (2025). OGC – Advancing geospatial standards. https://www.ogc.org/

Pestana, C. J., Hui, J., Camacho-Muñoz, D., Edwards, C., Robertson, P. K. J., Irvine, J. T. S., & Lawton, L. A. (2023). Solar-driven semiconductor photocatalytic water treatment (TiO_2, g-C_3N_4, and TiO_2 + g-C_3N_4) of cyanotoxins: Proof-of-concept study with microcystin-LR. Chemosphere, 310, 136828.

Percheron, G., Bernet, N., & Moletta, R. (1997). Start-up of anaerobic digestion of sulfate wastewater. Bioresource Technology, 61(1).

Pintó, J., Garcia-Lozano, C., & Varga, D. (2023). Using dune-restricted species to assess the degree of natural diversity of dune systems on Mediterranean tourist coasts. Ecological Indicators, 147, 110004.

Pintó, J., Panareda, J. M., & Martí, C. (2012). Fitogeografía de las dunas de la costa catalana. VII Congreso Español de Biogeografía, 132–138.

Rijkswaterstaat. (2025). The Delta Works. Ministry of Infrastructure and Water Management. Government of the Netherlands. https://www.rijkswaterstaat.nl/water/waterbeheer/bescherming-tegen-het-water/waterkeringen/deltawerken

Rød, J. K., et al. (2024). Troms: Klimasårbarhetsanalyse for kommunene i Troms. Troms Fylkeskommune.

SDSN Europe (2024): Sustainable Development Solutions Network (SDSN) Europe. IMPETUS Climate Solutions Forum (2024, April 25): Turning research into impact for a resilient future. https://sdsn.eu/event/impetus-climate-solutions-forum-turning-research-into-impact-for-a-resilient-future/

SenUMVK. (2022). Masterplan Wasser Berlin – 1. Bericht. Senatsverwaltung für Umwelt, Mobilität, Verbraucher- und Klimaschutz, 30 September 2022, 115 pp.

Senadheera, U. E., Abeykoon, A. D., Sewmini, P. M., Weerasekara, W. R., Darshani, N. P., Jayasanka, J., … Jayawardena, T. U. (2025). Up-flow anaerobic sludge bed reactors for sustainable wastewater management: Challenges, innovations, and future directions. Water, 15, 476.

Shen, Q., Zhu, J., Cheng, L., Zhang, J., Zhang, Z., & Xu, X. (2011). Enhanced algae removal by drinking-water treatment of chlorination coupled with coagulation. Desalination, 273, 236–240.

Smith, S. K., Tayman, J., & Swanson, D. A. (2002). State and local population projections: Methodology and analysis. New York: Kluwer Academic/Plenum Publishers.

Sustainable Development Solutions Network (SDSN). (2025). Impetus climate solutions forum – Turning research into impact for a resilient future. https://sdsn.eu/event/impetus-climate-solutions-forum-turning-research-into-impact-for-a-resilient-future/

Tranquillini, P., Beozzo, W., Cestari, P., Dall'Amico, M., Tasin, S., Trenti, A., & Cappelletti, S. (2019). Analisi storica del parametro SWE in Trentino. Neve e Valanghe, 93. AINEVA. https://www.aineva.it/wp-content/uploads/2019/12/NV93_2b.pdf

Tsoukalas, I., Efstratiadis, A., & Makropoulos, C. (2018). Stochastic periodic autoregressive to anything (SPARTA): Modeling and simulation of cyclostationary processes with arbitrary marginal distributions. Water Resources Research, 54(1), 161–185. https://doi.org/10.1002/2017wr021394

Tsoukalas, I., Efstratiadis, A., & Makropoulos, C. (2019). Building a puzzle to solve a riddle: A multi-scale disaggregation approach for multivariate stochastic processes with any marginal distribution and correlation structure. Journal of Hydrology, 575, 354–380. https://doi.org/10.1016/j.jhydrol.2019.05.017

Tsoukalas, I., Kossieris, P., & Makropoulos, C. (2020). Simulation of non-Gaussian correlated random variables, stochastic processes and random fields: Introducing the anySim R-package for environmental applications and beyond. Water, 12(6), 1645. https://doi.org/10.3390/w12061645

Van Rijn, L. C. (1993). Principles of sediment transport in rivers, estuaries and coastal areas. Aqua Publications, Amsterdam.

Viviroli, D., Archer, D. R., Buytaert, W., Fowler, H. J., Greenwood, G. B., Hamlet, A. F., … Lorentz, S. (2011). Climate change and mountain water resources: Overview and recommendations for research, management and policy. Hydrology and Earth System Sciences, 15(2), 471–504. https://doi.org/10.5194/hess-15-471-2011

Xiao, X., Peng, Y., Zhang, W., Yang, X., Zhang, Z., Ren, B., Zu, G., & Zhou, S. (2024). Current status and prospects of algal bloom early warning technologies: A review. Journal of Environmental Management, 349, 119510.
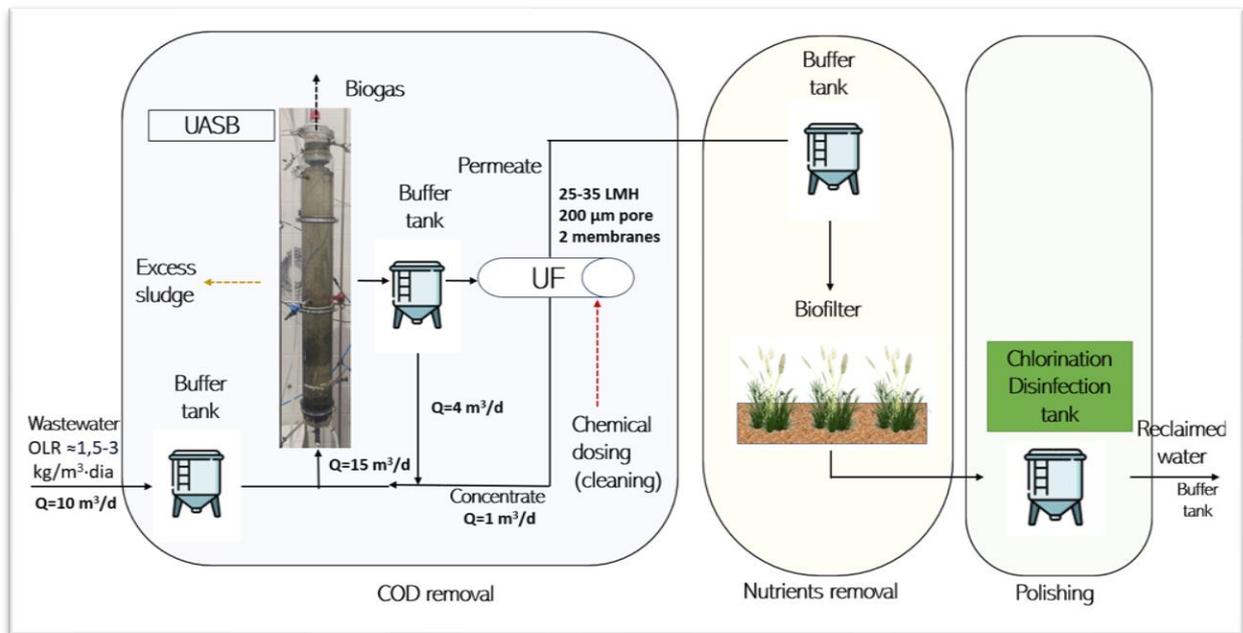
6 Annex

6.1 Annex T4.5.1

Figure 66 Treatment scheme used for the pilot plant. It consists of an UASB anaerobic reactor, a UF unit, a biofilter used as a nature-based solution and finally a chlorination disinfection tank for obtaining reused wastewater.

Table 9 Quality classes and limits of the RD 1085/2024 for reuse of treated wastewater.

Use of the water	Minimum Quality Class of Reclaimed Water	Crop category in agricultural/Urban use	Turbidity (NTU)	SS (mg/L)	E.coli (ufc/100mL)	Helmint eggs (eggs/L)	Legio-nella spp (ufc/1L)	Bacterio-phages (UFP/100mL)
Agricultural use	Quality A. A.	Food crops eaten raw where the edible part is in direct contact with reclaimed water.	5	10	10	1	<1000	-
		Tuber crops that are eaten raw.						
	Quality A. B.	Food crops eaten raw when the edible part grows above ground level and are not in direct contact with reclaimed water.	No limit	35-60	100	1	<1000	-

Use of the water	Minimum Quality Class of Reclaimed Water	Crop category in agricultural/Urban use	Turbidity (NTU)	SS (mg/L)	E.coli (ufc/100mL)	Helmint eggs (eggs/L)	Legio-nella spp (ufc/1L)	Bacterio-phages (UFP/100mL)
		Processed food crops.						
	Quality A. C.	Non-food crops, including crops used to feed animals that produce meat or milk.	No limit	<35	1000	1	<1000	100
		Woody crops where contact of reclaimed water with fruits consumed by humans is prevented.						
		Ornamental flowers, nurseries, greenhouses without reclaimed water with production.						
Urban Use	Quality U. A+	Irrigation of private gardens	5	10	Absence	1	<1000	100
	Quality U. B.	Clearing streets	No limit	35-60	100	-	<1000	100

6.2 Annex T4.5.2

Figure 67 The Sewer Mining configuration along with the photovoltaic system integrated in a tilted pergola.
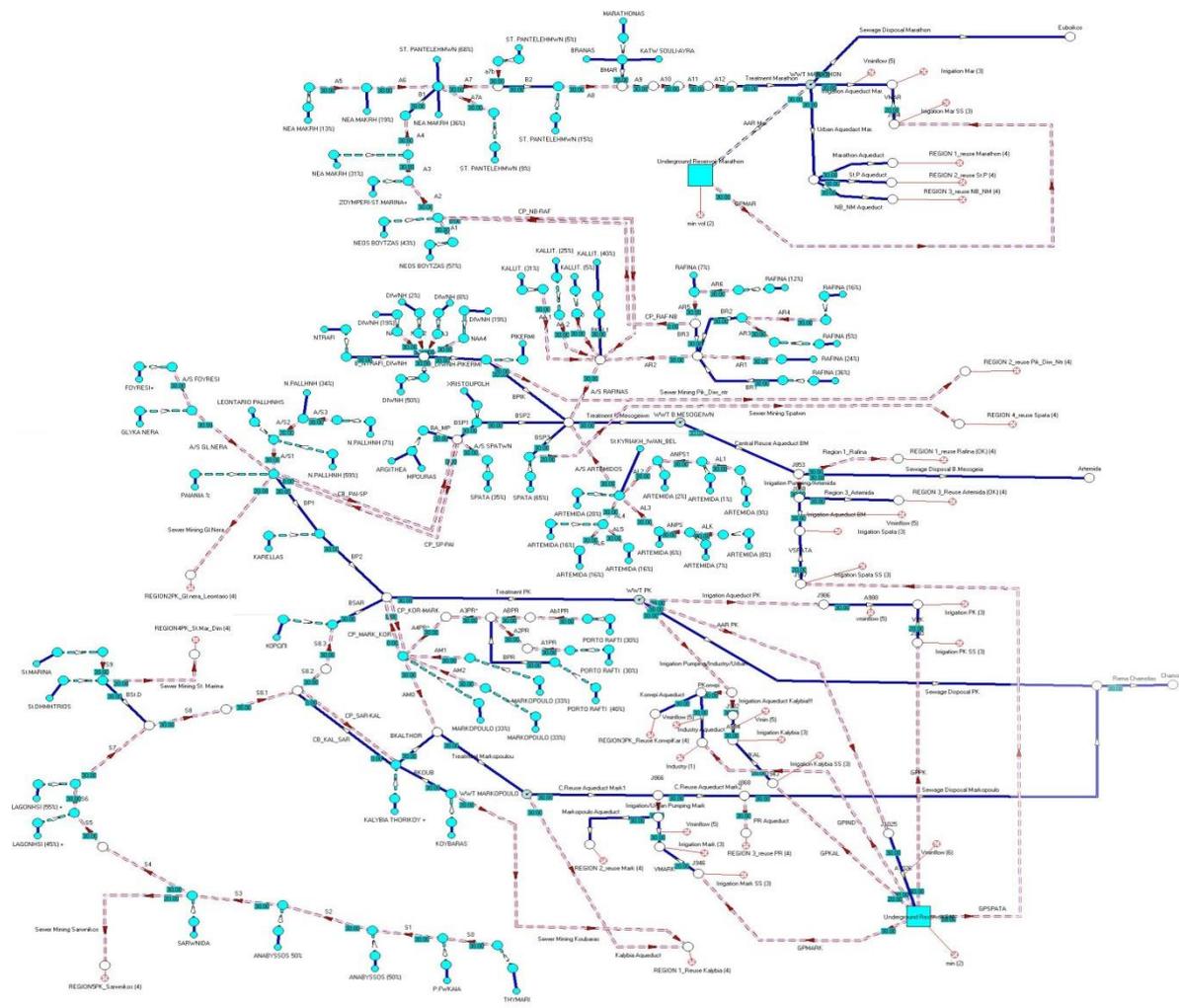
6.3 Annex T4.5.3

Figure 68: EAWWS - GUI of HYDRONOMEAS software.

Table 10 Various Data Sources.

No	Title	Year	Institution	Designer
	General Plan for the Reuse of Treated Effluents of the Wastewater Treatment Plants (WWTPs) of East Attica - WWTP MUNICIPALITY OF MARATHONAS	2018	EYDAP SA	DIMITRIS SOTIROPOULOS & ASSOCIATES SA.
	General Plan for the Reuse of Treated Effluents of the Wastewater Treatment Plants (WWTPs) of East Attica – WWTP MUNICIPALITY OF RAFINA-PIKERMI AND SPATA-ARTEMIDA	2018	EYDAP SA	DIMITRIS SOTIROPOULOS & ASSOCIATES SA.
	General Plan for the Reuse of Treated Effluents of the Wastewater Treatment Plants (WWTPMUNICIPALITY OF MARKOPOULO	2018	EYDAP SA	DIMITRIS SOTIROPOULOS & ASSOCIATES SA.

No	Title	Year	Institution	Designer
	Update of the Study on the Reuse of Treated Wastewater from the Paiania-Koropi WWTP for Irrigation of Agricultural Lands and Preparation of the Design and Implementation Deliverable	2020	EYDAP SA	EMBIS ENGINEERING CONSULTANTS SA.
	Special Hydrogeological Study for Investigating the Effects on the Groundwater Systems of the Greater Area of the Paiania-Koropi WWTP from the Reuse of Treated Wastewater for Artificial Recharge and Irrigation	2020	EYDAP SA	EMBIS ENGINEERING CONSULTANTS SA.
	General Plan for the Reuse of Treated Effluents from the Wastewater Treatment Plants (WWTPs) of East Attica	2018	EYDAP SA	DIMITRIS SOTIROPOULOS & ASSOCIATES SA.
	Preliminary Study of Sewage Conveyance Projects for the Coastal Municipalities of Kropia and Saronikos	2021	EYDAP SA	HYDROMENT ENGINEERING CONSULTANTS SA.
	Provision of Consulting Services for the Collection and Provision of Data for the Sewage Projects within the Service Area of the Paiania-Koropi Wastewater Treatment Plant	2020	EYDAP SA	HYDROMENT ENGINEERING CONSULTANTS SA.
	River Basin Management Plan, Attica Water District GR06 (2009-2015)	2012	-	Consortium of Consultants
	River Basin Management Plan 1st revision, Attica Water District GR06 (2015-2021)	2017	-	Consortium of Consultants

Table 11 Average (50y) monthly precipitation – comparison

Average Precipitation of:	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Stochastic	65.9	58.3	55.7	28.6	18.2	14.5	2.5	1.0	21.0	37.0	64.8	86.6
SSP-1	81.8	59.6	43.9	29.1	18.8	10.5	3.9	3.7	16.3	56.6	86.6	91.3
SSP-2	74.9	60.5	40.7	30.2	18.6	10.5	4.3	3.7	15.5	56.8	83.8	88.3
SSP-5	77.8	59.4	42.3	28.1	18.4	9.1	3.8	3.3	15.0	57.2	83.8	85.3

Table 12 Maximum (50y) monthly precipitation – comparison

Max Precipitation of:	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Stochastic	132.9	147.2	172.5	100.8	58.8	30.4	56.3	7.6	94.0	98.1	190.3	224.4
SSP-1	297.4	209.8	165.1	109.5	103.3	81.4	101.3	37.9	168.4	280.1	246.6	333.3
SSP-2	257.8	204.5	150.3	134.3	90.0	74.7	66.0	47.2	127.9	256.0	255.9	246.7
SSP-5	300.7	225.0	162.3	102.5	104.7	80.4	26.6	39.3	153.9	302.1	260.2	253.1

Table 13 Minimum (50y) monthly precipitation – comparison

Min Precipitation of:	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Stochastic	15.9	12.6	11.5	1.7	0.4	0.0	0.0	0.0	0.0	0.2	4.3	8.4
SSP-1	3.3	1.1	2.7	0.7	0.1	0.0	0.0	0.0	0.2	0.6	6.9	9.2
SSP-2	3.6	1.7	0.9	1.0	0.4	0.0	0.0	0.0	0.1	0.8	1.8	3.3

SSP-5	4.1	3.3	1.4	1.1	0.1	0.0	0.0	0.0	0.2	0.6	5.2	5.1

Table 14 Average (50y) monthly temperature – comparison

Average Temp of:	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
SSP-1	11.7	11.8	13.1	15.8	19.8	24.2	26.9	27.0	24.3	20.3	16.3	13.3
SSP-2	11.8	11.8	13.2	15.8	19.9	24.3	27.1	27.2	24.5	20.4	16.4	13.4
SSP-5	12.0	12.0	13.3	16.1	20.2	24.8	27.5	27.8	25.0	20.8	16.7	13.6

Table 15 Maximum (50y) monthly temperature – comparison

Max Temp of:	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
SSP-1	15.9	15.8	16.8	19.2	23.1	26.9	29.5	29.0	27.2	24.3	20.0	16.8
SSP-2	15.2	15.8	17.4	19.7	23.7	27.5	30.4	30.5	27.8	24.3	20.5	16.7
SSP-5	15.9	16.1	17.4	19.3	24.5	28.1	31.5	31.1	28.0	24.6	20.7	17.7

Table 16 Minimum (50y) monthly temperature – comparison

Min Temp of:	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
SSP-1	9.5	9.7	11.1	14.2	18.1	22.0	25.7	25.7	22.6	18.6	13.9	11.1
SSP-2	7.6	8.3	9.5	11.6	17.1	21.0	24.8	24.8	21.5	16.9	12.2	9.9
SSP-5	8.0	7.2	9.2	13.7	17.1	21.8	24.9	25.1	21.8	15.9	12.3	9.6

Table 17 Overview of WWTPs, estimation methods used in the East Attica Region, and calculated errors for 2021.

WWTP	Municipality	Settlements	LINE	POLY	EXPO	CSNT	CSNT SHARE	SHIFT SHARE	Trend (2011-2021)	Avg. Popul. (30y) ≈1000	Error (2021)
Marathon	Marathonos Mun.	Marathonas	✓		✓	✓	✓	✓	↓		41
		Kato Soulion	✓		✓	✓	✓	✓	↓		24
		Agios Panteleimon	✓		✓	✓	✓	✓	↓		26
		Vranas	✓			✓	✓	✓	↓	✗	49
		Nea Makri	✓	✓		✓	✓	✓	↑		5
		Neos Voutzas	✓	✓	✓	✓	✓	✓	↑	✗	26
Rafina – Pikermi &Spata-Artemida	Rafina – Pikermi Mun.	Rafina	✓	✓	✓	✓	✓	✓	↑		-2
		Kallitechnoupoli	✓	✓		✓	✓	✓	↑	✗	20
		Pikermi	✓	✓		✓	✓	✓	→		28
		Dioni	✓			✓	✓	✓	↑		-2
		Drafi	✓			✓	✓	✓	↓		21
	Spata-Artemida Mun.	Artemi	✓	✓		✓	✓	✓	↑		12
		Agia Kyriaki	✓	✓		✓	✓	✓	↑		0
		Spata	✓	✓	✓	✓	✓	✓	↑		4
		Agios Nikolaos	✓		✓	✓	✓	✓	→	✗	-4
		Christopoli*	✓	✓		✓	✓	✓	→	✗	9
	Paiania Mun.	Argithea	✓			✓	✓	✓	→	✗	26
Koropi-Paiania (1st)	Pallini Mun.	Gerakas	✓			✓	✓		↑		-1
		Anthousa		✓		✓	✓		→		8
		Pallini	✓			✓	✓	✓	↑		5
		Leontario	✓	✓		✓	✓	✓	→		18
	Paiania Mun.	Gl. Nera	✓		✓	✓	✓	✓	↑		19
		Paiania	✓		✓	✓	✓	✓	↑		9
	Kropia Mun.	Karellas	✓		✓	✓	✓	✓	→		27

Koropi-Paiania (2nd)	Kropia Mun..	Koropi	✓	✓	✓	✓	✓	✓	↑		6
		Agia Marina	✓			✓	✓	✓	↓		31
		Agios Dimitrios				✓	✓		→		-2
		Kitsi	✓			✓	✓	✓	→		17
	Saronikos Mun.	Anavyssos	✓			✓	✓	✓	→		10
		Palaia Fokaia	✓			✓	✓	✓	↓		20
		Thymari	✓	✓		✓	✓	✓	↓	✗	80
		Saronida	✓	✓		✓	✓	✓	↑		18
Markopoulo	Saronikos Mun.	Kalybia Thorikou	✓	✓		✓	✓	✓	↑		5
		Kouvaras, N.Kouvaras	✓	✓	✓	✓	✓	✓	↓		26
	Markopoulo Mesogaias Mun.	Markopoulo	✓	✓	✓	✓	✓	✓	↑		0
		Agia Triada	✓			✓	✓	✓	↓	✗	29
		Porto Rafti	✓			✓	✓	✓	↑		8

Table 18 Assumption summary table.

Category/ Field	Assumption Description
General/Axis	• The masterplan titled "General Plan for the Reuse of Treated Effluents from the Wastewater Treatment Plants (WWTPs) of East Attica" constituted the main axis and premise of the work. • The developed model does not strictly adhere to the findings of the relevant EYDAP studies. It incorporates various alterations and assumptions.
Exclusions (Settlements, WWTPs)	• Settlements as Varnava, Grammatiko, and Vothon-Kaletzi, the Judicial Labor Camps, as well as areas north of Marathon Avenue including North Pallini, Gerakas, and Anthousa, will be serviced by the Psitalleia treatment plant via Marathon-Mesogeion Avenue and were excluded from the final model. • Lavrio and Keratea wastewater treatment plants are not included in the reuse plans.
People development	• The population change was assumed linear over the simulation period, independent of the climate scenarios. • The process of estimating the population for small regions is inspired by a methodology mention in Smith et al.
Climatic Data (Rainfall, Temperature)	• Twenty four (24) datasets were simulated, corresponding to three (3) SSPs x eight (8) realizations each. • All rainfall data were compared with a synthetic stochastic dataset produced by historic data from rain gauges of the greater East Attica Region.
Wastewater Discharge	• The water consumption time series from the Municipality of Kiourka was considered representative of the average consumer behavior in the settlements of East Attica for determining wastewater generation. • It is noted that these quantities are not guaranteed and depend on the completion of the project, the expected population increase, and connections to the sewer network (sewage inflow into the network). • Parasitic inflows and illegal connections are not taken into account.
Quality of recovered effluents	• Fully developed Wastewater Treatment Plants (WWTPs) serve the eastern Attica region, so as to produce recovered water for unlimited irrigation, urban-suburban use, industrial use, and artificial groundwater recharge. • Additional works are required at the WWTPs of the Municipality of Markopoulo and Marathon to ensure the aforementioned quality standards.
Irrigation	• Initial estimates for irrigated areas were derived from/based on the proposal of EYDAP SA. The resilience and the final performance of the system is tested based on developed scenarios. • The crops for each region were determined according to the crop surveys (RBMP, 2009-2015).

Category/ Field	Assumption Description
	• Irrigation network is developed in two phases (A and B). Upon completion of Phase A (20 years), expansion of the irrigation networks (Phase B projects) is projected due to increased wastewater supply with population growth. • An efficiency rate of 85.5% is adopted, considering the irrigation method applied and the network water losses. • The empirical Blaney-Criddle method was implemented and irrigation upper limits were applied based on legislation. • Total irrigation demand along the system is concentrated in eight (8) nodes corresponding to the four (4) proposed irrigation areas of the model (1+1 for treated effluents and borehole sourced water).
Artificial Groundwater Recharge	• Net balance of natural inflow (precipitation, interaction with other hydrological units) and outflow is considered zero, indicating that the systems are in natural equilibrium (conceptual closed watertanks). Only source of disturbance is human activities to meet corresponding needs. • The aquifers are unconfined with a flat free surface. • Groundwater aquifers are considered prismatic and specific yield are constant throughout the area and at all depths. • Utilization of the Water Table Fluctuation method according to Healy et al.
Urban and Suburban Reuse	• Urban and suburban usage is proposed and anticipated in all settlements. The needs are met either directly through the network due to proximity to Wastewater Treatment Plants (WWTPs) or decentralized through local deployed Sewer mining units. • Needs were estimated based on an empirical value of 50 L/(capita.day) and the annual population growth rate. • A lag of a 10-year period relative to population growth was considered. • Water demand for urban-suburban use in regions was grouped into clusters for model simplification.
Industrial Reuse	• Based on the data from the first revision of the RBMPs for the period 2015-2021, it is estimated that approximately 20% of the industrial capacity of Attica, and thus water consumption, is located in the Paiania-Koropi area. • Industrial demand is concentrated in a single model node, covering the broader industrial area.
Main Sewer Conduits	• There are no restrictions in the main sewer conduits, and pumping stations e.g. discharge capacity. • The demand driven conceptual model yields results for the optimal flows of untreated-treated effluents to meet water needs.
Targets	• Aquifer Recharge and Industry hold the highest priority amongst the reuse options, as explained in Section 2.3.1.1.1. • Urban suburban-with lower priority given its lesser significance and considering its proximity to existing water supply networks.
Watertanks	• The reclaimed water distribution tanks of treated water are designed for daily-regulation and represented in the monthly model as simple nodes.
Pumping stations	• A collective approach is being taken due to lack of extensive consistent data.
Sewer Mining Units/ WWTPs	• The energy cost of wastewater treatment (WWT) and sewer mining units, is treated as a fixed cost for converting sewage into treated, reusable water. • Sewer mining units were deployed in the study area's hotspots.

6.4 Annex T4.6

Development of the Bernoulli equation for open systems:

$$P_1 + \frac{1}{2}\rho v_1^2 + \rho g z_1 = P_2 + \frac{1}{2}\rho v_2^2 + \rho g z_2 \tag{1}$$

When considering a system open to the atmosphere, the pressure terms P_1 and P_2 are equal to zero. Thus, by rearranging the equation and adding friction losses, the following expression results.

$$\frac{v_1^2}{2g} + z_1 = \frac{v_2^2}{2g} + z_2 + f\frac{x_2 - x_1}{D_h} \cdot \frac{v_{av}^2}{2g} \tag{2}$$

The velocity terms are equivalent to the flow rate divided by cross section, thus resulting in:

$$\frac{Q^2}{2A_1^2 g} + z_1 = \frac{Q^2}{2A_2^2 g} + z_2 + f\frac{x_2 - x_1}{2D_h g} \cdot \left(\frac{Q}{2A_1} + \frac{Q}{2A_2}\right)^2 \tag{3}$$

The above expression relates the cross-sectional area of the river between two consecutive points A_1 and A_2. Considering that the cross-sectional area is equivalent to the width of the river multiplied by the water column, the height of the water column at one point can be determined from the previous one. It is only necessary to know the value of the first point of the streamline to carry out the calculation (see). Subsequently, the velocity profile can be obtained from the following expression.

$$Q = vA \equiv v(by) \tag{4}$$
$$v = \frac{Q}{by} \tag{5}$$
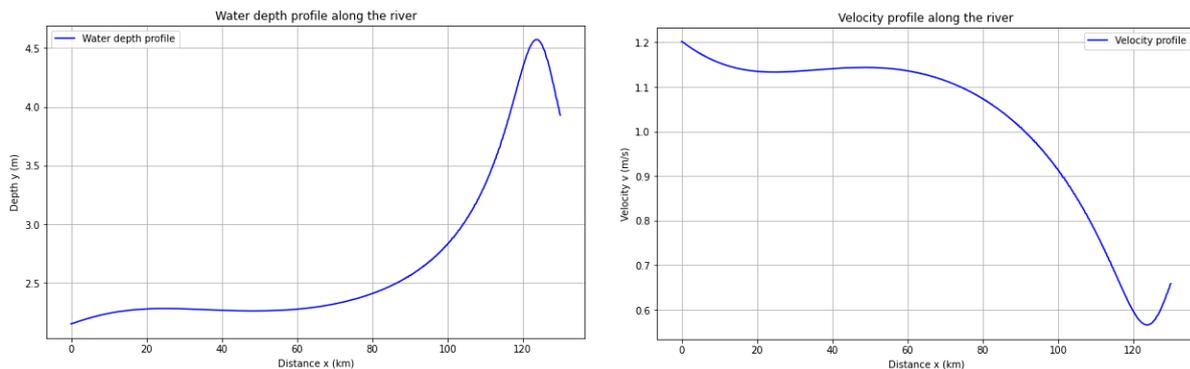
Figure 69 Water depth (left) and velocity profiles (right) obtained from the Bernoulli equation along the river, respectively.
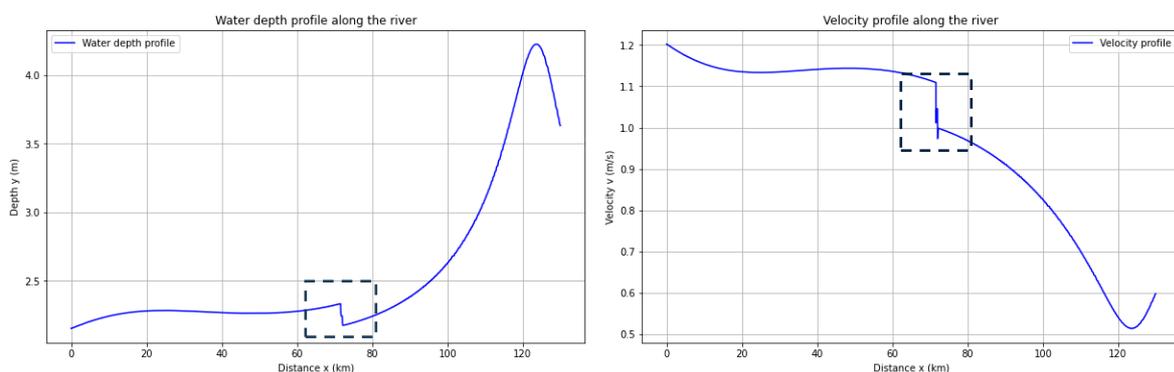
Figure 70 Water depth profile (left) and velocity profile (right) along the river for 100% opening of the irrigation gates, respectively.
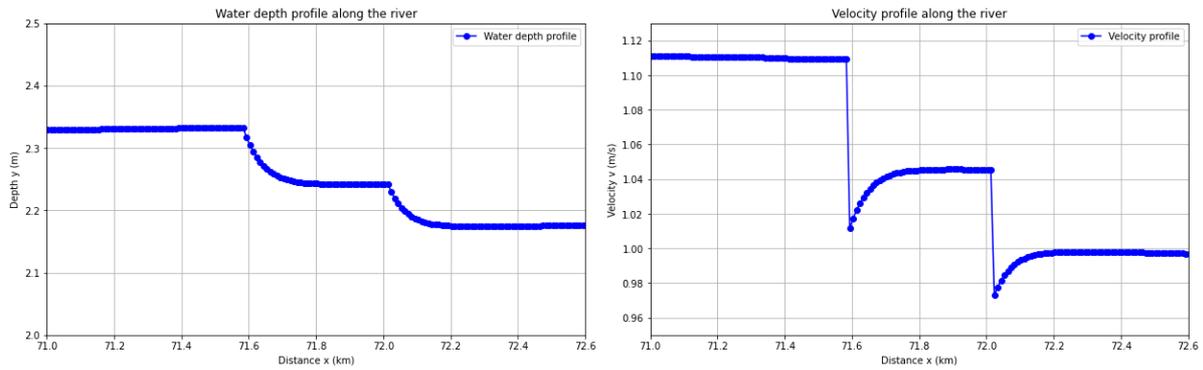
Figure 71 Water depth profile (left) and velocity profile (right) along the river for 100% opening of the irrigation gates, zoomed to the gates section, respectively.
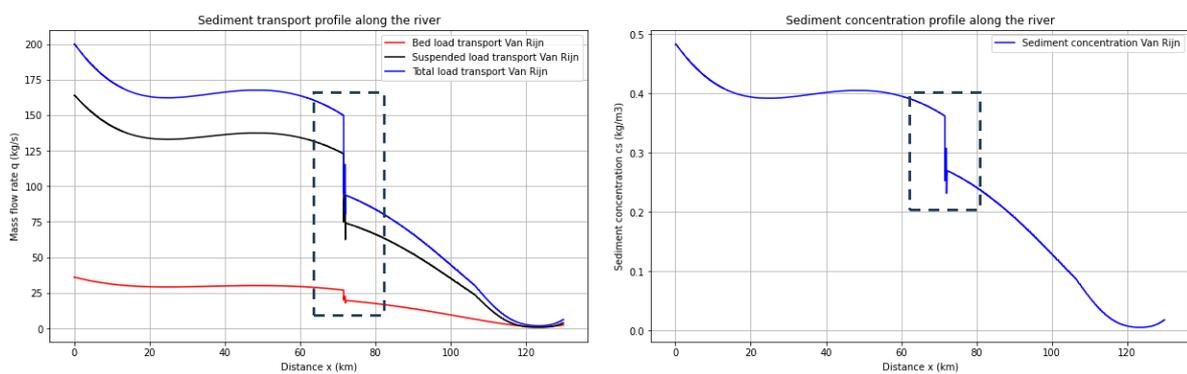
Figure 72 Sediment mass flow rate and sediment concentration profiles along the river for 100% opening of the irrigation gates, respectively.
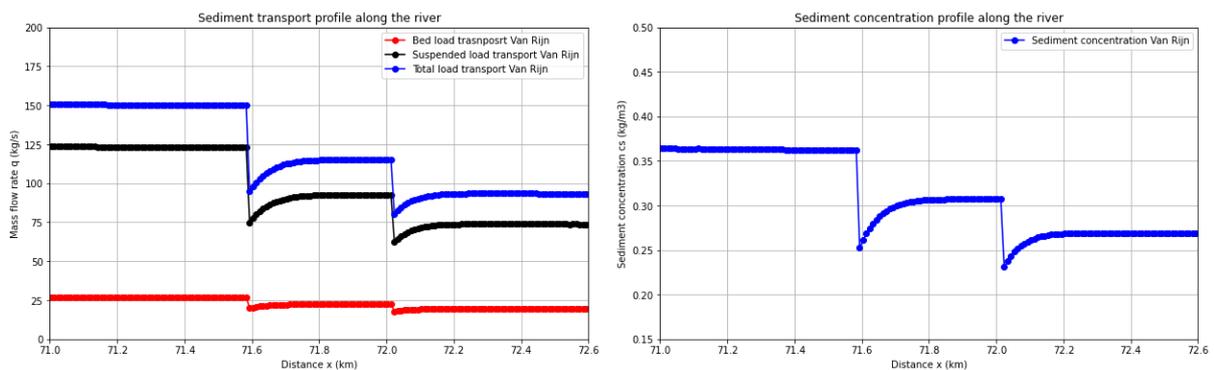

Figure 73 Sediment mass flow rate and sediment concentration profiles along the river for 100% opening of the irrigation gates, zoomed to the gates section, respectively.

6.5 Annex T4.7.1
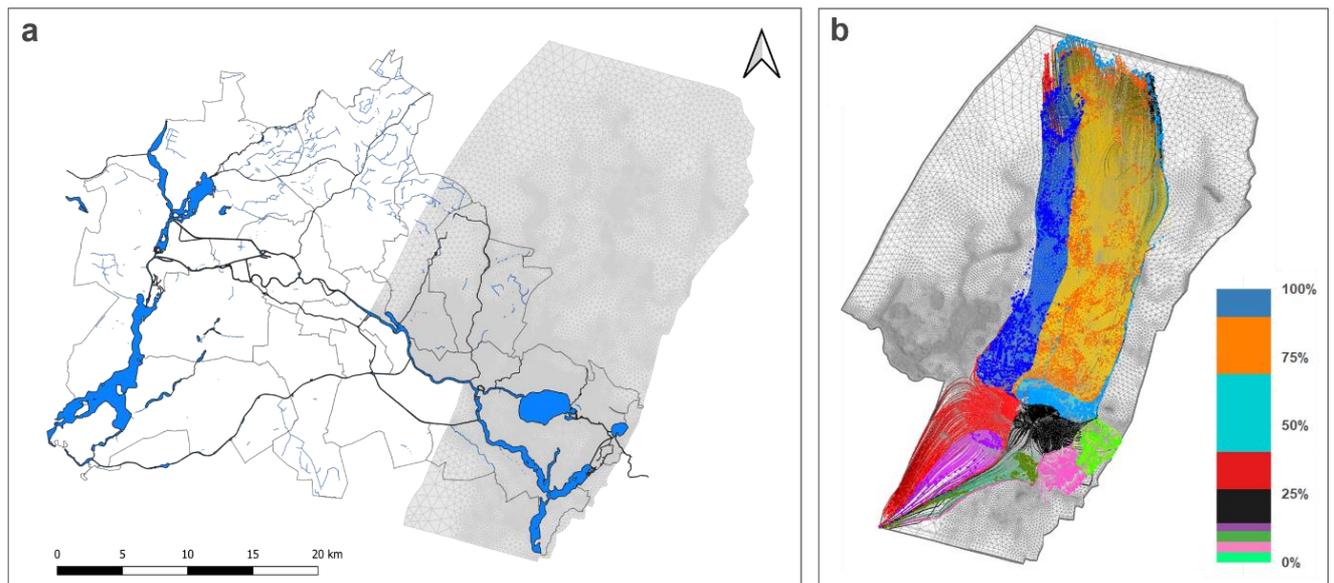
Figure 74 (a) Map of Berlin showing the city outline, surface water bodies (blue), and the model domain (grey) used for simulating bank filtration processes. (b) Simulated flow pathlines within the model domain delineate the catchment areas of different well galleries (coloured). The example shown corresponds to a total extraction of 60 Mio m³/yr, based on 2019 abstraction data. The bar chart indicates the share of total extraction per gallery.
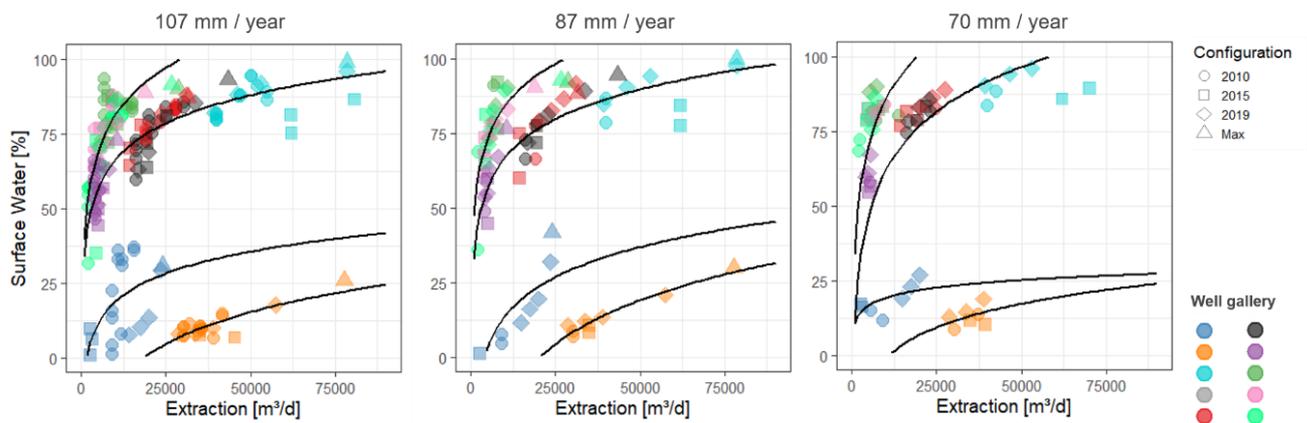
Figure 75 Change in bank filtrate fraction across scenarios with differing groundwater recharge rates (107, 87 and 70 mm/year) at different model configurations.
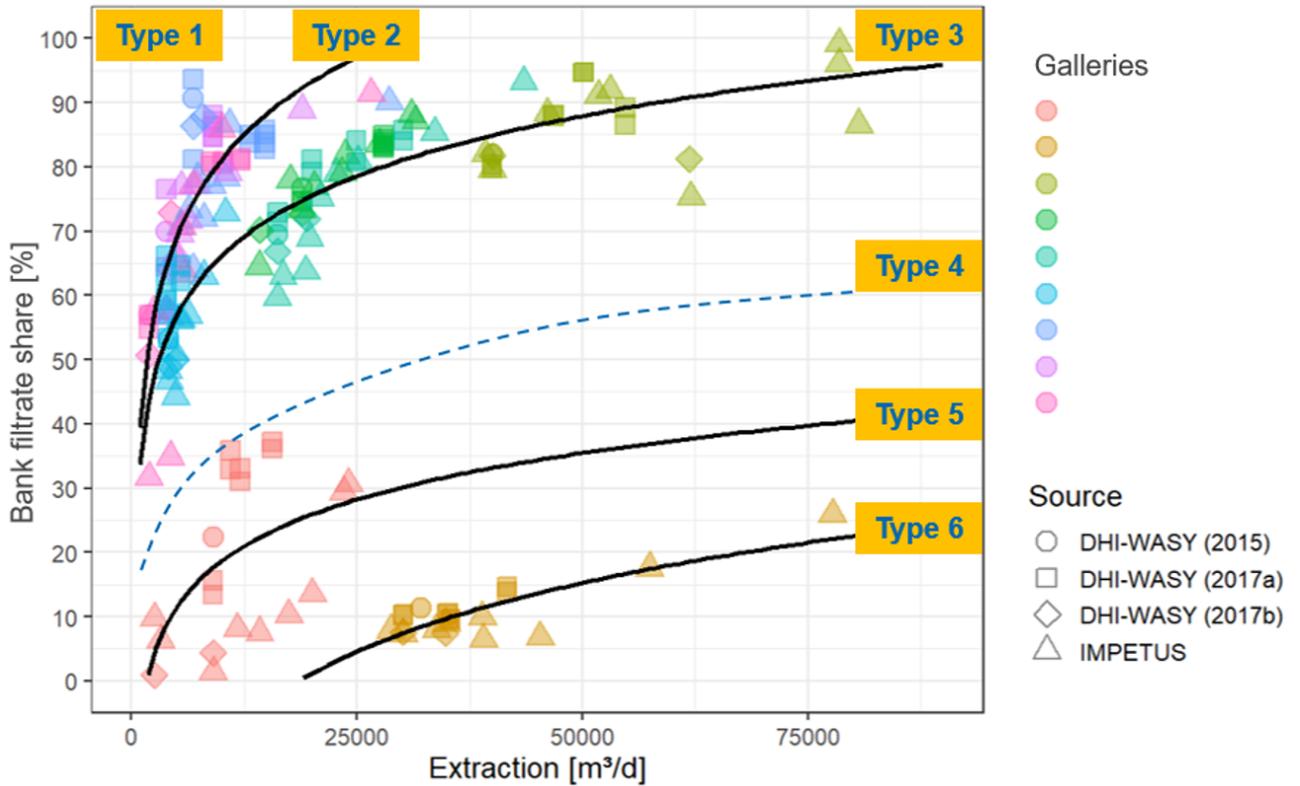
Figure 76: Relationship between total extraction and bank filtrate share, based on a combination of literature data and model results. The distribution allows for the identification of six distinct classes, each representing a different range of bank filtrate contribution: >90% (Type 1), 50-100% (Type 2), 50-90% (Type 3), 0-60% (Type 4), 0-40% (Type 5), and 0-20% (Type 6).
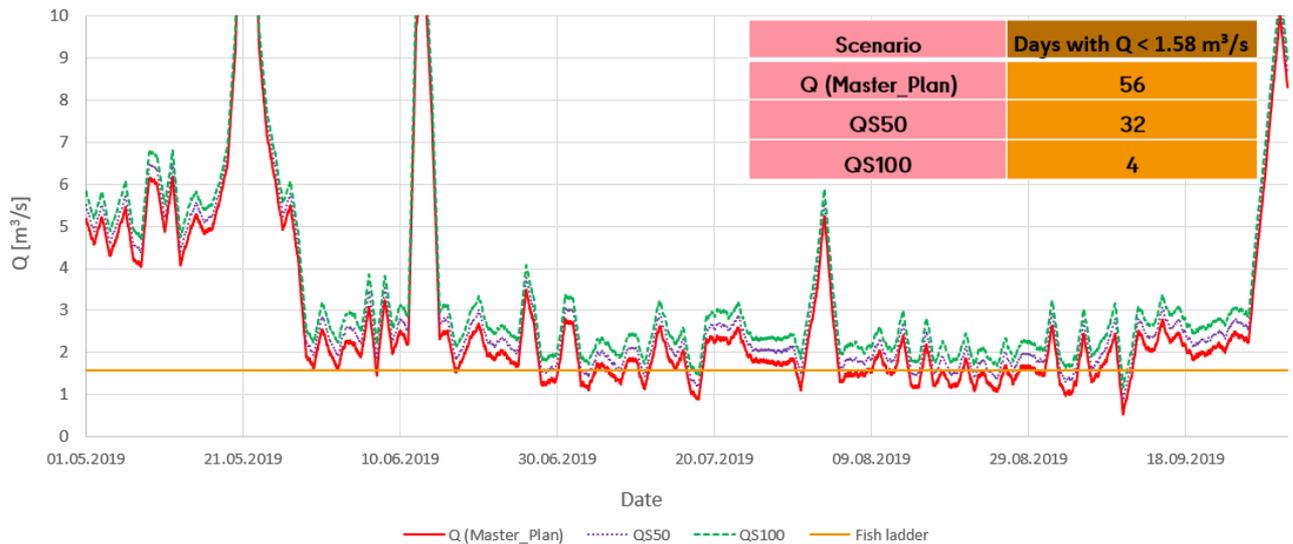
Figure 77: Flow at Mühlendamm lock for flow scenario S3.25 (2019 values -25% for Havel and Spree inflows = Q(Masterplan)) and alternative discharge routes for WWTP Stahnsdorf expansion (QS50 and QS100) together with number of days below minimum flows necessary for fish migration aids.
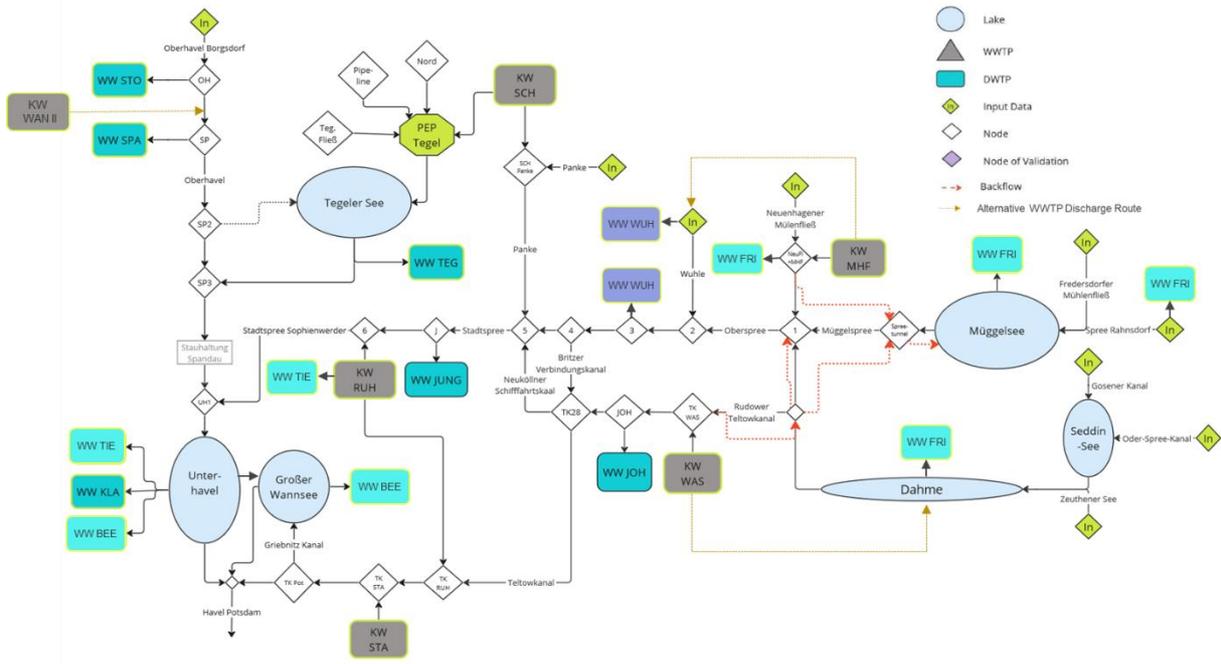
Figure 78 Schematic structure of the static mixing model with input parameters, balance points along the surface waters and for the waterworks sites.
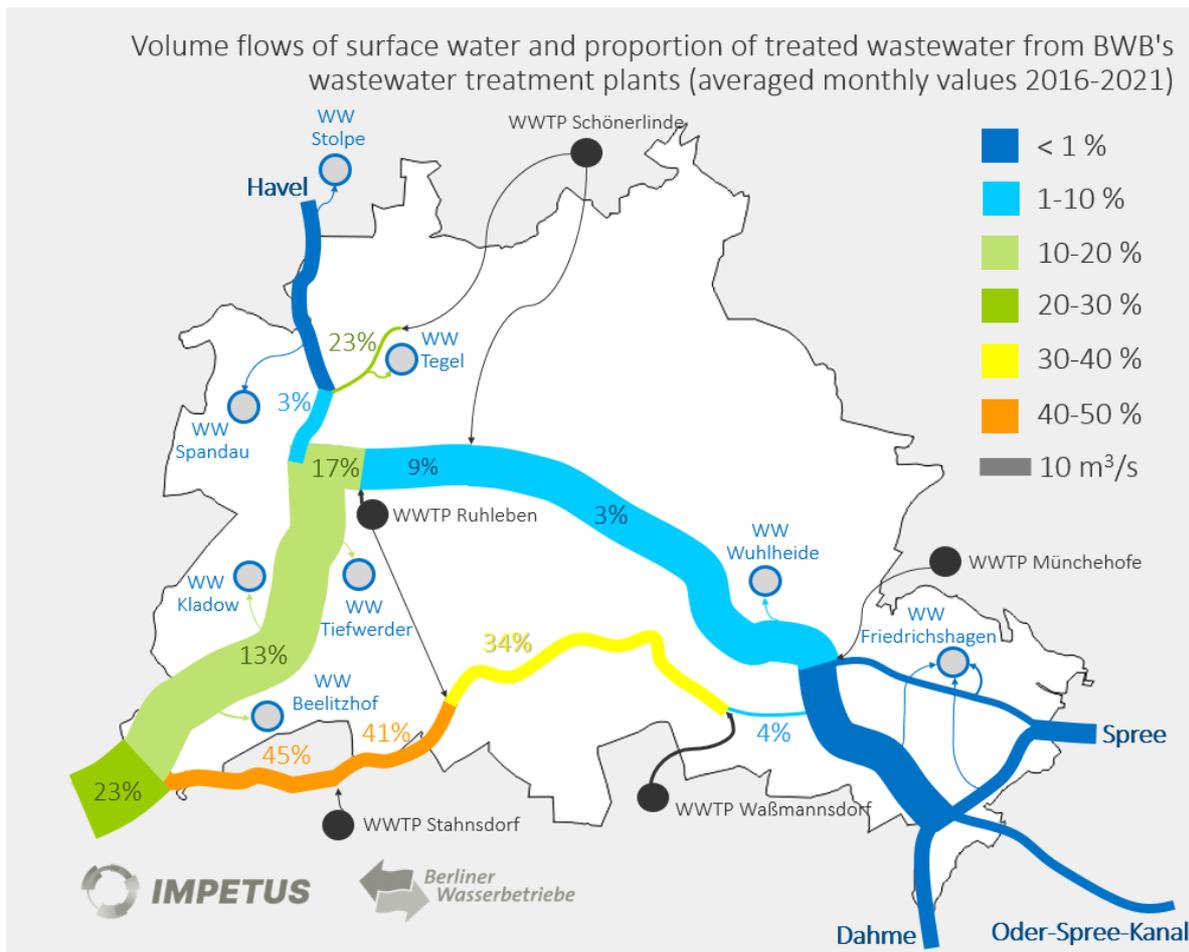

Figure 79 Modelled volume flows of Berlins surface waters and proportion of treated wastewater from BWB's wastewater treatment plants (averaged monthly values from 2016-2021).
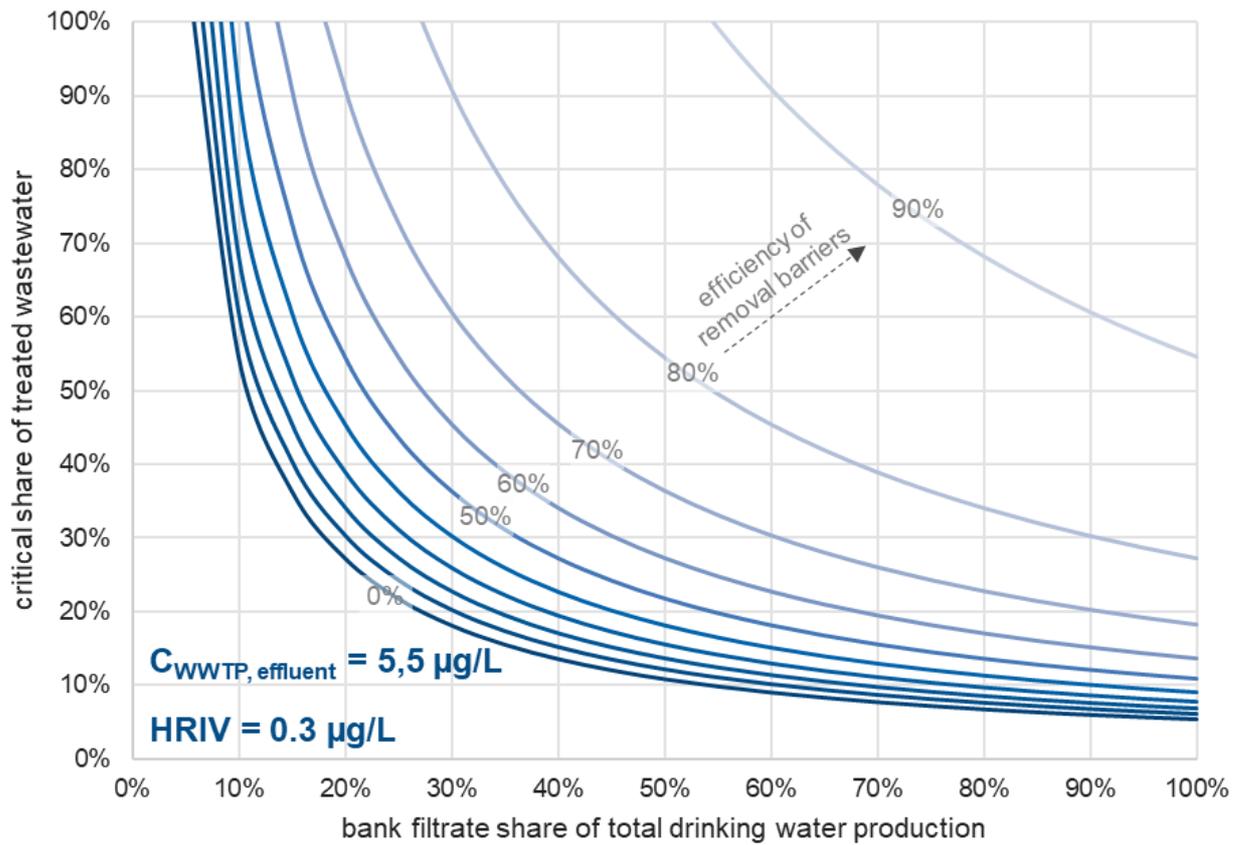
Figure 80 Dependency of the critical share of treated wastewater on the bank filtrate share and the efficiency of barriers based on a model substance with an average effluent concentration of 5.5 µg/L in wastewater treatment plants and a health-related indicator value (HRIV) of 0.3 µg/L.
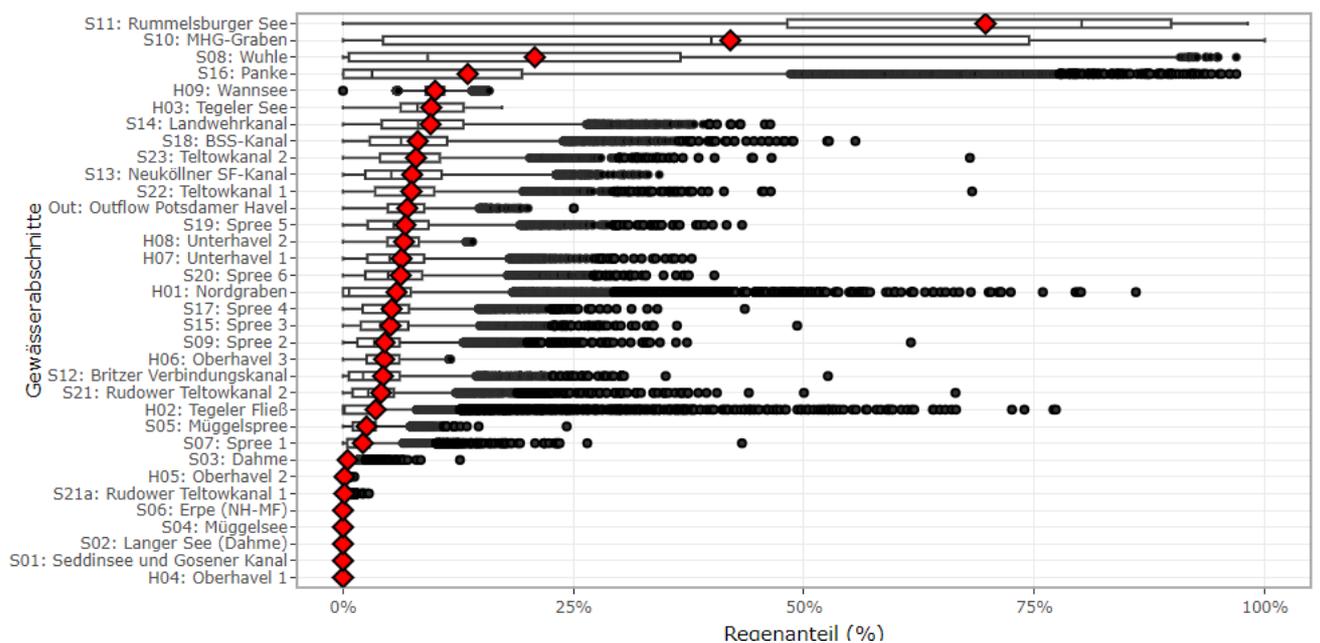

Figure 81 Share of stormwater runoff in each section (2002-2022), sorted by mean values (red diamonds), shown as boxplots of daily values.

Figure 82 Monthly shares of WWTP effluents (red boxplots) and stormwater runoff (blue boxplots) in section 19 (Spree) for time period 2002-2022.
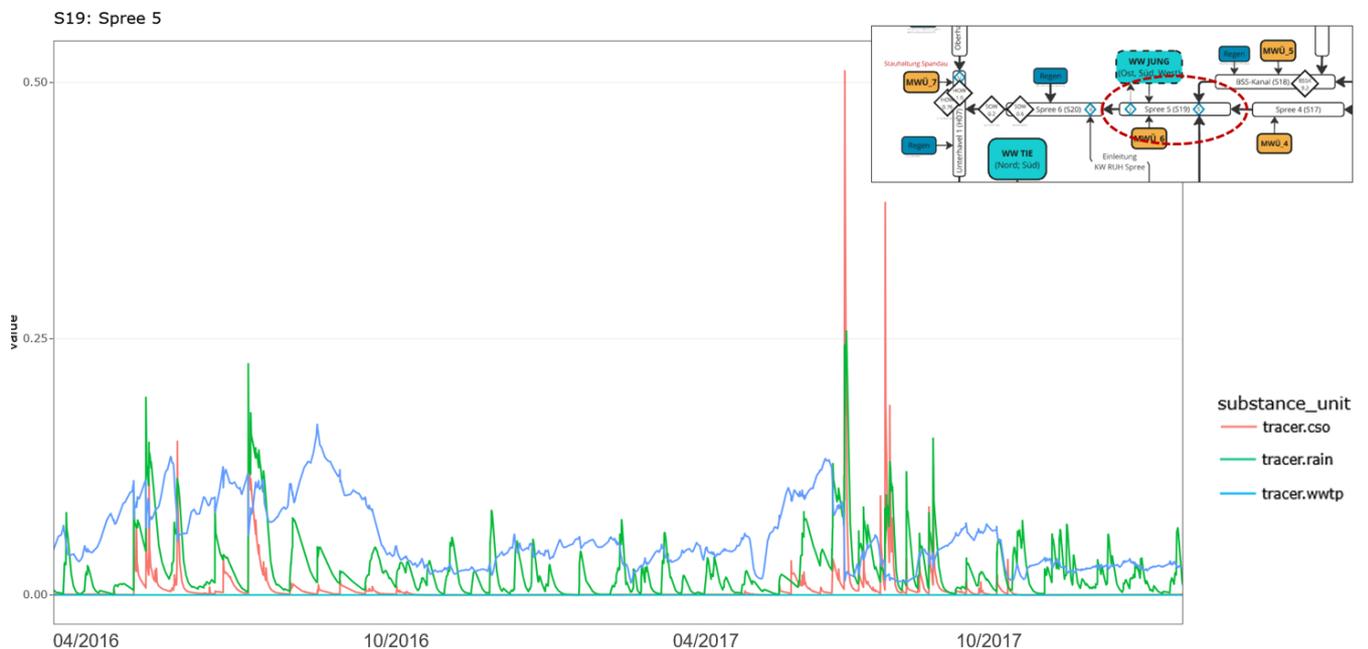

Figure 83 Time series for shares of WWTP effluents (blue), stormwater runoff (green) and CSO (red) in section 19 (Spree) for 2016 and 2017.

6.6 Annex T4.9

Table 19 A total of 147 different plant species included in the coastal dune species analysis, with the most abundant being: Elymus farctus farctus, Silene nicaeensis, Medicago marina, Cakile maritima marítima, Salsola kali, Cutandia marítima, Echinophora spinosa, Pancratium maritimum, Sporobolus pungens, Eryngium maritimum, Ammophila arenaria arenaria.

Aetheorhiza bulbosa	Carpobrotus edulis	Eryngium maritimum	Matthiola sinuata sinuata	Rostraria cristata
Agave americana	Catapodium marinum	Euphorbia paralias	Medicago littoralis	Rostraria litorea
Agave sp.	Catapodium rigidum	Euphorbia peplis	Medicago marina	Rubia peregrina
Ailanthus altissima	Cenchrus incertus	Euphorbia terracina	Nerium oleander	Salicornia arbustiva
Allium sp.	Centaurea aspera	Foeniculum vulgare	Oenothera biennis	Salsola kali
Allium sp.	Chamaerops humilis	Fraxinus angustifolia	Ononis natrix	Scabiosa atropurpurea
Alyssum maritimum	Chenopodium album	Fumana ericoides	Ononis natrix natrix	Scirpus holoschoenus
Ambrosia coronopifolia	Chenopodium sp.	Fumaria officinalis	Ononis natrix ramosissima	Scirpus maritimus
Ammophila arenaria	Cistus salviifolius	Gazania rigens	Oryzopsis miliacea	Scolymus hispanicus
Anacyclus valentinus	Clematis flammula	Geranium sp.	Otanthus maritimus	Sedum sediforme
Anthemis maritima	Convolvulus althaeoides	Glaucium flavum	Pancratium maritimum	Senecio inaequidens
Anthyllis cytisoides	Corynephorus divaricatus	Hedypnois rhagadioloides	Parapholis filiformis	Silene cerastoides
Arctotheca calendula	Crepis sp.	Helichrysum stoechas	Parapholis incurva	Silene nicaeensis
Artemisia campestris	Crithmum maritimum	Herniaria glabra	Paronychia argentea	Smilax aspera
Artemisia gallica	Crucianella maritima	Hordeum marinum	Phleum arenarium	Sonchus maritimus
Arthrocnemum fruticosum	Cutandia maritima	Hordeum murinum	Phragmites australis	Sonchus tenerrimus
Asparagus acutifolius	Cynanchum acutum	Hordeum sp.	Pinus halepensis	Sporobolus pungens
Asparagus horridus	Cynodon dactylon	Hyparrhenia hirta	Pinus pinea	Stachys maritima
Asphodelus fistulosus	Cyperus capitatus	Inula viscosa	Pistacia lentiscus	Suaeda sp.
Atriplex halimus	Dactylis glomerata	Juncus acutus	Plantago albicans	Tamarix africana
Atriplex portulacoides	Echinophora spinosa	Juncus maritimus	Plantago coronopus	Tamarix canariensis
Avena barbata	Echium vulgare	Juniperus phoenicea	Plantago crassifolia	Tamarix sp.
Avena sp.	Elymus farctus farctus	Lagurus ovatus	Plantago lagopus	Taraxacum sp.
Bidens sp.	Elymus pungens	Lamarckia aurea	Polycarpon polycarpoides catalaunicum	Teucrium polium
Blackstonia perfoliata	Elymus pungens pycnanthus	Limonium echioides	Polygonum maritimum	Thymelaea hirsuta
Brachypodium distachyon	Emex spinosa	Limonium sp.	Pseudorlaya pumila	Vulpia membranacea
Brassica sp.	Ephedra distachya distachya	Linum strictum	Psoralea bituminosa	Xanthium echinatum italicum
Bromus diandrus	Erianthus ravennae	Lotus creticus	Raphanus raphanistrum	
Cakile maritima maritima	Erigeron canadensis	Malcolmia littorea	Reichardia picroides	
Calystegia soldanella	Erodium laciniatum	Maresia nana	Rosmarinus officinalis	

Table 20 Habitat suitability and available area for the selection of waterbirds included in the SDM, under the current situation (2020) and throughout the three periods considered: near term (2021–2040); medium term (2041–2060) and long term (2081–2100), based on the Intergovernmental Panel on Climate Change (IPCC) RCP 4.5 and 8.5 (De la Cruz and Numa, 2024).

Scenarios	Habitat suitability area (km²)	Available habitat area after flooding (km²)	Percentage of change from 2020
Current situation (2020)	303	–	
RCP 4.5 near-term	306	241	20.46 %
RCP 4.5 medium- term	309	210	30.69 %
RCP 4.5 long-term	315	150	50.50 %
RCP 8.5 near-term	306	241	20.46 %
RCP 8.5 medium-term	313	209	31.02 %
RCP 8.5 long-term	299	92	69.64 %

Table 21 Scoring Framework for Assessing Potential Species Distribution Changes under Climate Change Using IUCN-Based Criteria.

Criteria	If	Score	Rationale
a. Red List Category	**Threatened species:** CR EN VU **OR Non-threatened species (DD, LC, NT) but restricted range**	-1	Species threatened by extinction might be more sensitive to new threats and changes in habitat
	DD, NT	0	
	LC	1	
b. Red List Criteria	**Threatening processes focused on climate change:** D2 B1, B2 A3, A4 C1, C2 E	-1	Based on: Akçakaya, H. R., S. H. M. Butchart, G. M. Mace, S. N. Stuart, and C. Hilton-Taylor. 2006. Use and misuse of the IUCN Red List Criteria in projecting climate change impacts on biodiversity. *Global Change Biology,* 12, 2037–2043.
	Any other criteria or NIL	0	Foden, W.B. and Young, B.E. (eds.) (2016). *IUCN SSC Guidelines for Assessing Species' Vulnerability to Climate Change* . Version 1.0. Occasional Paper of the IUCN Species Survival Commission No. 59. Cambridge, UK and Gland, Switzerland: IUCN Species Survival Commission. x+114pp. IUCN Standards and Petitions Committee. (2024). *Guidelines for Using the IUCN Red List Categories and Criteria.* Version 16. Prepared by the Standards and Petitions Committee. Downloadable from https://www.iucnredlist.org/documents/RedListGuidelines.pdf.
c. Threats	**Climate change and Severe Weather, including:** Habitat shifting & alteration Storms & flooding Invasive non-native/alien species/diseases	-1	Threats directly related to CC as per SiS Subdirections
	Any other threats or NIL	1	
d. Population trend	Decreasing	-1	Species already experiencing population declines are likely to be more sensitive to new threats and changes in habitat
	Unknown or NIL	0	
	Stable, Increasing	1	
f. Habitat	**Species ecologically flexible:** "generalists", "tolerant"	1	Species described as habitat generalists or tolerant of anthropogenic environments (e.g., farmland, urban areas) are more likely to expand their range.
	NIL	0	

Once summed, the scores for all the criteria combined provide a total value between -4 and +4. According to this value, each species is classified as:

-3 to -4	High probable loss
-1 to -2	Probable loss
0	Neutral
1 to 2	Probable gain
3 to 4	High probable gain

6.7 Annex T4.10.1

Figure 84 High-resolution heat stress maps (1×1 m) of the demo-site (Province of Zeeland and Rijnmond), extended to cover the full Netherlands. The heat stress map shows the PET indicator for a once-in-1,000-years extreme heat day. The developed data is open-source and available and presented via the Klimaateffectatlas (https://www.klimaateffectatlas.nl/en/), commissioned by the Ministry of Infrastructure and Water Management, and now forms the official basis for Dutch heat stress policy.
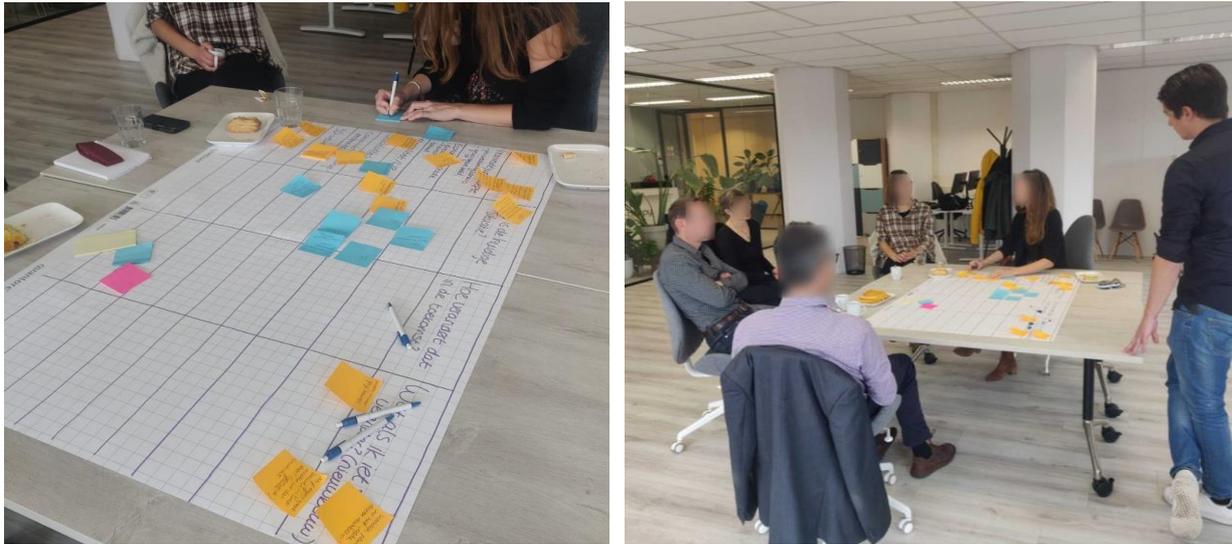
6.8 Annex T4.10.2

Figure 85 Visual impression of the second co-creation workshop held in October 2022 in Rotterdam. The figure shows session outcomes captured on post-its and a live discussion among stakeholders, including municipalities, flood experts, and provincial representatives. These sessions helped define the minimal functional requirements for the DSS and shaped the direction of technical development.