Final climate simulations and report on compatibility of planned actions with future climate in each Living Lab

Deliverable 4.4

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Water4All Water security for the planet — INTERLAYER Safeguarding water in hydroclimatic extremes

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Summary

This deliverable reports the work carried out in INTERLAYER under WP4 / Task 4.2 “Future climate modelling and resilience” to support resilience planning and to assess the compatibility of planned Living Lab actions with future hydro-climatic conditions. Because climate-change impacts vary substantially across regions and sectors, the analysis is performed at local scale and framed over the full area of influence of each Living Lab (catchment/sub-catchment), aligning climate information with the hydrological processes that govern water availability.

Building on the preliminary screening presented in D4.1, the project upgrades the assessment from a point-based approach (one representative meteorological station per Living Lab) to a spatially explicit, catchment-scale framework. Local-scale projections of temperature and precipitation are produced from CMIP6 information using statistical downscaling/regionalisation methods, supported by reanalysis-based reference fields. An ensemble of ten CMIP6 climate models combined with four SSP pathways provides 40 model–scenario combinations, enabling uncertainty to be quantified and communicated.

To translate meteorological change into water-relevant evidence for slow-hydrology systems, reference evapotranspiration (ETP) is computed and combined with precipitation to derive the climatic water balance (P–ETP). The ensemble is then reduced to three representative futures per Living Lab (dry, median and wet), selected using the distribution of projected hydro-climatic change, and a comprehensive set of hydro-climatic indicators is computed to capture long-term availability, persistence and extremes at both monthly/seasonal/annual and daily scales.

Across the Living Labs, warming emerges as a robust signal, reflected in shifts of the temperature distribution and in strong increases in heat-threshold exceedances. Precipitation changes are more heterogeneous and season dependent, and several sites show signals of intensified event characteristics, reinforcing the need to interpret totals together with frequency and intensity indicators. When supply and demand are integrated through P–ETP and related metrics (including wet-day frequency and intensity), clear contrasts emerge: some Living Labs retain a relatively favourable climatic water-balance outlook, while others become more deficit prone due to the combined effect of rising demand and changes in precipitation occurrence and seasonality.

Living Lab chapters present site-specific narratives and implications for slow hydrology, providing the evidence base to apply the compatibility assessment framework defined in this deliverable. Together, the results enable planned actions to be stress-tested under locally meaningful dry/median/wet

futures, supporting robust decision-making and helping identify where adaptation measures, monitoring triggers or design refinements are needed to maintain effectiveness under future climate uncertainty.

1. Introduction

Deliverable D4.4 provides the final set of future climate simulations developed under WP4 Activity 4.2 "Future climate modelling and resilience" and a consolidated assessment of the compatibility of planned actions with projected future hydro-climatic conditions in each Living Lab (LL). Building on the preliminary point-based screening presented in D4.1, which relied on a general analysis using one meteorological station per LL, D4.4 delivers a spatially explicit, catchment-scale perspective designed to better represent slow-hydrology processes and upstream water contributions. This step change is essential to move from an indicative climate signal to operational information that can support resilience planning and action design in each LL.

A common methodological framework is applied consistently across all LLs. First, future climate projections for temperature and precipitation are generated over a regular grid covering the full area of influence of each LL, i.e., the relevant catchment or sub-catchment domain, to capture spatial variability and upstream contributions. Second, a basic climatic water balance is computed as precipitation minus reference evapotranspiration (P-ETP), providing an integrated metric of potential water availability that is particularly meaningful for slow hydrology. Third, the initial ensemble (40 projections) is ranked using Δ(P-ETP) and reduced to three representative projections selected at the P10, P50 and P90 quantiles, representing dry, median and wet hydro-climatic futures. This scenario reduction yields a practical set of futures suitable for testing robustness of actions while still reflecting the spread of plausible outcomes.

Using the selected representative projections, hydro-climatic indicators are computed to translate climate information into variables directly relevant for water resources and resilience-oriented planning. Results are presented for each LL, including the spatial and temporal evolution of key variables and indicators at catchment/sub-catchment scale. On this basis, D4.4 discusses the compatibility of planned actions with future climate conditions, focusing on whether actions remain robust across the dry, median, and wet hydro-climatic futures, and identifying where adaptive adjustments, monitoring needs, or design refinements may be required. The planned actions considered correspond to those defined and agreed within the LL implementation and project planning processes. Importantly, the report provides scenario-based evidence to support decision-making and does not constitute deterministic predictions.

To ensure usability for both technical and non-technical stakeholders, this report is structured with a concise main narrative describing context, common methodology, and cross-LL synthesis, followed by LL-specific chapters. Detailed figures, maps, time series, and supporting diagnostics are provided in annexes to maintain readability while ensuring full transparency and traceability of results. In line with the deliverable's "publication anticipated" orientation, the document is written to be suitable for wider dissemination as a technical reference on the hydro-climatic basis for resilience assessment in the project's Living Labs.

2. Scientific and operational background

This section provides the scientific and operational rationale underpinning the approach adopted in INTERLAYER. It explains why future climate information is required to support resilience planning in slow-hydrology contexts, how core climate variables are translated into water-relevant metrics and indicators, why uncertainty must be addressed through an ensemble and an operational scenario set, and why a catchment-scale, spatially explicit assessment is necessary to represent the full area of influence of each Living Lab and the upstream contributions that shape water availability.

Why future climate information is needed for slow-hydrology contexts

Living Lab actions linked to water resources, ecosystems, and land management are shaped by hydrological processes that often respond slowly to climate forcing. Soil moisture storage, groundwater recharge, baseflow contribution, and delayed catchment response create memory effects that integrate climate anomalies over weeks, months, or even years. In such systems, resilience is not only challenged by short-lived extremes, but also by gradual shifts in mean conditions and seasonality that modify the long-term balance between water inputs and atmospheric demand. Future climate information is therefore required to anticipate whether the hydro-climatic conditions that support planned actions today are likely to persist, weaken, or strengthen over the planning horizon of the project.

From an operational perspective, planned actions typically have multi-year lifetimes and are expected to perform under a range of conditions. Relying solely on historical climate can lead to maladaptation: measures might be optimised for past variability while becoming less effective under emerging trends such as increasing temperatures, changing precipitation patterns, or more frequent compound situations (e.g., warm and dry periods). Providing scenario-based projections enables actions to be stress-tested and prioritised based on robustness, helping stakeholders understand not only the most likely future but also plausible dry and wet pathways that could challenge implementation and long-term outcomes.

From climate variables to water-relevant information

Temperature and precipitation are the fundamental climate drivers controlling water availability, but their combined effect is what ultimately matters for slow hydrology and for many action-relevant stressors. Temperature affects snow and melt processes where relevant, but more generally it governs atmospheric evaporative demand, influencing how quickly water is removed from soils and vegetation. Precipitation sets the primary input, yet its hydrological effectiveness depends on intensity, timing, antecedent moisture conditions, and concurrent evaporative demand. As a result, changes in precipitation alone cannot be interpreted without considering how warming alters ETP and therefore the net hydro-climatic balance.

To translate climate signals into a metric that is both operational and physically interpretable, INTERLAYER uses a basic climatic water balance defined as precipitation minus reference evapotranspiration (P-ETP). This formulation provides a consistent proxy for potential water availability and hydro-climatic stress across Living Labs. While it does not represent full hydrological modelling, it captures the first-order competition between water supply and demand and supports cross-site comparability. It also provides a meaningful basis for deriving indicators (e.g., cumulative deficits, seasonal balances, persistence of dry conditions) that can be directly linked to the performance and resilience requirements of planned actions.

Uncertainty in climate projections and the need for scenario reduction

Climate projections involve multiple sources of uncertainty: differences among climate models, internal climate variability, and (where relevant to the dataset) the influence of future forcing pathways. For resilience-oriented planning, acknowledging this uncertainty is essential, because actions must cope with a range of plausible outcomes rather than a single “best estimate”. Ensemble approaches address this by providing a distribution of futures that reflects model spread and variability. However, using a large ensemble directly in operational planning can be impractical for Living Lab stakeholders and for action compatibility discussions, which require a small number of clearly interpretable futures.

INTERLAYER addresses this practical constraint through an explicit and transparent scenario reduction step. The set of projections are ranked using the basic climatic water balance evolution Δ(P-ETP), and three representative projections are selected at the P10, P50, and P90 quantiles. These are interpreted as a dry, median, and wet hydro-climatic future, respectively, and form an operational scenario set suitable for stress-testing planned actions. By basing the reduction on P-ETP, the selection remains directly aligned with slow hydrology and water availability rather than relying on generic temperature-only or precipitation-only criteria. This approach preserves the essential spread of plausible hydro-climatic conditions while enabling structured comparison, communication, and decision support.

Spatial representativeness: from point-based screening to catchment-scale evidence

Meteorological stations provide valuable local observations, but point-based information cannot fully represent the spatial variability that governs catchment processes, especially in areas with complex topography or strong precipitation gradients. For water-related planning, the relevant unit of analysis is typically the catchment or sub-catchment that contributes to the system where actions are implemented. Upstream contributions and spatially distributed inputs determine whether water is available where and when it is needed, and these controls cannot be assessed robustly from a single station. Moreover, actions may be sensitive to spatial contrasts within the area of influence, such as differing exposure across elevations or sub-basins.

A catchment-scale, gridded approach provides an operationally stronger basis for resilience assessment. By generating projections over a regular grid covering the full area of influence, INTERLAYER enables consistent spatial aggregation and reporting for each Living Lab and for sub-catchments where relevant. This supports the calculation of hydro-climatic indicators that reflect spatial heterogeneity and upstream inputs, aligning the climate analysis with how hydrological systems function and how actions interact with them. In practice, this shift from station-based screening (D4.1) to spatially explicit catchment evidence (D4.4) improves interpretability and relevance for planned actions, because it connects projected climate change to the hydrological context in which the actions take place.

3. Data and study domains

This section describes the spatial domains and datasets used to produce the gridded climate projections, compute the climatic water balance (P-ETP), and derive hydro-climatic indicators for action compatibility assessment. The objective is to ensure that inputs and spatial definitions are consistent, traceable, and fit for representing slow-hydrology processes at catchment and sub-catchment scale. The section also documents the choices that control interpretability and comparability across Living Labs, including the definition of the area of influence, the spatial grid set-up, the baseline/reference information used for context and plausibility checks, and the characteristics of the climate projection ensemble.

3.1 Living Labs and delineation of catchments/sub-catchments

For each Living Lab (LL), the analysis domain is defined as the full area of influence relevant for the planned actions and for the hydrological processes that control water availability. In slow-hydrology contexts, this area is typically the contributing catchment or a set of sub-catchments that feed the system where actions are implemented. Defining the domain at this hydrologically meaningful scale is essential because it captures upstream contributions and the spatial integration of climate signals that drive storage, recharge, and baseflow.

Catchment and sub-catchment boundaries are delineated using authoritative hydrographic and topographic datasets, complemented where necessary by project-specific knowledge (e.g., local management units, action influence zones, and stakeholder-relevant sub-basins). Boundaries are reviewed to ensure that they are consistent with the location and intended impact area of planned actions, and that they represent realistic flow connectivity and contributing areas. Where LL actions are localised but depend on upstream inputs, the domain explicitly includes upstream contributing areas rather than focusing only on the immediate action footprint.

All subsequent spatial aggregation and reporting (climate variables, P-ETP metrics, and indicators) are performed using these catchment/sub-catchment units. This ensures that results can be interpreted directly in terms of hydrological functioning and operational planning.

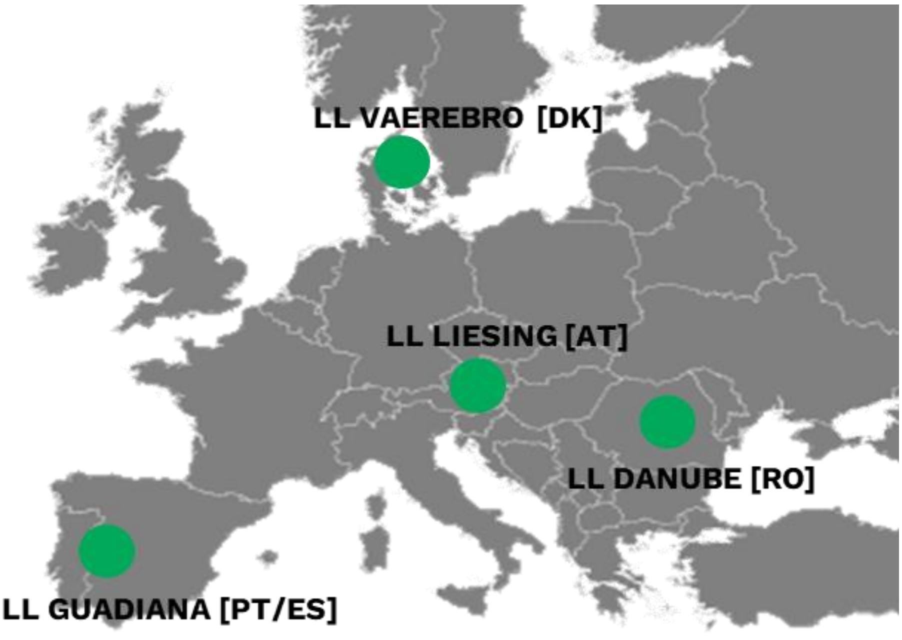

Figure 1.INTERLAYER's four LL's, located in contrasting watersheds in different regions of Europe.

3.2 Spatial grid definition and harmonisation

Future climate projections for temperature and precipitation are generated on a regular grid covering the full analysis domain for each LL. The grid extent is defined to fully encompass the catchment/sub-catchment system, with an additional buffer where needed to avoid edge effects in spatial processing and to ensure seamless aggregation. The grid resolution is selected to balance three requirements: (i) representing relevant spatial gradients (e.g., topographic controls on precipitation), (ii) maintaining computational feasibility across all LLs and across the full ensemble, and (iii) producing outputs that remain usable for indicator calculation and stakeholder communication.

A consistent spatial reference system is adopted within each LL to avoid misalignment between catchment boundaries, action layers, and gridded climate data. All gridded datasets used in the workflow (projected temperature, projected precipitation, derived ETP, derived P-ETP and indicators) are harmonised to the same grid definition, including coordinate system, spatial resolution, extent, and grid alignment (origin and pixel registration). This harmonisation step is critical to ensure that spatial summaries over catchments and sub-catchments are internally consistent and reproducible.

In addition to the climate grid, supporting layers used for interpretation (e.g., digital elevation model, land cover, hydrography) should be prepared at compatible resolution to contextualise patterns. While the deliverable focuses on climate and derived hydro-climatic metrics, documenting the grid set-up ensures that results can be traced back to a clear spatial representation of the area of influence.

3.3 Gridded reference datasets

The production of local-scale climate projections relies on gridded datasets that provide spatially and temporally consistent fields over each Living Lab domain. These gridded datasets are a core component of the analogue-based regionalisation approach applied in the project. In this framework, gridded reference fields provide the local-scale target representation over the catchment/sub-catchment area, enabling the construction of analogue relationships between large-scale climate information (from CMIP6 GCMs) and local-scale variability on the analysis grid.

In practice, the gridded datasets are used to (i) define the spatial patterns and temporal behaviour that the analogue method aims to reproduce at local scale, (ii) ensure that the resulting projections are generated directly on a regular grid consistent with the catchment/sub-catchment masks, and (iii) provide a coherent baseline framing for subsequent computations (ETP, P-ETP, and indicators). This ensures that the analogue-based projections preserve physically meaningful spatial gradients and remain operationally compatible with catchment-scale aggregation required for slow-hydrology interpretation.

Beyond their role in the analogue method itself, gridded reference datasets support internal consistency and plausibility checks of baseline climatologies and derived metrics, particularly where in situ information is sparse or not representative of spatial variability. This contributes to traceability and strengthens confidence in the coherence of the projection products used for indicator derivation and action compatibility assessment.

The specific gridded datasets used in each Living Lab, including their spatial and temporal resolution, coverage, and any pre-processing applied for the analogue procedure, are documented in the corresponding Living Lab chapter (Section 7) to keep this section focused on the common framework while ensuring full site-level traceability.

3.4 Climate projection ensemble and time windows

The project's future climate assessment builds on information from the Coupled Model Intercomparison Project Phase 6 (CMIP6), which provides a coordinated international framework where multiple Global Climate Models (GCMs) simulate the evolution of the climate system under harmonised experimental protocols. GCMs are physically based numerical models that represent the atmosphere, ocean, land surface and cryosphere and solve the governing equations of climate dynamics and thermodynamics. Their strength is capturing large-scale circulation patterns and climate responses to external forcing, but their spatial resolution is typically too coarse to represent local-scale variability relevant for catchment processes, topographic gradients, and Living Lab planning needs.

For this reason, the project does not use raw CMIP6 outputs directly at local scale. Instead, CMIP6 information is used as the large-scale driver for a downscaling/regionalisation procedure that translates coarse-scale model information into gridded local-scale projections over each Living Lab area of influence. In INTERLAYER, an ensemble of 10 CMIP6 GCMs is combined with four Shared Socioeconomic Pathways (SSPs), namely SSP1-2.6, SSP2-4.5, SSP3-7.0, and SSP5-8.5, resulting in 40 projection members (10 models × 4 SSPs**)** per Living Lab domain. This ensemble design spans a broad range of plausible future evolutions by combining (i) structural differences among climate models and (ii) different future forcing trajectories associated with alternative socioeconomic and emission pathways. The SSP framework describes alternative future global development pathways and their associated greenhouse gas concentration trajectories, enabling the assessment to cover lower to higher forcing futures and to quantify uncertainty relevant for robust planning.

Table 1. Information about the 10 climate models belonging to the 6 Coupled Model Intercomparison Project (CMIP6) corresponding to the IPCC AR6. Models were retrieved from the Earth System Grid Federation (ESGF) portal in support of the Program for Climate Mode

CMIP6 MODELS	Resolution	Responsible Centre	References
ACCESS-CM2	1,875° x 1,250°	Australian Community Climate and Earth System Simulator (ACCESS), Australia	Bi, D. et al (2020)
BCC-CSM2-MR	1,125° x 1,121°	Beijing Climate Center (BCC), China Meteorological Administration, China.	Wu T. et al. (2019)
CanESM5	2,812° x 2,790°	Canadian Centre for Climate Modeling and Analysis (CC-CMA), Canadá.	Swart, N.C. et al. (2019)
CMCC-ESM2	1,000° x 1,000°	Centro Mediterraneo sui Cambiamenti Climatici (CMCC).	Cherchi et al, 2018
CNRM-ESM2-1	1,406° x 1,401°	CNRM (Centre National de Recherches Meteorologiques), Meteo-France, Francia.	Seferian, R. (2019)
EC-EARTH3	0,703° x 0,702°	EC-EARTH Consortium	EC-Earth Consortium. (2019)
MPI-ESM1-2-HR	0,938° x 0,935°	Max-Planck Institute for Meteorology (MPI-M), Germany.	Müller et al., (2018)
MRI-ESM2-0	1,125° x 1,121°	Meteorological Research Institute (MRI), Japan.	Yukimoto, S. et al. (2019)
NorESM2-MM	1,250° x 0,942°	Norwegian Climate Centre (NCC), Norway.	Bentsen, M. et al. (2019)
UKESM1-0-LL	1,875° x 1,250°	UK Met Office, Hadley Centre, United Kingdom	Good, P. et al. (2019)

Downscaling and regionalisation are essential to ensure that projections are expressed on a regular grid compatible with catchment/sub-catchment aggregation and hydro-climatic indicator derivation. In the project, these techniques are applied consistently across all ensemble members to generate local-scale projections for temperature and precipitation. The specific downscaling approach, including the analogue methodology and its configuration, is described in detail in Section 4 (Methodology).

A key element supporting the downscaling framework is the use of ERA5 reanalysis. ERA5 is a global atmospheric reanalysis produced by the Copernicus Climate Change Service, which combines a numerical weather prediction model with a wide range of observations through data assimilation to generate a physically consistent reconstruction of the atmosphere over time. ERA5 provides spatially and temporally complete fields with consistent coverage, making it particularly suitable as a reference backbone for regionalisation methods. In INTERLAYER, ERA5 is used to support the construction of relationships between large-scale climate conditions and local-scale variability, enabling the production of gridded projections that reflect both the large-scale drivers from CMIP6, and the spatial/temporal structure required for catchment-scale interpretation.

4. Methodology

The methodology implemented in INTERLAYER follows a common, reproducible workflow across all Living Labs (LLs) to generate local-scale climate projections, reduce the projection ensemble into an operational scenario set, and compute hydro-climatic indicators for resilience-oriented interpretation.

First, the analysis domain is defined as the full area of influence of each LL, typically the contributing catchment or relevant sub-catchments, and a regular analysis grid is established to ensure spatial consistency in subsequent steps. Second, local-scale gridded projections of temperature and precipitation are produced from CMIP6 information through the project's downscaling/regionalisation approach (analogue-based), ensuring that projections are expressed on the target grid and are suitable for catchment-scale aggregation. Third, reference evapotranspiration (ETP) is computed consistently across LLs and combined with precipitation to derive the basic climatic water balance (P-ETP) at grid level and aggregated to catchment/sub-catchment units.

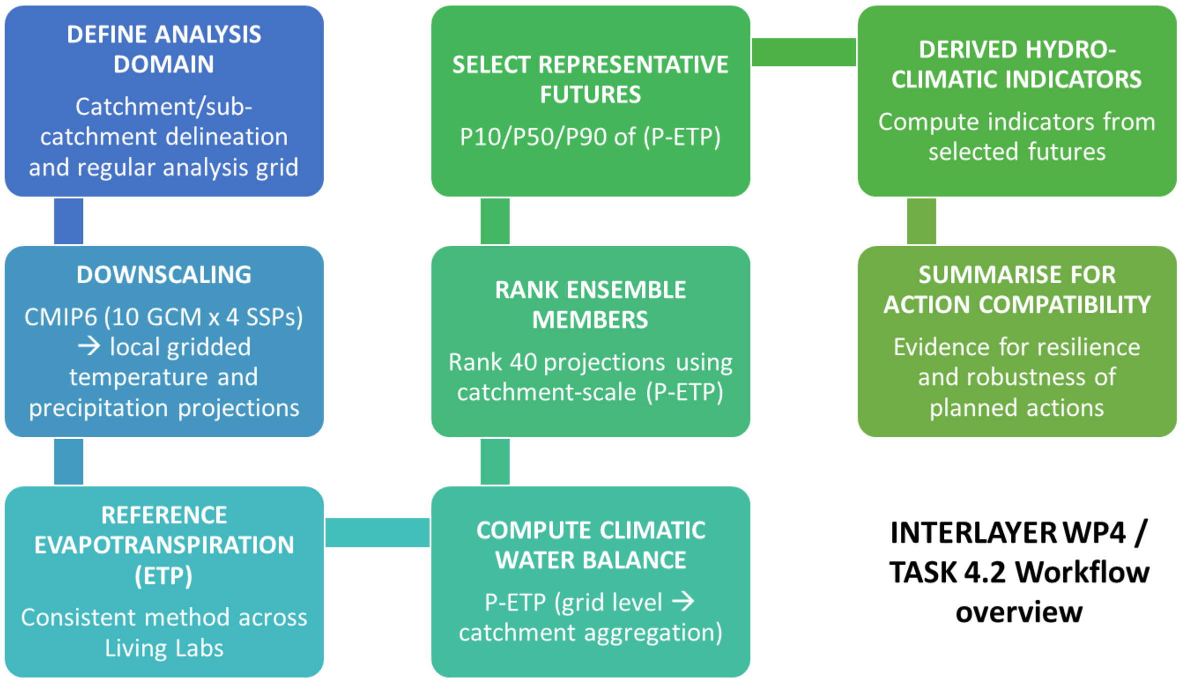

Figure 2. Workflow overview of Task 4.2.

Fourth, the full ensemble of 40 projections (10 CMIP6 models × 4 SSPs) is ranked using catchment-scale P-ETP, and three representative projections are selected at the P10, P50, and P90 quantiles. This produces an operational set of dry, median, and wet hydro-climatic futures that preserves the key spread in plausible outcomes while remaining practical for planning and communication. Fifth, hydro-climatic indicators are computed from these selected futures to translate projected changes into variables directly relevant for slow hydrology and for the assessment of action robustness. Finally, results are summarised per LL to support the discussion of action compatibility and resilience under the three representative futures.

4.1 Generation of local-scale climate

To assess climate risk, it is essential to define it based on the extent of climate impacts on the sector being analyzed. It is important to consider that the effects of climate change do not impact all regions or socio-economic sectors uniformly. Therefore, these impacts need to be evaluated at the local scale. To estimate climate risk, it is necessary to have climate projections at the local level (such as the future evolution of basic meteorological variables like temperature or precipitation), analyze the impacts and implications of these projections for the sector under study (using indicators tailored to its needs), and identify the potential risks that may arise in the coming decades. Once the impacts are identified, adaptation measures can be defined to address them, minimizing negative effects as much as possible while trying to take advantage of the positive ones.

4.1.1 State of the art in climate modelling

Climate models are the most advanced tools available for simulating the climate system, ranging from simple representations to sophisticated Earth System Models (ESMs). ESMs incorporate physical, chemical and biological processes, including interactions between the atmosphere, oceans, cryosphere and biosphere, as well as the carbon cycle and other components such as atmospheric chemistry or dynamic vegetation. These models are run under different greenhouse gas concentration pathways defined by the CMIP6 framework, known as Shared Socioeconomic Pathways (SSPs), which describe plausible futures combining socio-economic development, technological advances and emissions trajectories. Using these scenarios, climate models generate projections that help assess future climate conditions. International efforts like the IPCC and the CMIP6 modelling framework coordinate and advance global climate research, are providing the most up-to-date and comprehensive climate simulations.

As mentioned, global models operate at coarse spatial resolutions, therefore they cannot accurately capture local climate features, especially in complex terrain. To overcome this, regionalization or downscaling techniques are applied to translate large-scale climate information into local variables such as rainfall, wind or temperature. Two main approaches exist: dynamic and statistical. For this study, the validated statistical methods FICLIMA will be used. Ensuring that downscaled projections meet strict technical criteria guarantees that the resulting climate scenarios are robust, reliable and suitable for assessing future climate impacts at local scales.

Rigorous verification and validation procedures are required before generating future climate scenarios. This ensures that the statistical downscaling methodology and the selected Climate Models can reliably reproduce past climate conditions in the study area. To quantify methodological and model errors, the downscaling framework was first applied to ERA5 reanalysis data (1970-2020), comparing downscaled results with observations on a daily basis. This step verifies that the methodology is able to reproduce the underlying physical links between large-scale predictor variables and local predictands, rather than relying only on statistical fitting. In this way, it helps ensure that the relationships used by the model are physically meaningful and not merely artifacts of the calibration period. It also helps reduce biases associated with the stationarity assumption, that is, the idea that predictor-predictand relationships remain unchanged over time, which may not always hold under changing climate conditions. In parallel, each climate model was validated by comparing its downscaled Historical simulation (1979–2015) with the corresponding ERA5-based downscaling, assessing its capacity to reproduce mean climate conditions and natural variability. All climate variables and derived indicators are subjected to the same verification and validation processes to ensure the robustness of the full set of climate projections.

4.1.2- Two-step statistical downscaling methodology: FICLIMA

In the INTERLAYER project a two-step statistical regionalisation methodology (FICLIMA, Ribalaygua et al., 2013) has been used. This methodology has been applied to the variables: temperature (both maximum and minimum) and precipitation.

The methodology requires a prior selection of fields to be used as predictors and, once these have been selected, it performs a treatment based on the analogue’s methodology. In general terms, the methodology follows the scheme below: for a specific problem day ‘X’, where the low-resolution atmospheric fields (geopotentials, temperatures at different pressure levels...) are known (through the outputs of the Climate Models for day ‘X’), the aim is to estimate the value of the surface meteorological variables (maximum and minimum temperatures, precipitation i.e) for day ‘X’ at a specific location (observatory) from these known fields. The method works in two successive steps:

- The first step, called analogue stratification, consists of selecting, from a reference data bank, those n days with atmospheric configurations most similar to those of the problem day ‘X’. The similarity measure used compares the resemblance between the predictor variables used to characterise the atmospheric synoptic situations (as for example, geopotential or wind); these variables determine the synoptic forcing causing the descents and ascents of air, which generate cloudiness and precipitation. The aim is also to provide information on the surface wind direction, which allows us to study the effects that topography has on the rising air masses and, therefore, on the spatial distribution of cloudiness and precipitation.

- The second step applies different methods depending on the variable to be calculated:

  To estimate daily minimum and maximum temperatures, a multiple linear regression with automatic forward and backward predictor selection is performed for each variable. The data population will consist of the n (analogue) days selected in the previous step. As potential predictors, on the one hand, the values of atmospheric variables related to temperature forcings (such as the thickness of the air layers) in the vertical of the point for which the surface temperature is to be estimated, and on the other hand, predictors related to other temperature forcings, such as an indicator of the duration of the day in question (related to the radiative warming potential) and a weighted average of the temperatures of the previous days (which considers the effect of the thermal inertia of the ground) are offered. Once the linear relationship between the selected predictors and the predictand (minimum, maximum temperature) has been established, this relationship is applied to the predictor values for day 'X' to estimate the value of the predictand on that day.

  In the case of precipitation, precipitation is obtained by averaging the k analogous days most similar to 'X'. In addition to estimating the amount of rainfall, this method allows obtaining the probability of rain or dry weather.

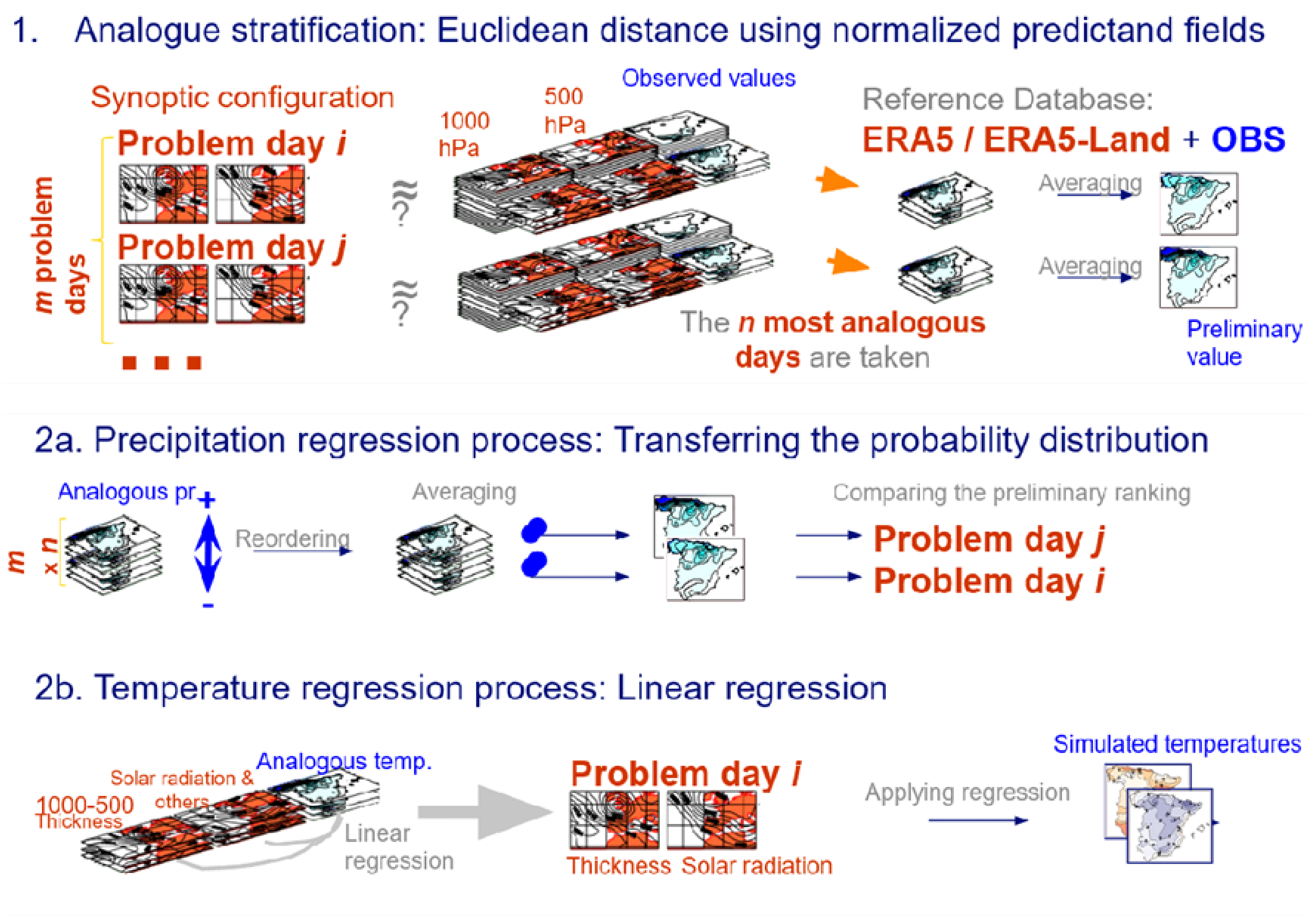

Figure 3. FICLIMA statistical downscaling: key features.

4.2 Reference evapotranspiration (ETP): method and assumptions

Reference evapotranspiration (ETP) is computed to represent the atmospheric evaporative demand in a consistent and physically interpretable way across all Living Labs (LLs). ETP provides the "demand side" of the hydro-climatic balance and is therefore a key variable to translate warming-driven changes into potential water stress, particularly in slow-hydrology contexts where soil moisture and groundwater recharge respond to the long-term balance between water availability and demand.

Monthly ETP is calculated on the same spatial grid as the downscaled temperature and precipitation projections, ensuring full consistency with subsequent water-balance calculations. The project applies to a single, harmonized ETP method across LLs to guarantee comparability of results. The selected method is Hargreaves (Hargreaves and Samani, 1985), chosen to balance physical robustness with the availability of the required meteorological variables across the full ensemble. Assumptions linked to the use of "reference" evapotranspiration (standard reference surface and conditions) are made explicit, and it is recognized that ETP is not the same as actual evapotranspiration, which depends on water availability and land-surface conditions.

Where needed, unit conversions, calendar harmonisation, and missing-value handling are applied consistently across all ensemble members and time windows. ETP outputs provide the basis for the basic climatic water balance (P–ETP) and the subsequent scenario selection and indicator computation.

4.3 Basic climatic water balance (P–ETP): computation and aggregation

The basic climatic water balance is computed as:

P–ETP = precipitation (P) minus reference evapotranspiration (ETP).

This metric is used as an integrated proxy for potential water availability and hydro-climatic stress because it combines the two first-order drivers of the long-term water balance: water supply (precipitation) and atmospheric demand (ETP). In slow-hydrology contexts, P–ETP is particularly informative because it relates directly to conditions influencing soil moisture persistence, groundwater recharge potential, and the likelihood of prolonged deficit periods.

P–ETP is computed at grid-cell level for each day and then aggregated over relevant temporal windows aligned with the needs of hydrological interpretation and Living Lab planning (e.g., seasonal and annual balances, cumulative deficits/excesses). Spatial aggregation is then performed over each LL's catchment/sub-catchment masks to produce domain-representative summaries that incorporate upstream contributions and spatial gradients. Depending on the reporting purpose, aggregation may be expressed as area-weighted means or spatial totals.

The resulting P–ETP time series and summaries provide the quantitative foundation for ordering the ensemble and selecting representative hydro-climatic futures, as well as for deriving water-relevant indicators used in the action of compatibility assessment.

4.4 Ensemble ordering and selection of three representative projections (P10/P50/P90 of Δ(P–ETP))

To make the full set of projections operational for Living Lab planning while preserving the spread of plausible futures, the project applies an explicit scenario reduction step. From the ensemble of 40 local-scale projections (10 CMIP6 models × 4 SSPs), three representative futures are selected based on the distribution of catchment-scale P–ETP, targeting the P10, P50, and P90 percentiles. These three members are interpreted as a dry, median, and wet hydro-climatic future, respectively, and are subsequently used for indicator derivation and for testing the robustness of planned actions.

A key principle of this selection is that percentiles are computed independently for each Living Lab, using the P–ETP distribution obtained over that LL's specific area of influence and time window(s). This is essential because Living Labs differ in baseline climate, hydro-climatic variability, catchment characteristics, and the magnitude and direction of projected change. Selecting P10/P50/P90 at project-wide level could misrepresent local hydro-climatic stress for a given LL; therefore, the percentile-based ranking and the identification of representative members are performed LL-by-LL to ensure local relevance and a consistent interpretation of "dry/median/wet" within each domain.

The procedure consists of (i) computing a domain-aggregated P–ETP metric for each of the 40 projections for both the reference period 1985–2014 and the future period 2071–2100, (ii) deriving the projected change Δ(P–ETP) as the difference between the future and reference periods, (iii) ranking the ensemble members according to this Δ(P–ETP), and (iv) selecting the member closest to each target quantile (P10, P50, P90) of the Δ(P–ETP) distribution, applying a consistent tie-breaking rule if needed. The full ranking distributions, selection diagnostics, and the resulting three-member scenario set are documented and discussed for each Living Lab in Section 7, where LL-specific interpretation is provided alongside the corresponding indicator results.

4.5 Hydro-climatic indicators derived from the selected projections

Hydro-climatic indicators are used to translate local-scale climate projections into information that is directly usable for hydrological interpretation, ecosystem relevance, and resilience planning. While temperature and precipitation are the core meteorological drivers, water-related impacts depend on how these variables accumulate over time, how they interact with atmospheric demand (ETP), and how often thresholds associated with stress and extremes are exceeded. This is particularly important in slow-hydrology contexts, where the dominant responses are controlled by storage and persistence, including soil moisture memory, groundwater recharge potential, and baseflow support.

For this reason, the indicator set is designed to capture both long-term hydro-climatic pressure and event-scale behavior. Monthly, seasonal and annual indicators describe the background evolution of water availability and demand, which is central to slow hydrology because recharge and sustained water availability are driven by persistent conditions rather than isolated events. At the same time, daily-based indicators are needed to characterize changes in wet-day frequency, rainfall intensity and threshold exceedances, because these control the occurrence of effective recharge opportunities, the alternation of wet and dry spells, and the potential shift toward fewer but more intense events that may increase runoff and reduce infiltration efficiency.

The precipitation-related indicators provide complementary perspectives on water supply, persistence, and extremes. Accumulated precipitation at monthly, seasonal and annual scales characterizes changes in totals and, critically, shifts in seasonality that can modify recharge windows. Maximum accumulated precipitation over 1, 5 and 10 consecutive days captures multi-day intensity and clustering, which can influence whether rainfall translates into recharge pulses or increased runoff and erosion. Wet-day counts (defined using the project's wet-day threshold) and Simple Daily Intensity Index (SDII) jointly describe the frequency of meaningful rainfall and the typical intensity on wet days, supporting detection of structural changes such as a redistribution toward fewer but more intense precipitation events.

The demand side and the integrated availability signal are represented through ETP and P–ETP. ETP captures how warming-driven atmospheric demand evolves across months and seasons, which can intensify deficits even when precipitation changes are modest. The climatic water balance (P–ETP) provides a physically interpretable proxy for potential water availability and hydro-climatic stress and is therefore particularly relevant for slow hydrology. A complementary aridity indicator (AI = P/ETP) supports clear communication of climate-regime shifts toward more arid conditions and helps interpret how supply and demand co-evolve.

To characterize distributional changes beyond means, annual percentiles of precipitation and temperature are included. These percentiles provide insight into how typical conditions (e.g., median values) and the tails of the distribution evolve, which is important for understanding the likelihood of dry-type versus wet-type years and the warming signal across the full range of conditions. In addition, daily threshold-based indicators quantify the frequency of precipitation above fixed intensity thresholds as well as the frequency of very wet days defined relative to high precipitation percentiles. These indicators link directly to hydrological mechanisms and operational concerns, including infiltration versus runoff behavior, erosion risk, and the stress placed on measures sensitive to intense rainfall.

Finally, temperature threshold indicators based on maximum temperature provide a direct measure of heat-stress frequency, which is tightly connected to evaporative demand and the acceleration of soil moisture depletion, thereby amplifying slow-hydrology deficits. IDF curves complement the daily extreme precipitation indicators by describing intensity–duration–frequency characteristics, supporting stress-testing and design considerations for actions and infrastructure sensitive to short-duration heavy rainfall.

All indicators are computed for the three representative futures selected independently for each Living Lab (P10, P50 and P90), ensuring that the "dry/median/wet" framing is locally meaningful. The resulting indicator values provide a coherent basis to interpret slow-hydrology implications under contrasting future conditions and to support the subsequent discussion of action robustness and compatibility.

Table 2. List of hydrological indicators

Indicator	Main hydrological meaning	Key relevance for slow hydrology
Accumulated precipitation (monthly/seasonal/annual)	Water input and seasonality	Controls recharge windows and long-term water availability.
Max accumulated precipitation in 1, 5, 10 consecutive days	Multi-day intensity / clustering	Recharge pulses vs runoff/erosion; indicates concentration of rainfall.
Wet days per year (P ≥ 1.5 mm)	Frequency of meaningful rainfall	Controls persistence of soil moisture and recharge opportunities.
SDII	Mean intensity on wet days	Detects "fewer but more intense" pattern affecting infiltration efficiency.
ETP (monthly/seasonal/annual)	Atmospheric demand	Warming-driven demand increases depletion and reduces effective recharge.
Climatic water balance (P–ETP)	Net surplus/deficit proxy	Core indicator for long-term stress, recharge potential and baseflow support.
Aridity Index (AI = P/ETP)	Supply-to-demand ratio	Communicates regime shift toward drier conditions; complements P–ETP.
Annual precipitation percentiles (P10–P90)	Distribution shift of P	Shows changes in typical vs dry vs wet years relevant for drought/recharge.
Annual temperature percentiles (T10–T90)	Distribution shift of T	Indicates changes in demand across the distribution, not only mean warming.
Days per year with P > X mm (1.5, 10, 15, 20, 30)	Threshold-based event frequency	Links to infiltration/runoff thresholds and moisture maintenance frequency.
Days per year with P > P90 and P95	High-percentile extremes	Captures intensification of "extreme wet days" relative to local climate.
Days per year with P > P95	Very extreme events	Important for runoff-dominated responses and risk to measures/infrastructure.
Days per year with Tmax > 25°C	Heat-stress frequency	Increases evapotranspiration and accelerates depletion/persistent deficits.
Days per year with Tmax > 28°C	Stronger heat-stress frequency	Highlights higher-demand extremes that amplify drought persistence.
IDF curves	Intensity-duration-frequency extremes	Supports design/stress-testing under heavy rainfall extremes.

4.6 Consistency checks and quality assurance

To ensure that the projections, scenario selection, and derived indicators are internally consistent and fit for decision support, the project applies quality assurance procedures throughout the workflow. The purpose is not only to detect technical errors, but also to guarantee that outputs remain physically interpretable and comparable across Living Labs and across the three representative futures.

Quality control begins with input and processing consistency checks. These include verifying units and unit conversions (e.g., precipitation, temperature and ETP units), ensuring calendar and temporal alignment across daily series and aggregation windows, and confirming that all datasets share the intended grid definition within each Living Lab. Grid alignment and masking are checked to avoid unintended spatial shifts, partial overlaps, or inconsistencies when aggregating gridded variables to catchment and sub-catchment domains.

A second layer of checks focuses on physical plausibility and “sanity” of the resulting fields and summaries. Derived variables are screened for expected ranges and sign conventions, with particular attention to metrics such as P–ETP to avoid interpretation errors introduced by processing. Seasonal behavior is inspected to confirm that monthly and seasonal cycles are coherent with the climatic setting of each Living Lab, and spatial patterns are reviewed to identify any artefacts that could arise from gridding or processing steps.

Because the three representative futures (P10/P50/P90) underpin indicator computation and action stress-testing, the scenario reduction step is verified explicitly. The distribution of the ranking metric is checked to confirm that the ensemble spread is correctly computed for the defined reference and future periods, and that the selected members are indeed the closest to the target quantiles under the selection rule. Additional checks confirm that the selected dry, median and wet futures preserve a meaningful separation in the ranking metric for each Living Lab, recognizing that the magnitude of separation may vary across domains.

Indicator calculations are then verified to ensure methodological consistency across variables and time scales. Temporal aggregations (monthly/seasonal/annual) are checked to ensure that sums and means are applied appropriately, and threshold or percentile exceedance logic is verified for daily-based indicators. Cross-indicator coherence is also assessed, for example by confirming that precipitation totals, wet-day frequency and SDII changes are logically consistent, that multi-day precipitation maxima align with extreme-day exceedances, and that warming signals reflected in temperature percentiles and maximum temperature thresholds are consistent with the evolution of ETP.

Any Living Lab-specific issues, data limitations, or deviations from the standard workflow are documented transparently, so that interpretation can be made with appropriate confidence and so that downstream users understand the conditions and limitations under which the scenario set and indicators should be used.

5. Cross-Living Lab synthesis

This section provides a cross-Living Lab (LL) synthesis of the hydro-climatic information generated in INTERLAYER under WP4 / Task 4.2. Its purpose is to summarise the main signals emerging from the ensemble-based local-scale projections and the indicator set, and to highlight common patterns and contrasts across LLs before presenting the site-specific results in Section 7. The synthesis is designed to be readable as a standalone overview while remaining consistent with the LL-by-LL percentile-based scenario selection (P10/P50/P90 of Δ(P–ETP)) and the indicator definitions described in Sections 4–6. Quantitative values, figures and LL-specific evidence can be inserted where indicated once the Section 7 chapters are finalised.

5.1 Ensemble-level signals in temperature and precipitation (local scale)

Across all Living Labs, the temperature signal is unambiguous: warming emerges consistently by mid-century and strengthens toward late century, with a clear upward shift not only in mean conditions but also in the warm tail of the temperature distribution. This shift is particularly relevant because it increases atmospheric demand and lengthens the period of high evaporative pressure. The strongest operational expression of this is the systematic increase in heat-threshold exceedances (days above 25°C and above 28°C), which becomes prominent in the southern and continental domains and is already detectable in the more maritime setting.

Precipitation signals are more heterogeneous, with strong dependence on local hydro-climatic regime and season. In the maritime lowland Living Lab (Værebro, Denmark), precipitation tends to increase across seasons, including a clearer signal of wetter conditions in the cool season, together with a detectable intensification of event-scale precipitation characteristics. In the alpine/mountain Living Lab (Liesing, Austria), precipitation changes appear more mixed, consistent with strong orographic controls and seasonal redistribution, while warming-driven processes (including snow-related seasonality) are likely to dominate the hydrological interpretation. In the Mediterranean Living Lab

(Guadiana, Portugal), precipitation exhibits a clear seasonal reorganisation, with relative gains in the cool season but drying tendencies in spring–summer and reduced wet-day frequency, reinforcing warm-season water limitation. In the continental riverine Living Lab (Danube, Romania), precipitation tends to increase in accumulated terms, but with simultaneous intensification of event characteristics and seasonal nuances that interact with rapidly increasing demand.

5.2 Changes in reference evapotranspiration (ETP) and implications

The warming signal translates into increased evaporative demand across the Living Labs, reinforcing the central role of ETP as the bridge between climate change and slow-hydrology interpretation. Even where precipitation increases (e.g., maritime and continental settings), higher demand can reduce the effectiveness of additional rainfall for long-term storage and recharge, particularly if precipitation becomes more concentrated into short events. This is especially important because slow hydrology depends on persistent, seasonal surpluses rather than isolated wet extremes.

The strongest demand-driven pressure emerges in the warm-season constrained systems. In Guadiana, increasing heat exposure and the strong rise in hot-day frequency imply a substantial intensification of warm-season atmospheric demand. In the Danube Living Lab, strong warming and a pronounced increase in heat-threshold exceedances similarly imply a significant increase in demand during summer, increasing the likelihood of prolonged demand-driven deficits. In the alpine Liesing Living Lab, increasing demand interacts with elevation-driven seasonality and potential shifts in snow accumulation/melt, which can alter the timing of water availability and reduce persistence of soil moisture outside the recharge season. In contrast, Værebro shows an increase in demand but the precipitation signal is also positive, so the key issue becomes how the additional inputs are distributed in time and whether intensification reduces infiltration efficiency.

5.3 Integrated hydro-climatic signal: Δ(P–ETP) and aridity tendencies

The integrated hydro-climatic signal captured by P–ETP highlights clear contrasts among Living Labs once supply and demand are considered jointly. In the maritime lowland LL (Værebro), precipitation increases tend to offset demand increases, resulting in a stable to more favourable climatic water balance, while event intensification remains a key operational risk. In the Mediterranean LL (Guadiana), the combination of higher heat exposure and reduced precipitation frequency (and seasonal drying) drives deficit-prone conditions and increases reliance on cool-season replenishment. In the alpine LL (Liesing), the integrated balance indicates increasing hydro-climatic stress, with demand increases dominating the net outcome and implying reduced climatic potential for recharge and greater deficit persistence, particularly toward late century. In the continental LL (Danube), despite precipitation increases in accumulated terms, the integrated signal points toward increasing hydro-climatic stress by late century, consistent with strong warming and a net deterioration of the climatic balance at catchment scale.

These patterns are consistent with expected aridity tendencies. In southern and more continental contexts, warming and heat-threshold increases drive a stronger movement toward aridity even when precipitation does not uniformly decrease, because demand rises faster than effective supply. In the maritime LL, aridity tendencies are weaker, but intensification of extremes and changes in event structure still affect hydrological risk and management needs. Where seasonality shifts reduce precipitation during warm months, aridity signals become more operationally critical because they align with periods of highest demand.

5.4 Operational scenario set: meaning of P10/P50/P90 across Living Labs

The scenario reduction approach supports robust interpretation because the dry/median/wet futures are defined locally for each Living Lab. This is important because the same absolute change can have very different significance depending on baseline regime, seasonality and variability. In practice, the local selection ensures that Scenario P10 (dry future) represents the lower tail of plausible hydro-climatic change for that specific LL, while Scenario P90 (wet future) represents the upper tail, regardless of whether the catchment is maritime, alpine, Mediterranean or continental.

5.5 Indicator-based synthesis: persistence, extremes and slow-hydrology relevance

The indicator set provides a coherent cross-LL picture of how background conditions and extremes evolve, and why both time scales are necessary for slow-hydrology interpretation. At monthly/seasonal/annual scales, accumulated precipitation, ETP and P–ETP diagnose whether the system is moving toward more persistent deficits or maintaining surplus conditions that support recharge. At daily scale, wet-day frequency and SDII describe whether precipitation becomes less frequent and/or more intense, while multi-day maxima and threshold exceedances indicate changes in extremes that can shift infiltration-runoff partitioning and increase erosion and peak-flow risk. Temperature thresholds and percentiles provide an operational link to demand-driven drying by capturing how frequently high-demand conditions occur.

Across the Living Labs, three cross-cutting patterns stand out. First, heat stress increases everywhere, but it is most operationally critical where water limitation already exists (Guadiana) or where warming is strong (Danube and Liesing), because it directly amplifies demand and deficit persistence. Second, precipitation organisation often shifts toward more intense behaviour, even in settings where totals increase, meaning that more water does not necessarily translate into more effective recharge if rainfall becomes more concentrated into short events (Værebro and Danube) or if wet-day frequency declines (Guadiana). Third, the integrated balance distinguishes LLs where net availability may remain favourable (Værebro) from those where the system becomes more deficit-prone (Guadiana, Liesing and Danube), reinforcing the relevance of the compatibility framework used in Section 6.

Table 3. Table X. Cross-Living Lab qualitative synthesis of projected changes relative to the reference period (1985–2014). Arrows (↑/↓) indicate the dominant direction of change across the ensemble and representative futures, while “Mixed” denotes no single consistent direction due to seasonal contrasts and/or model spread. The table summarises temperature warming and heat-threshold exceedances, precipitation seasonality, wet-day frequency (WD), intensity on wet days (SDII) and event-intensity behaviour, and the resulting integrated tendency in climatic water balance (P–ETP), highlighting implications for slow-hydrology processes

Living Lab	Warming (mean + distribution)	Heat thresholds (Tx>25 / Tx>28)	Precipitation totals & seasonality	Wet-day frequency (WD)	Intensity on wet days (SDII) / event intensity	Integrated balance (P–ETP)	Slow-hydrology relevance (summary)
Værebro River (Denmark)	↑ strong	↑ strong	↑ broadly (cool season important); uncertainty ↑ late century	↑	↑ and extremes ↑	↑ (more favourable)	Potentially more surplus at catchment scale, but increasing role of event intensity and extremes for infiltration/runoff efficiency.
Liesing River (Austria)	↑ strong (alpine amplification likely)	↑ strong	Mixed / seasonal redistribution	Mixed	↑ extremes/intensity	↓ (more deficit-prone)	Increasing demand dominates; reduced recharge potential and persistence, with added sensitivity to seasonal processes (incl. snow-related timing).
Guadiana River (Portugal)	↑ (clear)	↑ very strong	Seasonal redistribution: winter gains vs spring–summer drying	↓	↑ (more intense when it rains)	Deficit-prone (stress increases)	Strong warm-season stress: fewer wet days and higher demand increase deficit persistence; higher intensity raises runoff/erosion risk and reduces effective recharge.
Danube River (Romania)	↑ strong	↑ strong	↑ in accumulated terms, with seasonal nuances	Mixed to slightly ↓	↑ (intensification)	↓ (more deficit-prone by late century)	Demand-driven drying increases despite higher inputs; stronger contrast between intense events and longer drying periods, increasing variability and stress on storage/baseflow.

6. Compatibility assessment framework

This section defines how the project interprets local-scale climate projections and hydro-climatic indicators in order to assess the compatibility of planned Living Lab actions with future climate conditions. The framework is designed to be transparent, reproducible, and operational for decision support. It does not aim to provide deterministic predictions of impacts, but rather to support robust planning by testing whether actions remain feasible and effective under a range of plausible hydro-climatic futures.

6.1 Definition of "compatibility of planned actions with future climate"

In the context of INTERLAYER, an action is considered *compatible with future climate* when it can reasonably be expected to function as intended under projected future hydro-climatic conditions in the Living Lab area of influence, without requiring unrealistic assumptions. Compatibility therefore refers to the alignment between (i) the climate- and water-related conditions that an action implicitly relies on (e.g., sustained water availability, manageable extremes, suitable seasonal timing) and (ii) the conditions indicated by the projected future climate. Where projected conditions challenge these requirements, the action may still be viable but may require design adjustments, operational changes, monitoring, or complementary measures; such cases are described as conditionally compatible.

6.2 From projections to action-relevant stressors

The assessment is structured around a small set of action-relevant hydro-climatic stressors that capture the main pathways through which climate change can affect slow-hydrology systems and the performance of water-related measures. These stressors are derived from the indicator families defined in Section 4.6 and include, for example: (i) increasing atmospheric demand and drying pressure (ETP and P–ETP), (ii) persistence of deficit conditions (wet-day frequency, seasonality of P–ETP, distributional shifts), (iii) changes in precipitation organisation (SDII and wet-day counts), (iv) intensification of wet extremes (multi-day maxima, threshold exceedances, percentile exceedances, IDF), and (v) increasing heat stress frequency (Tmax thresholds and temperature percentiles). Each Living Lab may be sensitive to a subset of these stressors depending on its hydrological setting and the nature of the planned actions.

6.3 Evidence base and scenario logic (P10/P50/P90 per Living Lab)

Compatibility is evaluated using the three representative futures selected independently for each Living Lab: P10, P50 and P90 of the projected change in catchment-scale P–ETP (future period 2071–2100 relative to the reference period 1985–2014). These three futures provide an operational scenario set that represents a dry, median and wet pathway that is locally meaningful for the given Living Lab. All indicator values used in the compatibility assessment are computed for these three futures, ensuring that the assessment explicitly tests robustness across a plausible range of hydro-climatic outcomes rather than relying on a single central estimate.

6.4 Assessment approach: exposure, sensitivity and robustness

The framework combines three elements that together support a structured interpretation.

First, **exposure** characterises the direction and magnitude of projected hydro-climatic change as expressed by the indicators (e.g., shift in seasonal P–ETP, change in wet-day frequency, increase in ETP, change in multi-day precipitation maxima). Second, **sensitivity** characterises how strongly a planned action depends on the affected hydro-climatic conditions (e.g., reliance on sustained wet-season inputs, vulnerability to prolonged deficits, tolerance to intense rainfall events, dependence on low evaporative demand). Sensitivity is defined qualitatively using the action objectives and operational assumptions described for each Living Lab. Third, **robustness** is evaluated by examining whether the action's implied operating conditions remain satisfied across the three representative futures. An action that remains feasible and effective under P10, P50 and P90 is interpreted as robust; an action that performs under P50 and P90 but is challenged under P10 is considered vulnerable to drying futures and may require adaptation or contingency planning.

6.5 Compatibility categories and interpretation guidance

To support clear reporting and comparability across Living Labs, the framework uses a small set of qualitative categories. These categories are applied using the indicator evidence and the action-specific sensitivity assumptions documented in the Living Lab chapters.

- **Compatible (robust)**: the action remains aligned with projected conditions across P10/P50/P90; no major climate-driven constraints are identified.

- **Conditionally compatible**: the action is generally feasible but performance depends on future pathway and/or requires specific operational conditions (e.g., monitoring triggers, adaptive management, additional measures) to remain effective.
- **Requires adaptation**: projected conditions indicate that the action, as currently designed, is likely to face climate-driven limitations under at least one representative future (often P10), and design or operational changes are needed to meet objectives.
- **Not compatible as designed**: the action's underlying assumptions conflict strongly with projected conditions across most futures, and major redesign or alternative measures would be required.

The categories are intended for decision support and should not be interpreted as deterministic forecasts. They provide a structured way to communicate risk, identify where robustness is strong, and highlight where adaptation and monitoring can improve long-term effectiveness. Application of this framework and the resulting Living Lab-specific assessments are presented in Section 7.

7. Living Lab assessments: local-scale climate, hydro-climatic indicators and implications for resilience

This section builds directly on the preliminary climate screening presented in D4.1, which provided a first overview of future climate conditions using one representative meteorological station per Living Lab. In D4.4, the analysis is upgraded to a spatially explicit, catchment/sub-catchment framework by generating local-scale gridded projections and deriving hydro-climatic indicators that are specifically relevant for slow-hydrology processes. The Living Lab subsections that follow therefore move from point-based signals to area-of-influence evidence, presenting site-specific results for temperature, precipitation, evaporative demand and integrated water-balance indicators, and outlining the key hydro-climatic stressors that should be considered in subsequent resilience planning and action robustness testing.

Each LL section includes: (i) a description of the study area and input data used to generate the local scale projections, (ii) key conclusions from temperature and precipitation projections relative to the reference period, (iii) an integrated interpretation of the main hydro climatic indicators (including ETP, P–ETP, wet day frequency and intensity and selected extremes), and (iv) the implications of these results for slow hydrology and the robustness of planned actions. Figures showing the evolution of the hydrological indicators for each case study can be consulted in Annex 1-4 ("Evolution of the hydrological indicators for corresponding Living Labs").

7.1 Værebro River Living Lab (Denmark)

The Værebro River Living Lab is located in Denmark, within a lowland temperate setting influenced by a maritime climate. The hydro-climatic regime is characterised by moderate temperatures, precipitation distributed throughout the year, and hydrological behavior that is largely controlled by seasonal water balance dynamics and catchment storage processes. As a result, slow-hydrology mechanisms such as soil moisture persistence and groundwater recharge potential are key to interpreting how projected changes in temperature, precipitation and atmospheric demand may influence future water availability across the area of influence.

The baseline input data used to characterise local conditions and support the climate analysis consist of observed daily time series of precipitation and temperature at 11 grid locations within the study domain (Figure 4). These points are distributed approximately homogeneously across the catchment to capture spatial variability and to provide a representative baseline for the Living Lab area of influence. The daily temporal resolution of the records is consistent with the project workflow and enables the subsequent derivation of daily and accumulated indicators (monthly/seasonal/annual) used in the hydro-climatic assessment.

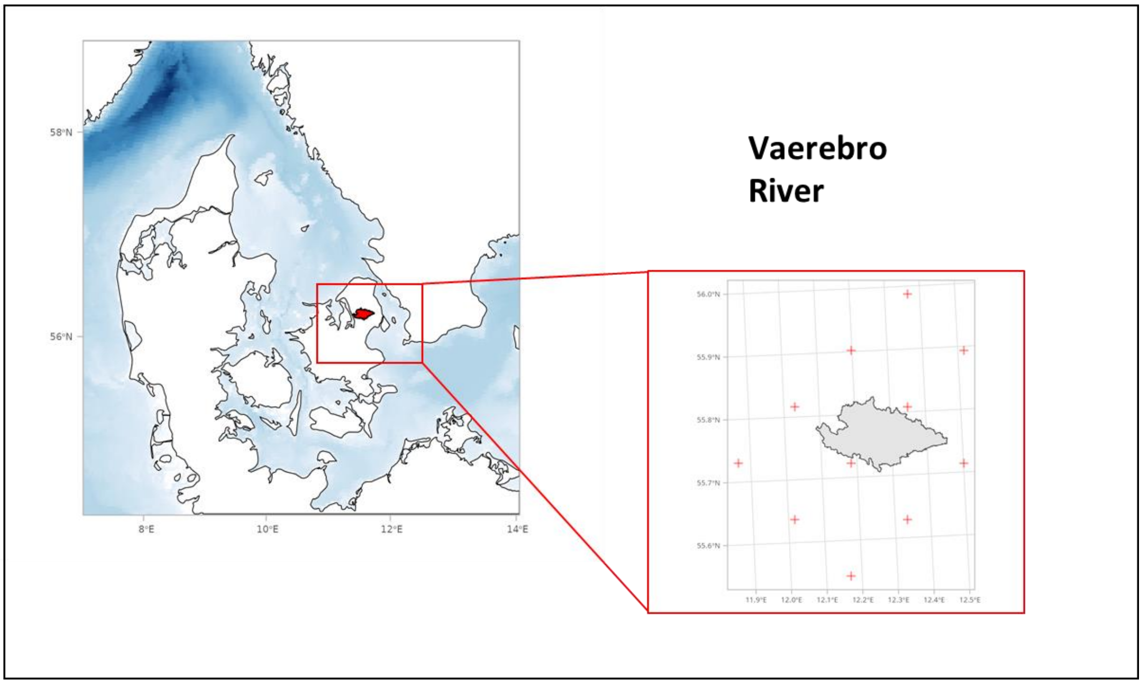

Figure 4. Location of the grid points with temperature and precipitation data used in the study for Vaerebro River.

7.1.1 Selection of the three representative futures

For the Værebro River Living Lab, three representative futures are selected from the ensemble and used consistently across all results and indicators. These futures are referred to as Scenario CNRM-ESM2-1 ssp126 (dry future), Scenario CNRM-ESM2-1 ssp585 (median future) and Scenario EC-EARTH3 ssp585 (wet future). Their position within the ensemble distribution and the corresponding selection are shown in Figure 5.

Model	Scenario	Difference
UKESM1-0-LL	ssp585	197.6
CanESM5	ssp585	181.5
ACCESS-CM2	ssp585	163.6
UKESM1-0-LL	ssp370	160.3
EC-EARTH3	ssp585	145.5
CanESM5	ssp370	141.9
CMCC-ESM2	ssp585	136.2
ACCESS-CM2	ssp370	131
UKESM1-0-LL	ssp245	124.3
EC-EARTH3	ssp370	117
CMCC-ESM2	ssp245	116.2
CMCC-ESM2	ssp370	112.7
CMCC-ESM2	ssp126	109.2
ACCESS-CM2	ssp245	95.4
CanESM5	ssp245	93.2
NorESM2-MM	ssp585	91.7
UKESM1-0-LL	ssp126	80.1
BCC-CSM2-MR	ssp370	79.4
MPI-ESM1-2-HR	ssp585	75.6
CNRM-ESM2-1	ssp585	74.2
NorESM2-MM	ssp370	72.1
EC-EARTH3	ssp245	70.8
MRI-ESM2-0	ssp585	70.8
ACCESS-CM2	ssp126	68.8
BCC-CSM2-MR	ssp585	68.4
MPI-ESM1-2-HR	ssp370	62.3
CanESM5	ssp126	60.2
CNRM-ESM2-1	ssp370	52.8
MRI-ESM2-0	ssp370	52
EC-EARTH3	ssp126	48.2
BCC-CSM2-MR	ssp245	43.5
NorESM2-MM	ssp245	43
MRI-ESM2-0	ssp245	38.6
CNRM-ESM2-1	ssp245	36.8
MPI-ESM1-2-HR	ssp245	35.5
BCC-CSM2-MR	ssp126	26.9
CNRM-ESM2-1	ssp126	23.6
NorESM2-MM	ssp126	20.5
MRI-ESM2-0	ssp126	13.2
MPI-ESM1-2-HR	ssp126	11

Figure 5. Ranked ensemble members (10 CMIP6 models × 4 SSPs) for the Værebro River Living Lab based on the projected change in climatic water balance Δ(P–ETP) for 2071–2100 relative to 1985–2014. The three representative futures selected for the subsequent analysis are highlighted in red and correspond to positions 4 (wet future), 21 (median future) and 36 (dry future) in the ordered list.

7.1.2 Future climate projections and hydro-climatic interpretation

The projections for the Værebro River Living Lab indicate a future climate characterised by a clear and consistent warming signal, accompanied by changes in precipitation and atmospheric demand that together shape the hydro-climatic conditions relevant for slow-hydrology processes. The results discussed below are reported relative to the reference period 1985–2014 and are summarised in Table 4. Both the boxplots and Table 4 report the interquartile uncertainty range (P25–P75) across the projection ensemble.

Temperature changes show a robust upward shift across the full distribution, not only in mean conditions. Annual mean, maximum and minimum temperatures all increase already by mid-century (P1: 2036–2065) and further by late century (P2: 2071–2100). Importantly, warming is also evident in the temperature percentiles meaning that both typically cold and typically warm conditions shift toward higher values. This indicates that the entire thermal regime is moving upward: cold-season conditions become less cold, and warm-season conditions become more frequent and more intense. Seasonal results confirm that warming occurs in all seasons, with particularly relevant implications during summer, when higher temperatures and a higher frequency of hot days are most directly connected to evaporative demand and stress conditions. In operational terms, the strong increase in the number of days exceeding high-temperature thresholds (such as days with Tmax above 25°C and above 28°C) implies a substantial increase in heat exposure and in the likelihood of prolonged warm spells, which can intensify water losses and accelerate depletion of catchment storage during warm periods.

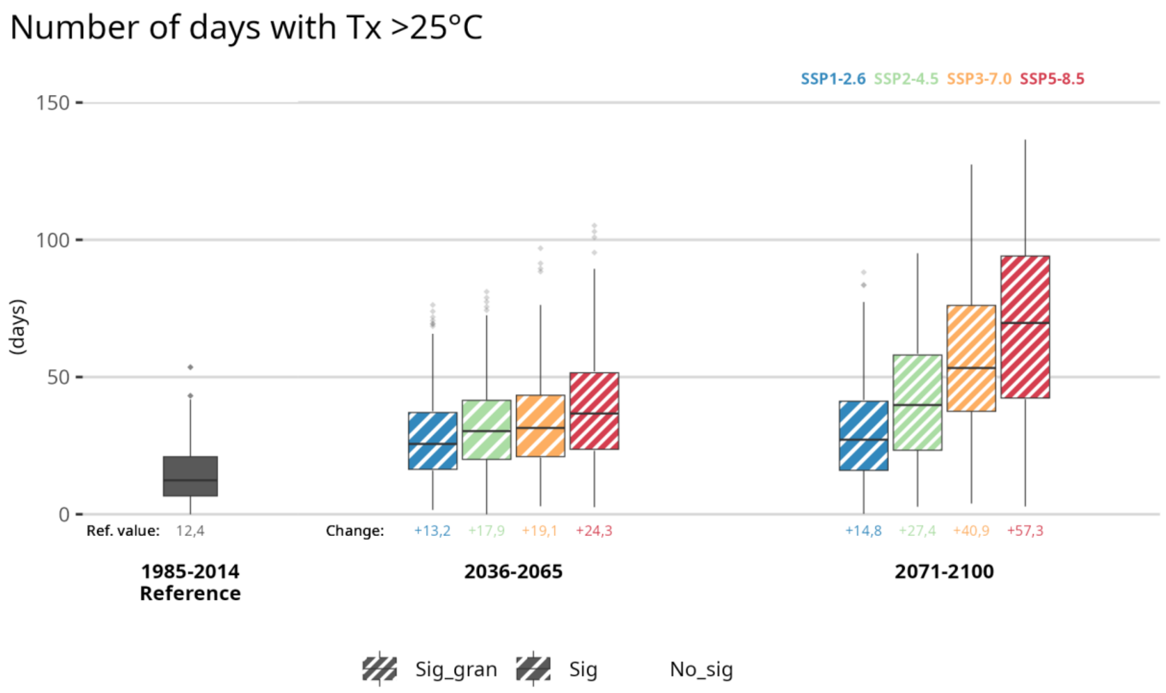

Figure 6. Expected evolution for the number of days with maximum temperature above 25oC for Vaerebro River.

This warming signal translates into an increase in reference evapotranspiration (ETP), which reflects higher atmospheric evaporative demand. As shown in Table 4, ETP increases relative to the reference period in both future windows, with a wider range by late century. For slow-hydrology systems, this change is critical because it increases the rate at which soil moisture and shallow storage can be depleted, potentially shortening the persistence of wet conditions between precipitation events and amplifying the impact of warm-season deficits. Even where precipitation increases, rising ETP can still intensify hydro-climatic stress in periods when the balance is demand dominated.

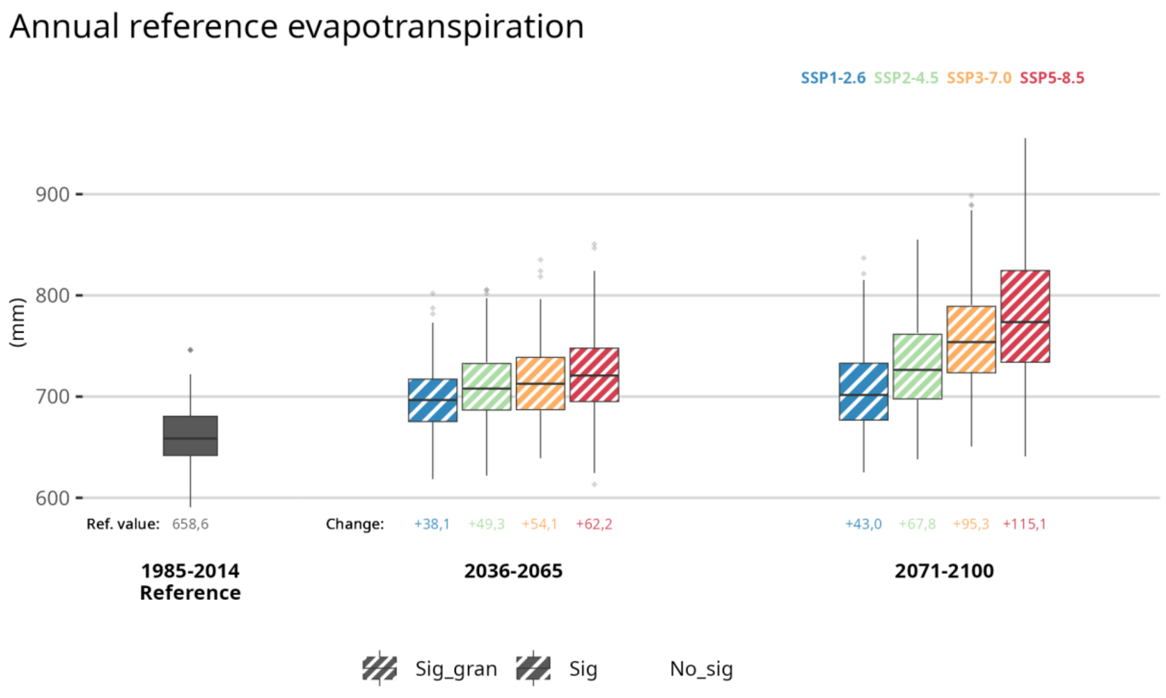

Figure 7. Expected evolution for the annual reference evapotranspiration for Vaerebro River.

Precipitation projections for Værebro River show an overall tendency toward higher totals relative to the reference period, with increases already in P1 and potentially stronger increases in P2. The precipitation signal is present across seasons, suggesting that the catchment may experience a higher average input of water. However, hydrological implications depend not only on total amounts but also on how precipitation is distributed over time and how event characteristics evolve. For this reason, the interpretation considers both accumulated precipitation at monthly/seasonal/annual scales and the daily-scale indicators that describe frequency and intensity.

Daily-scale precipitation indicators suggest that, alongside changes in totals, the precipitation regime becomes more energetic. In particular, indicators related to high-intensity events and extremes show increases, including maximum accumulated precipitation over short consecutive periods (1, 5 and 10 days) and the frequency of days exceeding higher precipitation thresholds. This points to a greater likelihood of intense rainfall events and multi-day wet spells. From a slow-hydrology perspective, this is an important nuance: multi-day wet spells can create recharge opportunities if soils and storage conditions are favourable, but more intense events can also increase surface runoff and erosion, reducing the fraction of precipitation that becomes effective infiltration. The net outcome therefore depends on how intensification interacts with catchment characteristics (soil permeability, topography, drainage connectivity) and on when these events occur within the seasonal cycle.

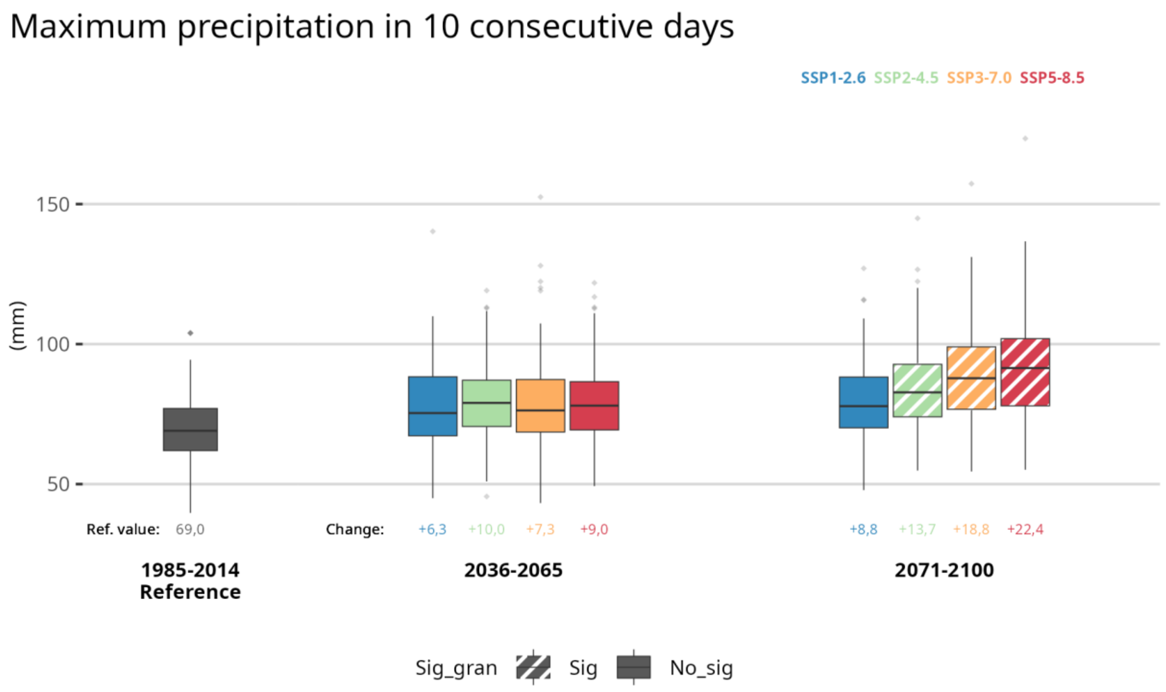

Figure 8. Expected evolution for the maximum accumulated precipitation in 10 consecutive days for Vaerebro River.

Indicators of wet-day occurrence and intensity provide further insight into precipitation organisation. Wet days (WD) increase relative to the reference period, indicating more frequent days with meaningful precipitation and therefore potentially more frequent replenishment opportunities for soil moisture. At the same time, the Simple Daily Intensity Index (SDII) increases, suggesting that wet days become, on average, more intense. Interpreted together, this pattern does not indicate a simple shift toward fewer wet days with stronger intensity; rather, it points to both an increase in wet-day occurrence and a tendency toward higher typical intensity on wet days, consistent with an intensifying precipitation regime. For slow hydrology, the increase in WD can favour persistence of moisture conditions and support recharge windows, while the increase in SDII and the growth of maxima and exceedances highlight an increasing role of higher-intensity events that may alter infiltration efficiency and increase short-term runoff responses.

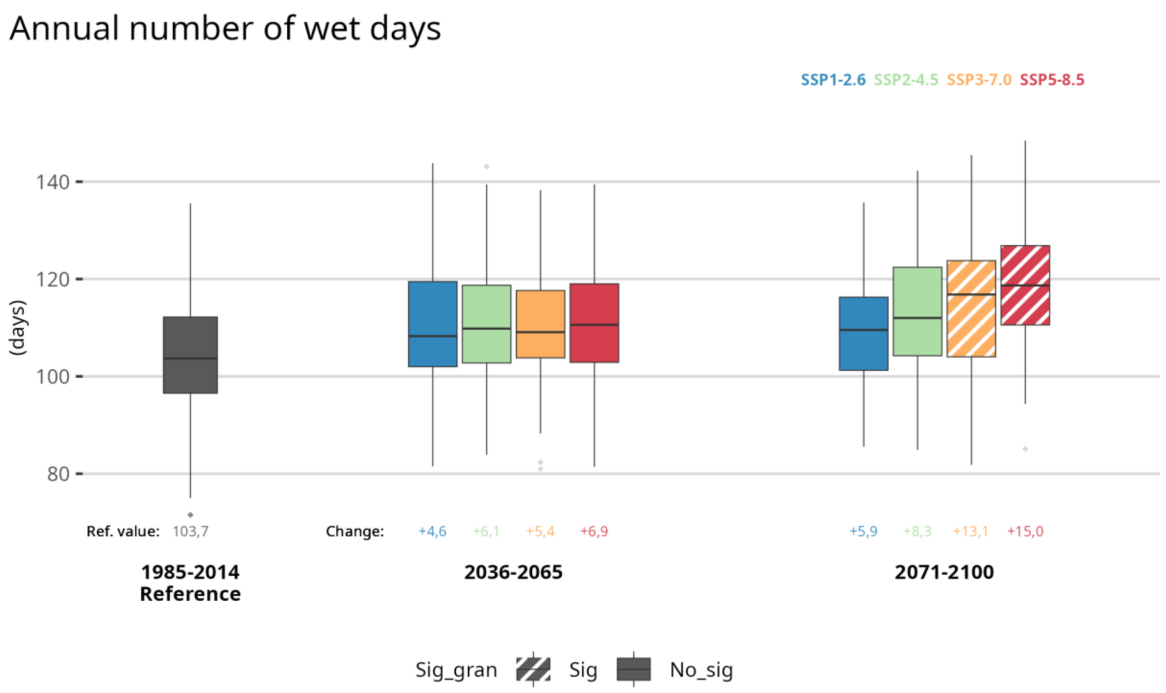

Figure 9. Expected evolution for the annual number of wet days for Vaerebro River.

The integrated hydro-climatic signal is captured by the climatic water balance P–ETP. Under reference conditions, P–ETP is positive for Værebro River, indicating a climatic surplus potential that can support recharge and storage maintenance at catchment scale. The projections show that P–ETP tends to increase in both future windows, implying that, on average, the projected precipitation increase is sufficient to offset the demand increase reflected by ETP. This result is relevant for slow hydrology because it suggests that, in an aggregated sense, the climatic margin for recharge does not deteriorate and may even strengthen. Nevertheless, interpretation must remain conditional on seasonality and event structure: a more favourable annual balance does not automatically translate into higher effective recharge if the surplus concentrates in short periods, if intense events increase runoff losses, or if warm-season demand increases reduce soil moisture persistence outside recharge windows. Therefore, P–ETP should be interpreted together with WD/SDII, multi-day maxima and threshold exceedance indicators to understand both background pressure and the mechanisms controlling effective infiltration.

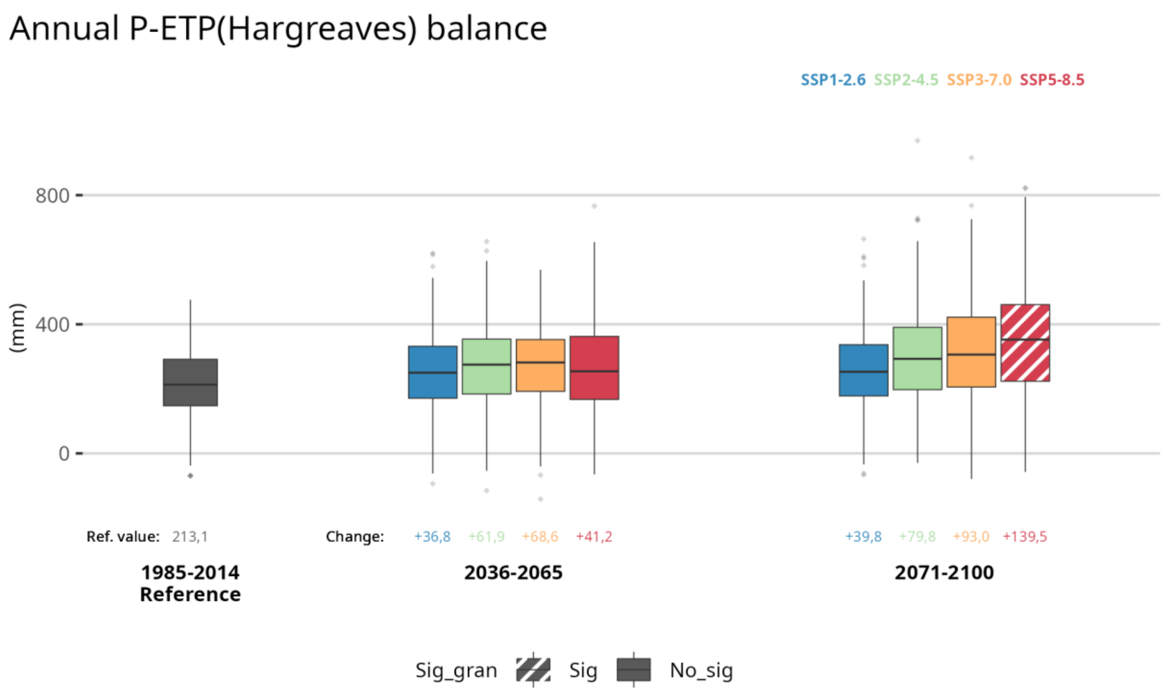

Figure 10. Expected evolution for the water balance evaluated as Precipitation minus ETP for Vaerebro River.

Drought indices introduce an additional, decision-relevant nuance. In terms of SPEI, which integrates precipitation and evaporative demand, the results indicate that drought periods are not expected to emerge strongly except toward the end of the century, and mainly when analysed over longer accumulation windows such as 24 and 60 months. In contrast, SPI, which reflects precipitation anomalies without explicitly accounting for demand, indicates drought intensity across all accumulated time scales, with a particularly pronounced signal at 24 and 60 months. This SPI–SPEI contrast is informative: it suggests that precipitation-driven deficits (meteorological drought) may occur across multiple time scales, while sustained hydro-climatic drought conditions that integrate demand effects become relevant mainly late in the century and at longer accumulation periods. For slow-hydrology systems, this distinction matters because long accumulation windows are closely linked to storage-driven behaviour and to the persistence of deficits that influence groundwater and baseflow support.

Overall, the Værebro River Living Lab is projected to experience a future climate with higher temperatures, higher evaporative demand, and increased precipitation on average, alongside intensification signals in precipitation extremes and event characteristics. The combined indicator evidence suggests a potentially favourable aggregated climatic water balance, but with growing importance of event intensity, distribution and seasonality for determining effective recharge and hydrological response. These results provide the hydro-climatic basis for interpreting slow-hydrology implications and for assessing the robustness of planned actions under the three representative futures, as further discussed in the subsequent subsections for this Living Lab.

	RP	P1-RP	P2-RP
	Temperature Indicators (ºC or days)		
T max	12.3	1.3-2.1	1.5-3.9
Winter Tmax	4	1.3-2	1.6-3.9
Spring Tmax	11	1.1-1.8	1.4-3.6
Summer Tmax	21.6	1.4-2.6	1.7-4.8
Autumn Tmax	12.2	1.7-2.4	1.9-4.7
Tmean	8.5	1.2-2	1.4-3.7
Winter Tmean	1.5	1.3-1.9	1.5-3.7
Spring Tmean	6.8	1-1.7	1.2-3.4
Summer Tmean	16.6	1.3-2.3	1.6-4.5
Autumn Tmean	9	1.6-2.3	1.8-4.5
Tmin	4.7	1.2-1.9	1.4-3.5
Winter Tmin	-1	1.2-1.7	1.3-3.4
Spring Tmin	2.6	0.9-1.6	1.2-3.2
Summer Tmin	11.5	1.3-2.1	1.5-4.1
Autumn Tmin	5.8	1.5-2.1	1.6-4.2
T10	2.9	1.5-2.2	2.1-4.2
T25	6.2	1.2-2	1.9-3.8
T50	11.4	1.2-1.9	1.9-4.1
T75	18.4	1.7-2.3	2.3-5.2
T90	22.4	1.7-2.6	2.2-5.6
Days Tmax>25	12.4	13.2-24.3	14.8-57.3
Days Tmax>28	1.8	5.2-11	5.7-30
	Precipitation Indicators (mm or days)		
Prec	783.1	69.9-102.7	79.4-230.3
Winter Prec	179.1	25.1-36.6	19.3-94.8
Spring Prec	144.3	15.2-20.2	21.5-48.2
Summer Prec	239.1	8.1-14.1	17.5-25.7
Autumn Prec	215.3	11.4-34.7	18.5-63.9
Days P>1mm	123.7	3.5-6.1	3.5-13
Days P>5mm	43.5	5.8-7.3	5.3-15.5
Days P>10mm	17	3-4.3	3.1-10.3
Days P>15mm	7.7	2-2.7	2.4-6.5
Days P>20mm	3.4	1.4-1.7	1.6-4.8
Days P>30mm	0.3	0.3-0.5	0.5-1.6
Days P>P95	19.5	3-4	3.1-10.3
Max Prec in 1 day	27.4	2.9-3.9	3.9-8.4
Max Prec in 5 days	52.7	3.6-5.5	5.8-14
Max Prec in 10 days	69	6.3-9	8.8-22.4
P75	2	0.2-0.3	0.2-0.7
P90	5.9	0.7-0.9	0.7-2.1
P99	19	1.9-2.5	2.3-6.2
	Water ability indicators		
AI	1.3	-	-
SDII	21.3	0.4-0.7	0.6-1.4
WD	103.7	4.6-6.9	5.9-15
ETP	658.6	38.1-62.2	43-115.1
Prec-ETP	213,1	36.8-68.6	39.8-139.5

Table 4. Summary of projected changes in temperature, precipitation and water-availability indicators for the Værebro River Living Lab. Values are reported relative to the reference period RP (1985–2014). P1–RP represents the change for the mid-century period P(2036–2065) with respect to RP, and P2–RP represents the change for the late-century period P2 (2071–2100) with respect to RP. Temperature indicators (°C) include annual and seasonal Tmax, Tmean and Tmin, temperature percentiles (T10–T90), and the annual number of days above heat thresholds (Days Tmax > 25°C and Days Tmax > 28°C). Precipitation indicators (mm) include accumulated precipitation at monthly/seasonal/annual scales, maximum accumulated precipitation over 1, 5 and 10 consecutive days, and frequency-based metrics (wet days and intensity-related indicators). Water-availability indicators summarise changes in SDII, wet days (WD), reference evapotranspiration (ETP) and the climatic water balance (P–ETP). For each entry, the table reports the P25 and P75 values of the projection ensemble (interquartile range) to summarise uncertainty across models and scenarios.

7.1.3 Implications for planned actions and resilience planning

The climate and indicator evidence for Værebro River provides the hydro-climatic basis to support resilience planning under uncertainty. The results point to consistent warming and higher evaporative demand, while precipitation tends to increase at aggregated scales. At the same time, indicators related to event characteristics suggest a more energetic precipitation regime, with a greater role of intense events and short-term maxima. From a slow-hydrology perspective, this combination suggests that mean climatic water availability may remain favourable, but the effectiveness of additional precipitation for recharge and storage will increasingly depend on seasonality and event structure (infiltration versus runoff partitioning under higher intensities).

It is important to note that this deliverable does not prescribe or implement measures; rather, it provides climate-driven evidence to stress-test planned actions. For Værebro River, the key climate stressors to consider in subsequent planning are (i) increased warm-season demand and heat exposure and (ii) intensification of precipitation events, which may affect runoff peaks, erosion risk and infiltration efficiency. These stressors can be used by Living Lab teams to assess whether planned actions remain robust across the selected dry/median/wet futures and to define monitoring needs and adaptive management triggers where appropriate.

7.2 Liesing River Living Lab (Austria)

The Liesing River Living Lab is located in Austria, within a pre alpine hill dominated environment where hydro-climatic conditions are strongly influenced by topography and elevation gradients. The catchment is characterised by marked seasonality, with temperature controlling snow accumulation and melt processes and precipitation exhibiting substantial spatial variability across the basin. These features make the Liesing River a hydrologically sensitive system, where slow-hydrology mechanisms such as seasonal storage (snowpack and soil moisture), recharge dynamics and delayed catchment response play a central role in shaping water availability and streamflow regimes.

The baseline input data used to support the local-scale climate analysis consist of gridded daily series of precipitation and temperature extracted at 105 grid points distributed across the Living Lab area of influence (Figure 11). This relatively dense grid-point sampling is intended to capture the strong spatial heterogeneity associated with steep terrain in the upper catchment and to provide representative coverage of the catchment and its elevation-driven climatic gradients. The daily temporal resolution is consistent with the project workflow and enables the derivation of both daily-based indicators (e.g., wet days, intensity and threshold exceedances) and accumulated indicators at monthly, seasonal and annual scales used in the hydro-climatic assessment.

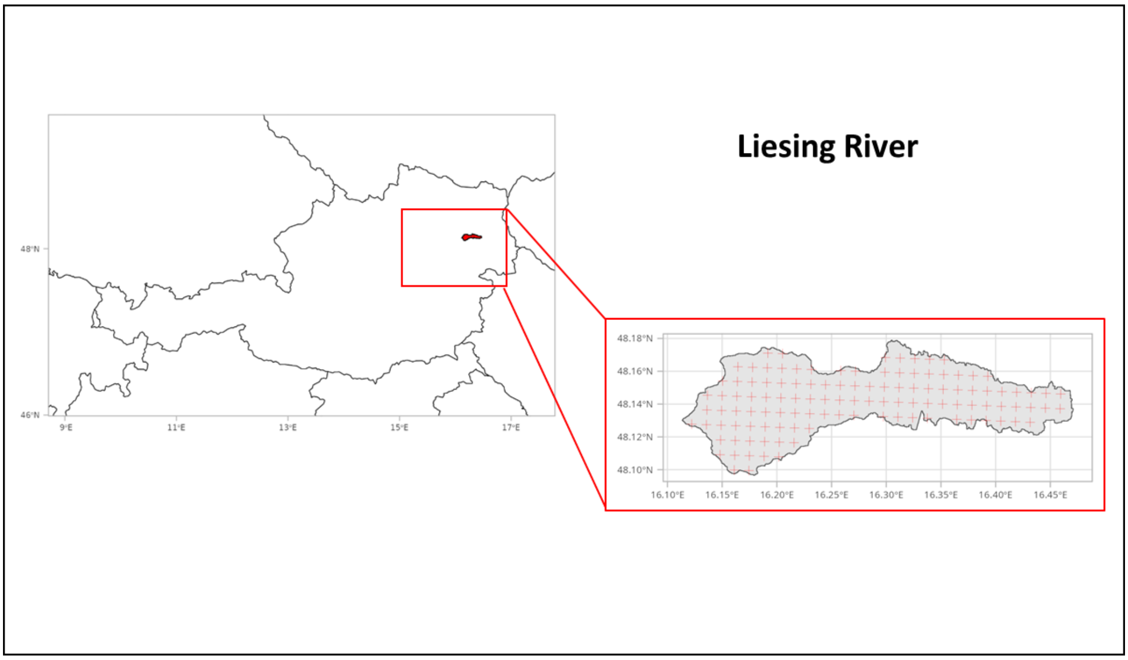

Figure 11. Location of the grid points with temperature and precipitation data used in the preliminary study for Liesing River.

7.2.1 Selection of the three representative futures

For the Liesing River Living Lab, three representative futures are selected from the ensemble and used consistently across all results and indicators. These futures are referred to as Scenario CNRM-ESM2-1 (dry future), Scenario MPI-ESM1-2-HR (median future) and Scenario CanESM5 ssp585 (wet future). Their position within the ensemble distribution and the corresponding selection are shown in Figure 12.

Model	Scenario	Difference
UKESM1-0-LL	ssp585	295.1
CMCC-ESM2	ssp585	247
UKESM1-0-LL	ssp370	238.3
ACCESS-CM2	ssp585	229.8
CanESM5	ssp585	226.8
CMCC-ESM2	ssp370	207.8
EC-EARTH3	ssp585	193.4
ACCESS-CM2	ssp370	190.2
CanESM5	ssp370	184
UKESM1-0-LL	ssp245	177.5
CMCC-ESM2	ssp245	175
NorESM2-MM	ssp585	174
EC-EARTH3	ssp370	170.9
NorESM2-MM	ssp370	139.8
BCC-CSM2-MR	ssp585	136.4
CNRM-ESM2-1	ssp585	135.1
ACCESS-CM2	ssp245	133.9
BCC-CSM2-MR	ssp370	131.5
MRI-ESM2-0	ssp585	130
MPI-ESM1-2-HR	ssp585	125.6
CMCC-ESM2	ssp126	125.4
UKESM1-0-LL	ssp126	110.9
CanESM5	ssp245	110.6
MRI-ESM2-0	ssp370	106.6
MPI-ESM1-2-HR	ssp370	96.5
ACCESS-CM2	ssp126	93.4
CNRM-ESM2-1	ssp370	89.5
NorESM2-MM	ssp245	86.9
EC-EARTH3	ssp245	83.9
CNRM-ESM2-1	ssp245	76.5
CanESM5	ssp126	74
MRI-ESM2-0	ssp245	72
BCC-CSM2-MR	ssp245	67
NorESM2-MM	ssp126	63.6
MPI-ESM1-2-HR	ssp245	62.4
EC-EARTH3	ssp126	53.4
CNRM-ESM2-1	ssp126	53.3
MRI-ESM2-0	ssp126	43.4
BCC-CSM2-MR	ssp126	42.9
MPI-ESM1-2-HR	ssp126	19.1

Figure 12. Ranked ensemble members (10 CMIP6 models × 4 SSPs) for the Liesing River Living Lab based on the projected change in climatic water balance Δ(P–ETP) for 2071–2100 relative to 1985–2014. The three representative futures selected for the subsequent analysis are highlighted in red and correspond to positions 4 (wet future), 21 (median future) and 36 (dry future) in the ordered list.

7.2.2 Future climate projections and hydro-climatic interpretation

The projections for the Liesing River Living Lab indicate a future climate characterised by a strong and consistent warming signal, combined with changes in precipitation and atmospheric demand that lead to a net increase in hydro-climatic stress at catchment scale. The results discussed below are reported relative to the reference period 1985–2014 and are summarised in Table 5. The ranges shown in the table represent the interquartile spread of the projection ensemble (P25–P75), and therefore provide a robust summary of uncertainty across models and scenarios.

Temperature changes are robust across indicators and time horizons. By mid-century (P1: 2036–2065), temperature-related indicators show increases typically of the order of about +1.2 to +3.7°C, depending on the variable and season, while by late century (P2: 2071–2100) the warming becomes substantially stronger, with ranges reaching approximately +4 to +7°C for the most responsive indicators in Table 5. The fact that increases are also evident across the temperature distribution (percentile-based indicators) indicates a broad shift of the thermal regime rather than an isolated change in mean conditions. In an alpine catchment such as Liesing, this matters because warming affects not only evaporative demand but also cold-season processes, including snow accumulation and the timing and intensity of melt, which can modify seasonal water availability and the partitioning between storage and runoff.

The intensification of warm conditions is also reflected in the heat-threshold indicators. Table 5 shows large increases in the annual number of days exceeding high-temperature thresholds already by mid-century, and even more pronounced increases by late century. This implies a substantial growth in the frequency of hot days and warm spells, increasing the likelihood of sustained warm-period stress, particularly during summer, when atmospheric demand is highest and catchment storage can be progressively depleted.

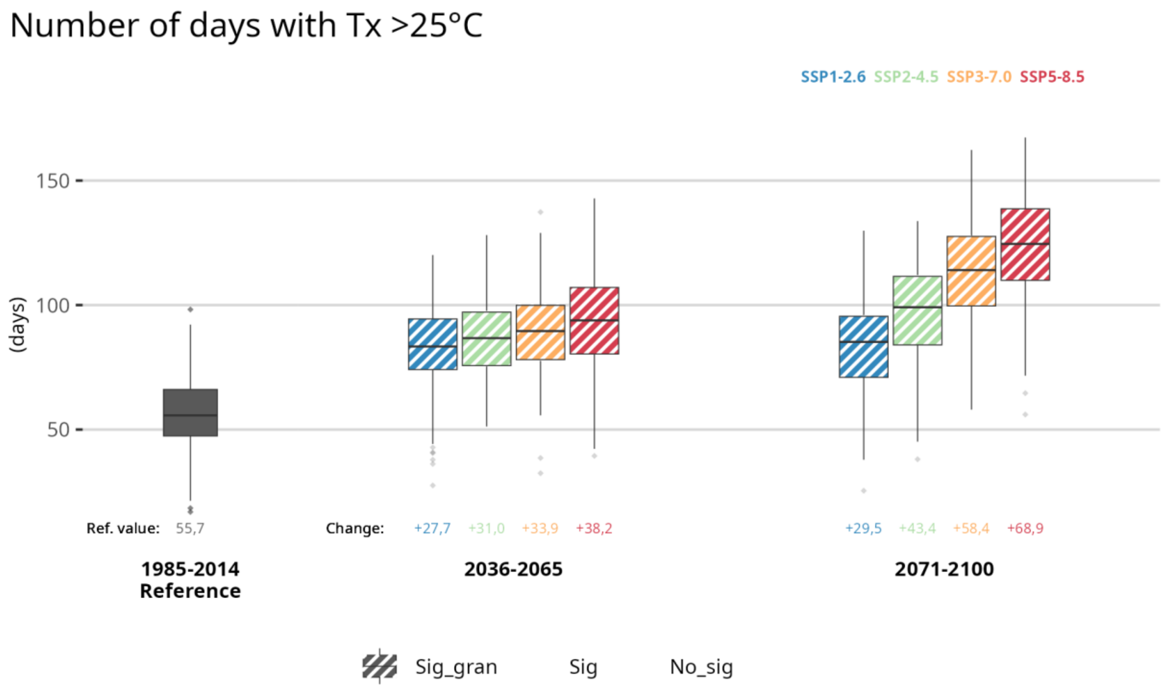

Figure 13. Expected evolution for the number of days with maximum temperature above 25oC for Liesing River.

Consistent with warming, reference evapotranspiration (ETP) increases markedly. Table 13 indicates mid-century increases on the order of roughly +60 to +91 (ETP units as reported), rising to about +68 to +181 by late century. This is a key driver for slow-hydrology interpretation, because higher ETP accelerates soil moisture depletion and reduces the persistence of wet conditions between precipitation events. In mountain environments, higher demand can also reduce the effective contribution of precipitation to recharge and storage, particularly during the warm season.

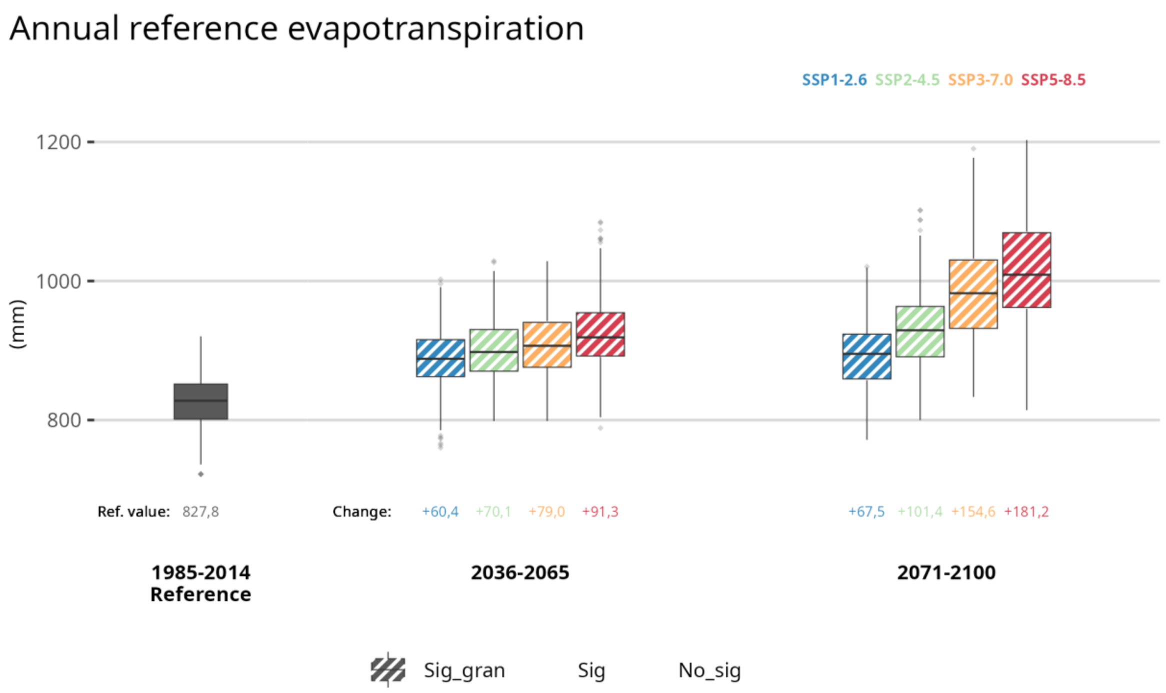

Figure 14.Expected evolution for the annual reference evapotranspiration for Liesing River.

Precipitation signals show a more mixed behaviour than temperature, which is typical of climate projections. Table 5 indicates that accumulated precipitation tends to increase for several indicators and periods, suggesting that water inputs may rise in parts of the year and/or for some accumulation metrics. At the same time, at least one precipitation component shows a negative change range (i.e., a decrease relative to the reference period), which is consistent with a seasonal redistribution pattern where some seasons become wetter while others become drier. This is particularly important for slow hydrology because the timing of precipitation relative to demand controls whether additional precipitation translates into recharge and sustained storage, or instead is offset by higher evaporative losses.

Daily-scale precipitation characteristics also point to changes in event structure. Indicators linked to multi-day maxima and threshold exceedances generally increase, suggesting that intense precipitation events and short-term accumulations become more frequent or more intense. In an alpine catchment, this has two complementary implications. On the one hand, more intense events can generate recharge opportunities if soils and storage are receptive and precipitation occurs in periods when demand is lower. On the other hand, intensification can increase runoff peaks and erosion risk, and may reduce infiltration efficiency during the most intense events, especially on steep slopes or where soil saturation dynamics promote rapid runoff generation.

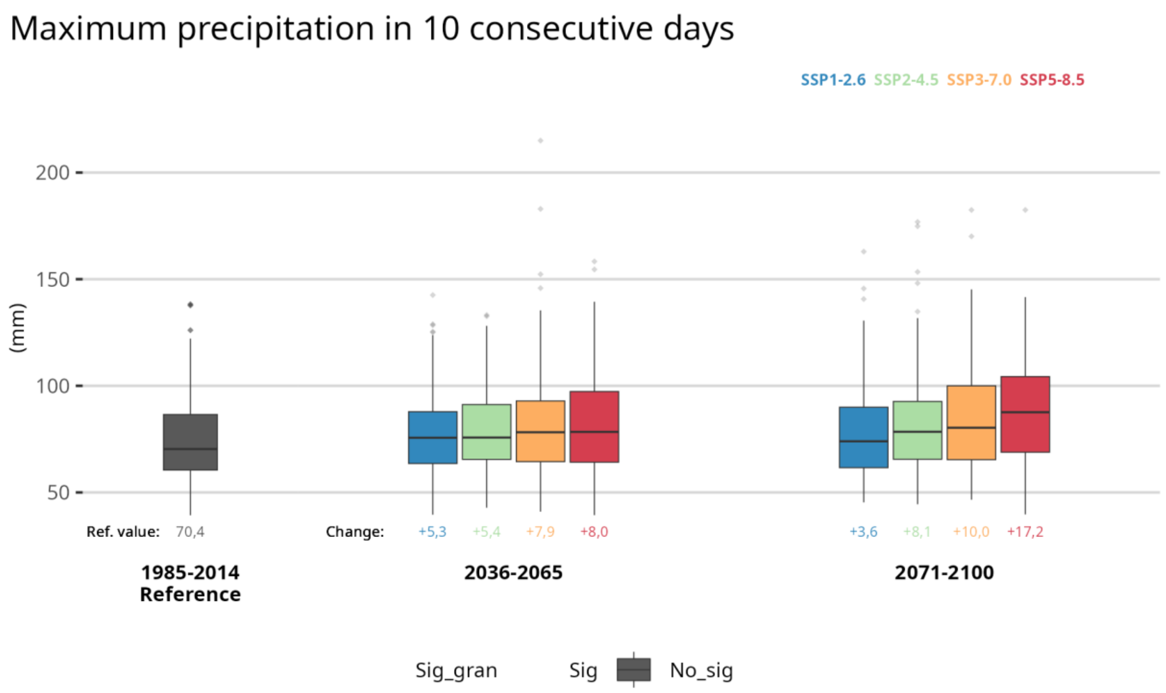

Figure 15.Expected evolution for the maximum accumulated precipitation in 10 consecutive days for Liesing River.

The combined "water availability" indicators show that the demand increase dominates the integrated hydro-climatic balance. In Table 5, SDII increases (indicating higher average intensity on wet days), while wet-day related behaviour suggests modest changes in rainfall occurrence depending on the period. Most importantly, the climatic water balance P–ETP becomes more negative: the projected change ranges are negative in both future windows, and the magnitude of the negative change strengthens toward late century. This indicates that, despite precipitation increases in parts of the indicator set, the increase in atmospheric demand (ETP) is large enough that the net climatic surplus decreases and the catchment shifts toward more deficit-prone conditions, particularly by the end of the century.

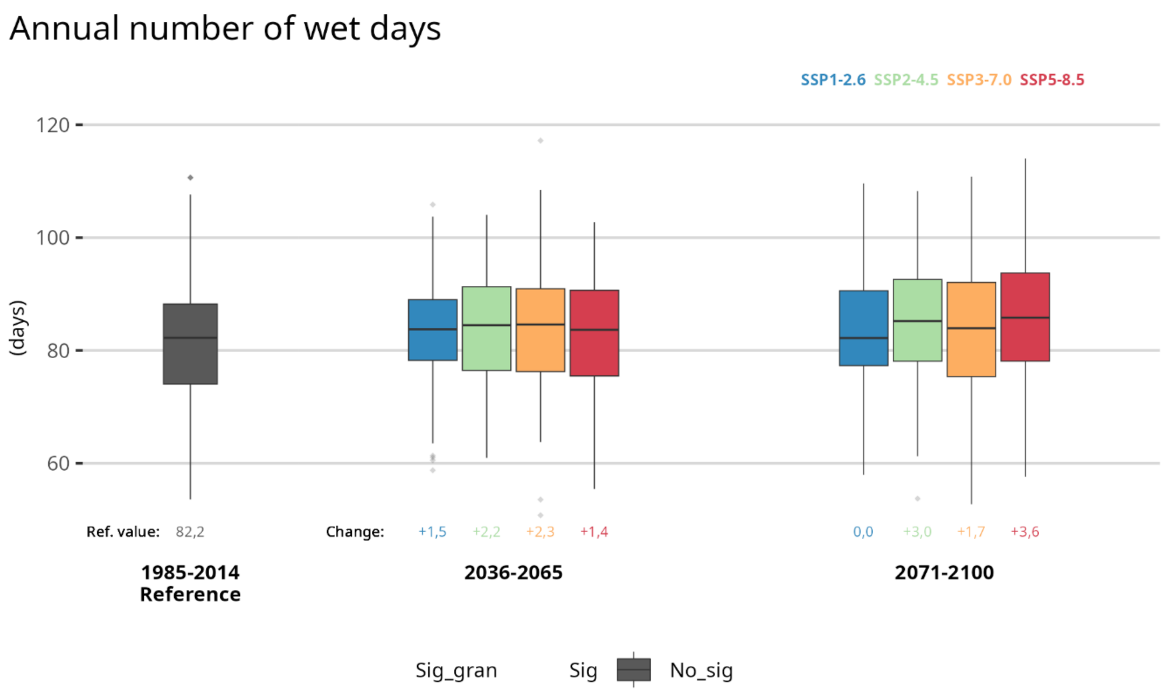

Figure 16.Expected evolution for the annual number of wet days for Liesing River.

For slow-hydrology processes, this integrated signal is highly relevant. A more negative P–ETP implies reduced climatic potential for recharge, lower persistence of soil moisture and storage, and a higher likelihood of sustained deficits affecting groundwater contributions and baseflow support. At the same time, the tendency toward more intense precipitation events means that the system may experience a greater contrast between short-lived wet extremes and longer periods of demand-driven drying. This combination is often challenging for resilience planning because it can increase both (i) warm-season water stress and (ii) sensitivity to event-scale impacts such as runoff peaks and erosion, even when annual precipitation does not decrease uniformly.

Annual P-ETP(Hargreaves) balance

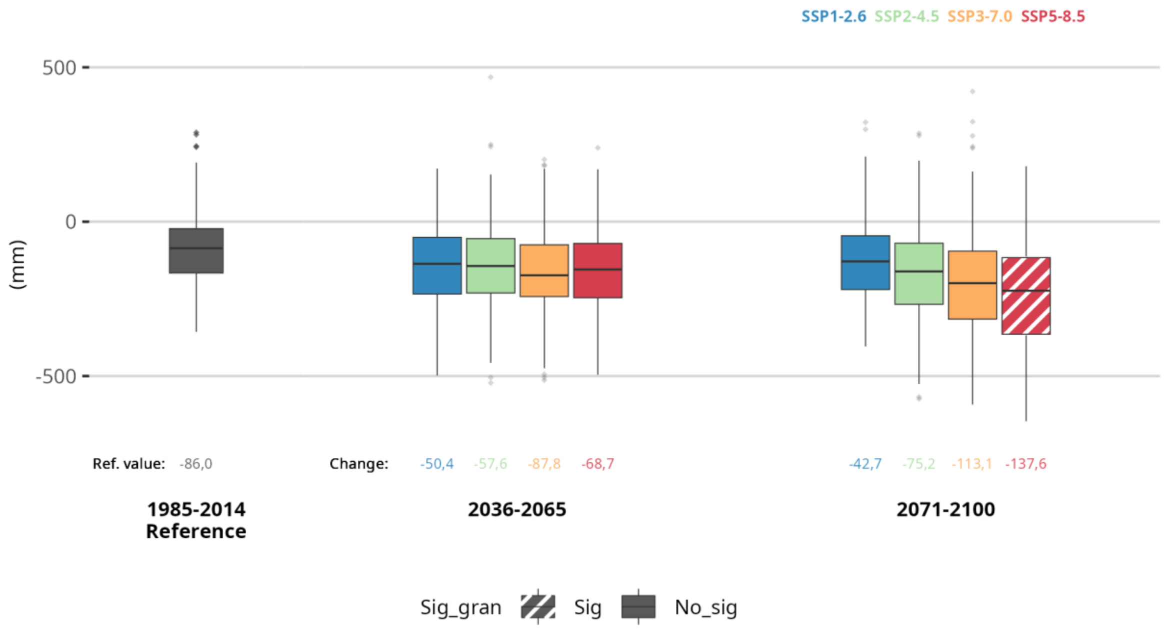

Figure 17.Expected evolution for the water balance evaluated as Precipitation minus ETP for Liesing River.

Overall, the Liesing River Living Lab is projected to warm substantially, with a clear intensification of hot-day frequency, strongly increasing ETP and shifting the catchment toward a more deficit-dominated hydro-climatic balance (negative changes in P–ETP) by mid- and especially late century. Precipitation changes show a mixed seasonal signature and an intensification of extremes, which reinforces the need to interpret totals together with event-scale metrics. These results provide the hydro-climatic basis for assessing slow-hydrology implications and, subsequently, the robustness of planned actions under the three representative futures for the Liesing River Living Lab.

	RP	P1-RP	P2-RP
	Temperature Indicators (°C)		
T max	14.5	1.7-2.7	1.8-5.1
Winter Tmax	4.3	1.2-2.1	1.5-4.2
Spring Tmax	13.8	1.4-2.1	1.6-4
Summer Tmax	25.3	2.5-3.7	2.8-7
Autumn Tmax	14.3	1.9-2.8	2-5.6
Tmean	10.3	1.6-2.5	1.7-4.7
Winter Tmean	1.3	1.2-1.9	1.4-4
Spring Tmean	9.4	1.4-1.9	1.6-3.7
Summer Tmean	20.1	2.2-3.3	2.4-6.3
Autumn Tmean	10.5	1.7-2.6	1.9-5.1
Tmin	6.2	1.4-2.2	1.6-4.3
Winter Tmin	-1.8	1.2-1.8	1.3-3.6
Spring Tmin	5	1.3-1.7	1.5-3.4
Summer Tmin	14.9	1.8-2.9	2.1-5.5
Autumn Tmin	6.5	1.6-2.4	1.7-4.7
T10	2.9	1.6-2.4	2.2-4.6
T25	7	1.4-2.3	1.9-4.5
T50	14	1.7-2.3	2-4.9
T75	22	2.3-3.2	2.8-6.8
T90	26.8	2.4-3.7	2.8-7.5
Days Tmax>25	55.7	27.7-38.2	29.5-68.9
Days Tmax>28	25.6	23.7-36.5	26-69.9
	Precipitation Indicators (mm)		
Prec	713.2	30.1-59.8	58.7-9.3
Winter Prec	132.1	10.9-16.6	12.6-35.2
Spring Prec	173.8	20.6-28.3	31.6-61.9
Summer Prec	236.1	-12.8 – (-10.1)	-27.8 – (-2)
Autumn Prec	167.3	5.1 - 14	8.8 -19.9
Days P>1mm	97	0.7-2	0.1-2.3
Days P>5mm	36.5	1.9-3.1	1.6-5.5
Days P>10mm	16.5	1.1-1.9	1.4-4.1
Days P>15mm	8.6	0.7-1.5	1.3-3.2
Days P>20mm	4.5	0.6-1.1	1.1-2.7
Days P>30mm	0.8	0.3-0.7	0.4-1.5
Days P>P95	17.1	1.1-2	1.5-4.1
Max Prec in 1 day	31.4	1.2-4.8	3.3-8.5
Max Prec in 5 days	56.2	3.9-6	4-14.1
Max Prec in 10 days	70.4	5.3-8	3.6-17.2
P99	20.9	0.6-1.8	1.5-4.1
	Water ability indicators		
AI	0.9	-	-
SDII	30.4	0.8-1.8	0.7-3.3
WD	82.2	1.4-2.3	0-3.6
ETP	827.8	60.4-91.3	67.5 – 181.2
Prec-ETP	-86	-68.7 – (-50.4)	-137.6 –(-42.7)

Table 5.Summary of projected changes in temperature, precipitation and water-availability indicators for the Liesing River Living Lab. Values are reported relative to the reference period RP (1985–2014). P1–RP represents the change for the mid-century period P1(2036–2065) with respect to RP, and P2–RP represents the change for the late-century period P2 (2071–2100) with respect to RP. Temperature indicators (°C) include annual and seasonal Tmax, Tmean and Tmin, temperature percentiles (T10–T90), and the annual number of days above heat thresholds (Days Tmax > 25°C and Days Tmax > 28°C). Precipitation indicators (mm) include accumulated precipitation at monthly/seasonal/annual scales, maximum accumulated precipitation over 1, 5 and 10 consecutive days, and frequency-based metrics (wet days and intensity-related indicators). Water-availability indicators summarise changes in SDII, wet days (WD), reference evapotranspiration (ETP) and the climatic water balance (P–ETP). For each entry, the table reports the P25 and P75 values of the projection ensemble (interquartile range) to summarise uncertainty across models and scenarios.

7.2.3 Implications for planned actions and resilience planning

For the Liesing River Living Lab, the climate projections and indicators indicate substantial warming and a strong rise in atmospheric demand, combined with precipitation changes that are mixed and season-dependent and with signals of intensified event characteristics. The integrated hydro-climatic interpretation points toward increasing deficit pressure over longer time windows, particularly toward late century, which is critical for slow-hydrology processes that depend on seasonal storage and recharge dynamics. In a prealpine context, these changes also have potential implications for the timing of water availability, as warming can modify cold-season processes and seasonal transitions that support storage-driven behaviour.

This deliverable provides the climate and hydro-climatic evidence base, but it does not implement measures. The results identify the main stressors that subsequent planning should account for: (i) demand-driven drying linked to strong warming, (ii) potential seasonal redistribution of precipitation, and (iii) increasing intensity of precipitation events that may alter runoff generation and reduce effective infiltration during the most intense episodes. These stressors provide a structured basis for Living Lab teams to test robustness of planned actions under the selected dry/median/wet futures and to identify where adaptation, monitoring or design refinements may be needed.

7.3 Guadiana/Toutalga River Watershed Living Lab (Portugal)

The Guadiana/Toutalga River Living Lab is located in southern Portugal, within a Mediterranean hydro-meteorological setting characterised by strong seasonality. Precipitation is typically concentrated in the cooler months, while summers are dry and hot, leading to a pronounced seasonal water deficit. Consequently, water availability is largely controlled by the balance between cool-season inputs and warm-season atmospheric demand, with slow-hydrology processes (soil moisture persistence, seasonal storage, and recharge dynamics) playing a key role in shaping catchment response.

For this Living Lab, a dedicated local gridded observational dataset was not available at the required spatial and temporal resolution. Therefore, the baseline input data used in the analysis are derived from ERA5-Land, extracting daily time series of precipitation and temperature at 16 points distributed approximately homogeneously across the area of influence (Figure 18). This set-up provides consistent spatial coverage of the domain and supports the computation of both daily-based indicators (e.g., wet days and intensity metrics) and accumulated indicators at monthly, seasonal, and annual scales used in the hydro-climatic assessment.

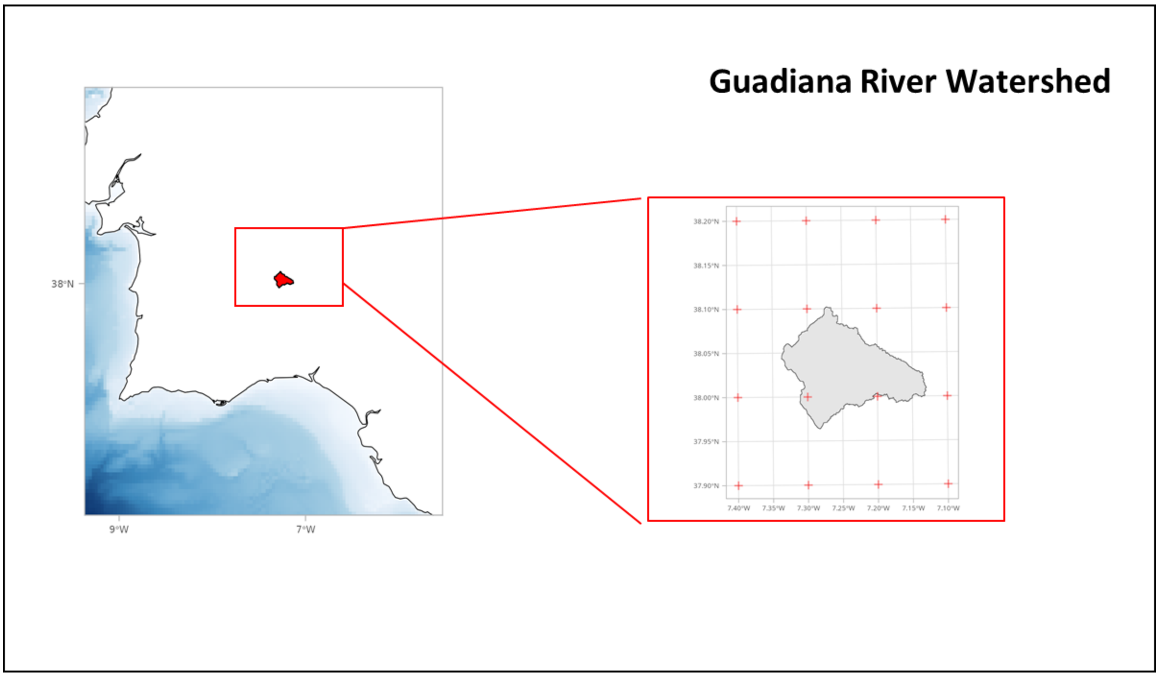

Figure 18.Location of the grid points with temperature and precipitation data used in the preliminary study for Guadiana River.

7.3.1 Selection of the three representative futures

For the Guadiana River Living Lab, three representative futures are selected from the ensemble and used consistently across all results and indicators. These futures are referred to as Scenario EC-EARTH ssp585 (dry future), Scenario MPI-ESM1-HR ssp126 (median future) and Scenario BCC-CSM2-MR ssp370 (wet future). Their position within the ensemble distribution and the corresponding selection are shown in Figure 19.

Modelo	Escenario	Diferencia
CMCC-ESM2	ssp126	50.5
MRI-ESM2-0	ssp126	40.6
CanESM5	ssp245	40
NorESM2-MM	ssp126	32.9
EC-EARTH3	ssp585	31
NorESM2-MM	ssp245	26.4
CanESM5	ssp585	17.4
NorESM2-MM	ssp370	17.3
CMCC-ESM2	ssp245	14.2
CanESM5	ssp126	13.5
MRI-ESM2-0	ssp245	11.6
MRI-ESM2-0	ssp370	11.6
UKESM1-0-LL	ssp126	10.7
NorESM2-MM	ssp585	6.5
EC-EARTH3	ssp126	3.7
CMCC-ESM2	ssp370	0
CMCC-ESM2	ssp585	-1.1
CNRM-ESM2-1	ssp126	-6.3
EC-EARTH3	ssp370	-15
MPI-ESM1-2-HR	ssp126	-15.4
EC-EARTH3	ssp245	-20.9
CNRM-ESM2-1	ssp245	-21.8
CanESM5	ssp370	-24.2
ACCESS-CM2	ssp245	-26.8
CNRM-ESM2-1	ssp370	-27.4
MPI-ESM1-2-HR	ssp370	-27.8
BCC-CSM2-MR	ssp245	-27.9
BCC-CSM2-MR	ssp126	-28.3
UKESM1-0-LL	ssp245	-29.7
MRI-ESM2-0	ssp585	-30.7
MPI-ESM1-2-HR	ssp585	-31.6
ACCESS-CM2	ssp126	-38.6
ACCESS-CM2	ssp585	-40.6
UKESM1-0-LL	ssp585	-49.8
ACCESS-CM2	ssp370	-54
MPI-ESM1-2-HR	ssp245	-56.7
BCC-CSM2-MR	ssp370	-56.9
CNRM-ESM2-1	ssp585	-57.9
BCC-CSM2-MR	ssp585	-67.5
UKESM1-0-LL	ssp370	-67.6

Figure 19.Ranked ensemble members (10 CMIP6 models × 4 SSPs) for the Guadiana River Living Lab based on the projected change in climatic water balance Δ(P–ETP) for 2071–2100 relative to 1985–2014. The three representative futures selected for the subsequent analysis are highlighted in red and correspond to positions 4 (wet future), 21 (median future) and 36 (dry future) in the ordered list.

7.3.2 Future climate projections and hydro-climatic interpretation

The projections for the Guadiana River Living Lab describe a future climate shaped by a clear warming tendency and a reorganisation of precipitation in time, which together modify the hydro-climatic conditions that matter for slow-hydrology processes (seasonal storage, persistence of soil moisture, and recharge potential). The results discussed below are reported relative to the reference period 1985–2014 and are summarised in Table 6. In this case study, both the boxplots and Table 6 show the interquartile uncertainty range (P25–P75) across the ensemble, while the P10 and P90 values are used only to define the representative futures introduced in the previous subsection.

Temperature indicators show a systematic increase across annual and seasonal metrics, with warming already evident by mid-century and strengthening toward late century. Crucially, the warming signal is not confined to averages: the temperature percentiles shift upward as well, indicating that the entire temperature distribution is moving toward warmer conditions. This means that typical conditions become warmer, but also that very warm conditions become more likely and more persistent. In Mediterranean climates such as Guadiana, this distributional shift is particularly relevant because it intensifies atmospheric demand and raises the probability that warm periods extend further into spring and autumn, effectively lengthening the high-demand season.

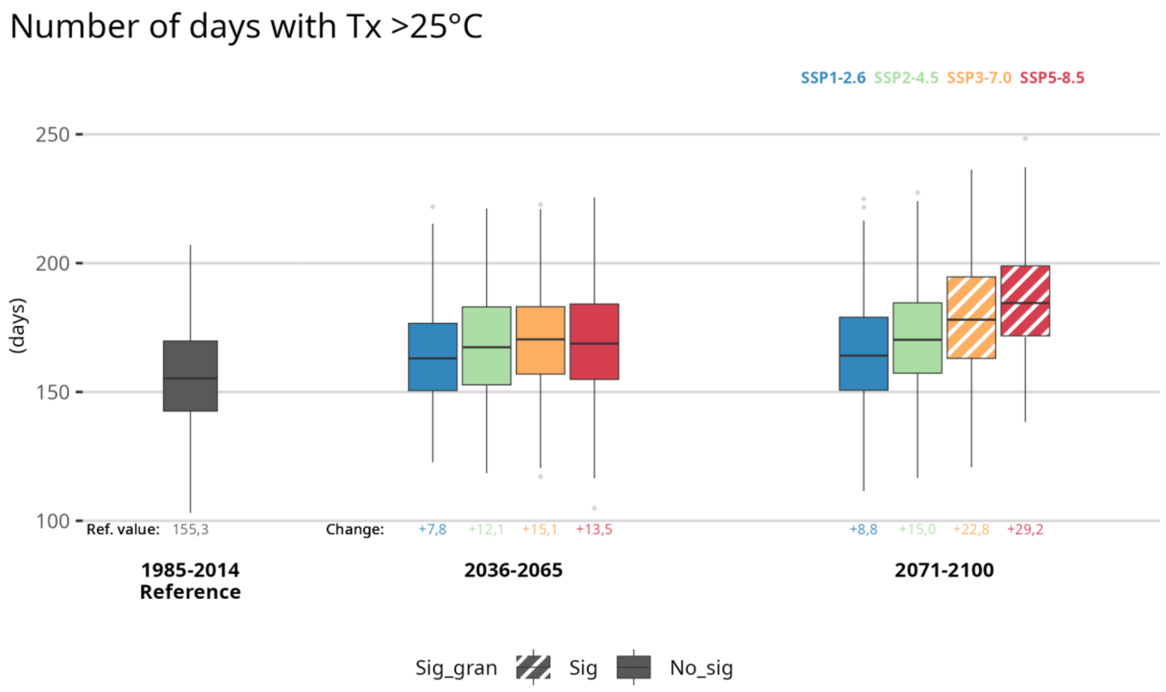

Figure 20.Expected evolution for the number of days with maximum temperature above 25ºC for Guadiana River.

Heat-threshold indicators provide a direct and operationally meaningful expression of this change. The projected increase in days exceeding high-temperature thresholds (such as Tmax > 25°C and Tmax > 28°C) indicates that hot conditions will become substantially more frequent and that the warm season will contain more days with very high evaporative demand. This is not only a heat-exposure signal; hydrologically, it implies faster depletion of soil moisture after rainfall, reduced persistence of wet conditions, and a higher likelihood that the catchment enters and remains in deficit conditions for longer periods. The fact that both thresholds increase reinforces that the change is not limited to moderately warm days: very hot days also become more frequent, which typically have a disproportionate effect on evaporative losses and plant water stress.

Seasonal temperature changes reinforce this interpretation. Warming in summer increases the intensity of the already dry season, while warming in spring and autumn can shift the onset and end of dry-season conditions, extending the period in which evaporative demand is high and precipitation is limited. This extension is particularly important for slow-hydrology behaviour because it reduces the time available for replenishment and increases the duration over which catchment storage must buffer atmospheric demand.

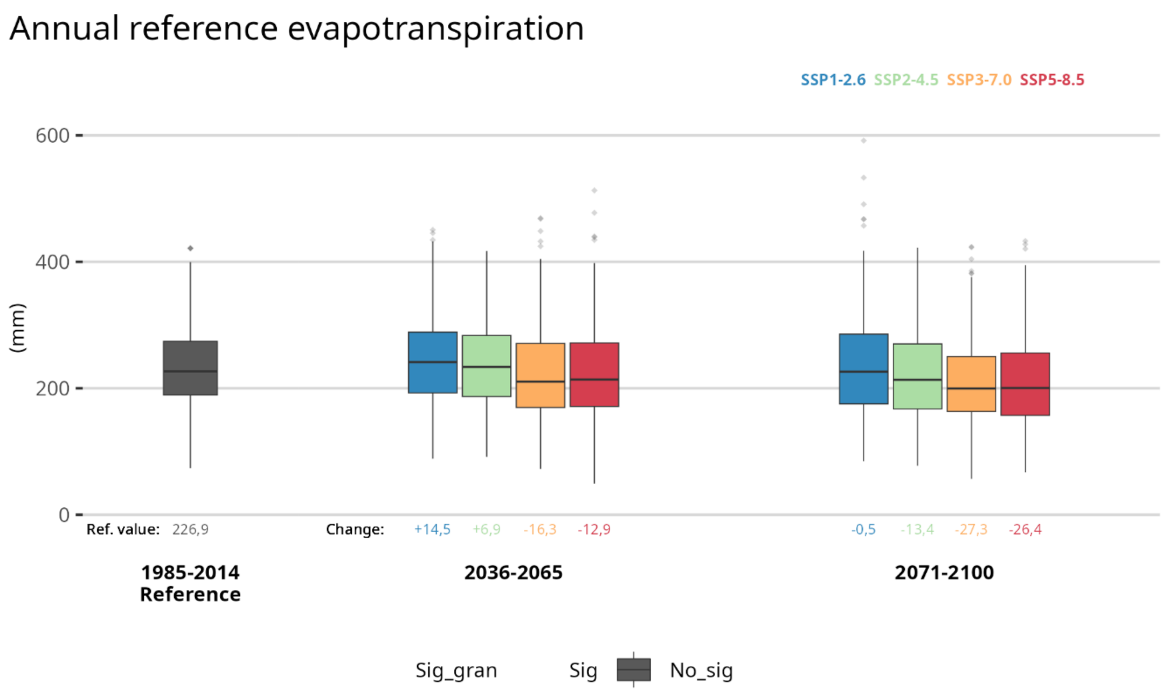

Figure 21.Expected evolution for the annual reference evapotranspiration for Guadiana River.

Precipitation signals are more complex than temperature and are best interpreted through their seasonal structure and event organisation rather than annual totals alone. The results indicate a redistribution of precipitation, with a tendency toward increased precipitation in the cooler season while spring and especially summer become drier, and autumn also shows predominantly negative changes. For slow hydrology, this timing matters: reduced precipitation during the warm season directly reinforces deficit conditions, while changes in the cool season control the potential for replenishment of soil moisture and groundwater stores that sustain conditions through summer.

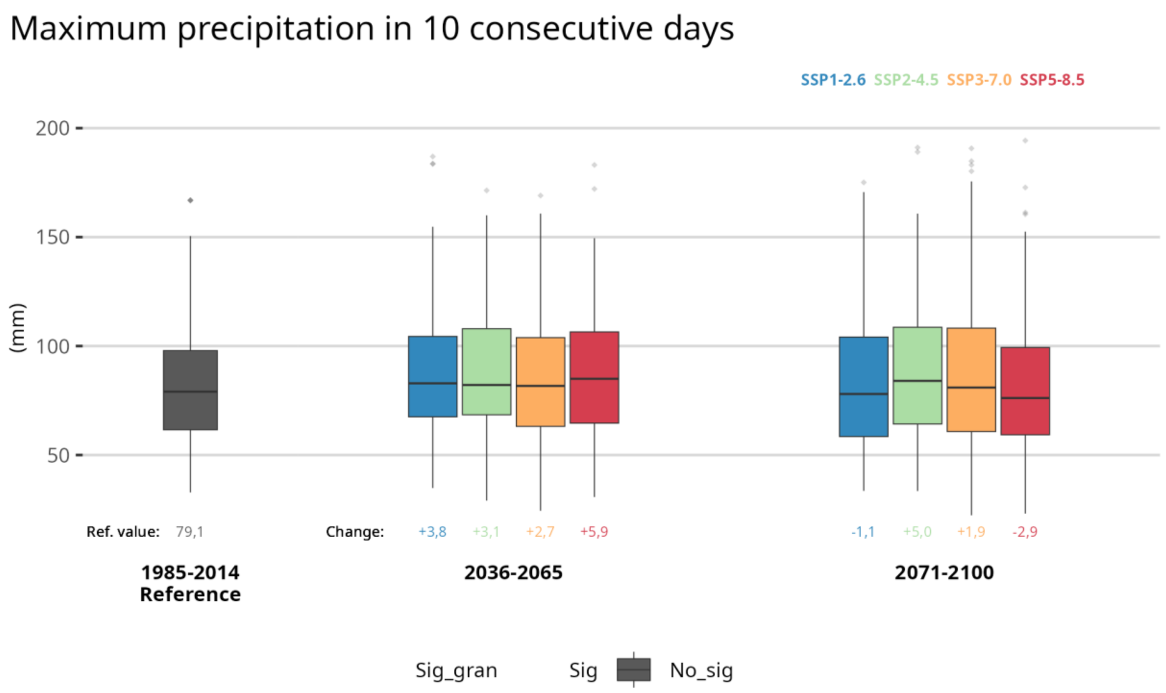

Figure 22.Expected evolution for the maximum accumulated precipitation in 10 consecutive days for Guadiana River.

Daily-scale indicators add an important nuance on how precipitation may be organised in the future. Wet-day indicators show a tendency toward fewer wet days, implying fewer opportunities for regular replenishment and a higher likelihood of longer dry spells. At the same time, intensity-related indicators such as SDII and short-duration maxima tend to increase, suggesting that when rainfall occurs it is more likely to be concentrated into more intense events. This combination is particularly relevant for Mediterranean catchments: fewer wet days weaken moisture persistence and reduce the continuity needed for recharge, while stronger intensities can increase runoff and erosion and reduce infiltration efficiency, especially when soils are dry or rainfall falls in short bursts.

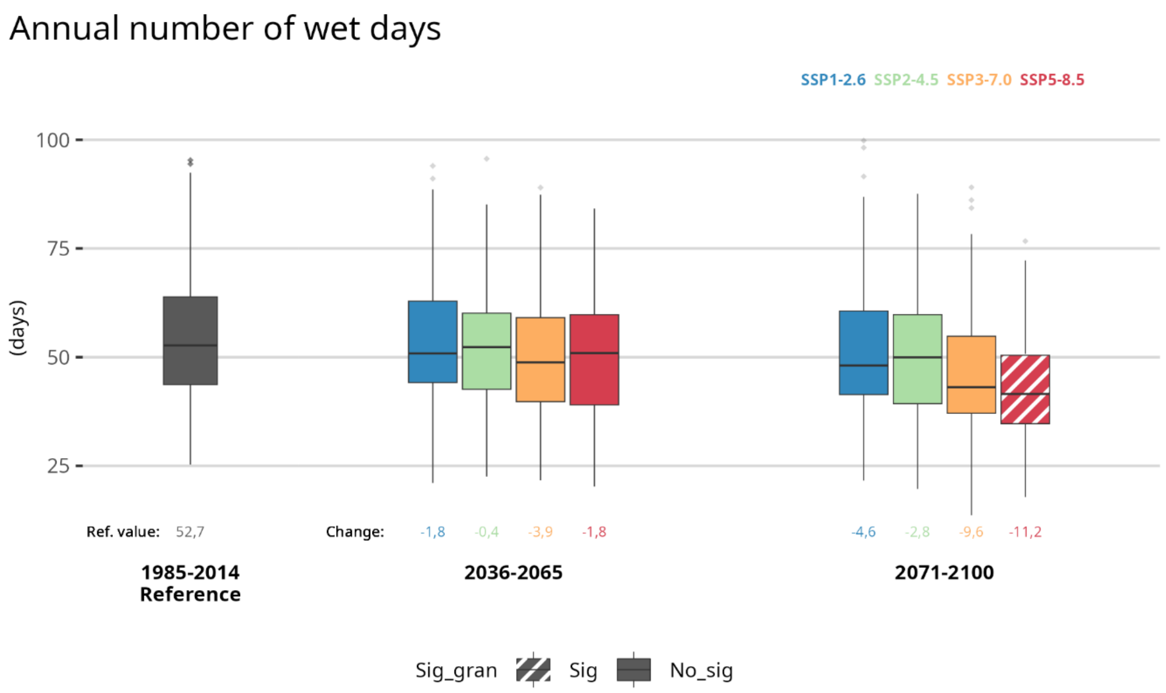

Figure 23.Expected evolution for the annual number of wet days for Guadiana River.

The water-availability indicators integrate supply and demand and confirm that the Guadiana system remains deficit-prone, with warm-season stress reinforced by both increasing heat exposure and reduced precipitation frequency. Even when parts of the cool-season precipitation increase, higher intensity combined with fewer wet days can limit how effectively rainfall contributes to slow storage and recharge. In practice, this means that the catchment becomes more dependent on the effectiveness of cool-season replenishment windows and more sensitive to sequences of dry months, while the warm season becomes increasingly demanding and prone to persistent deficits.

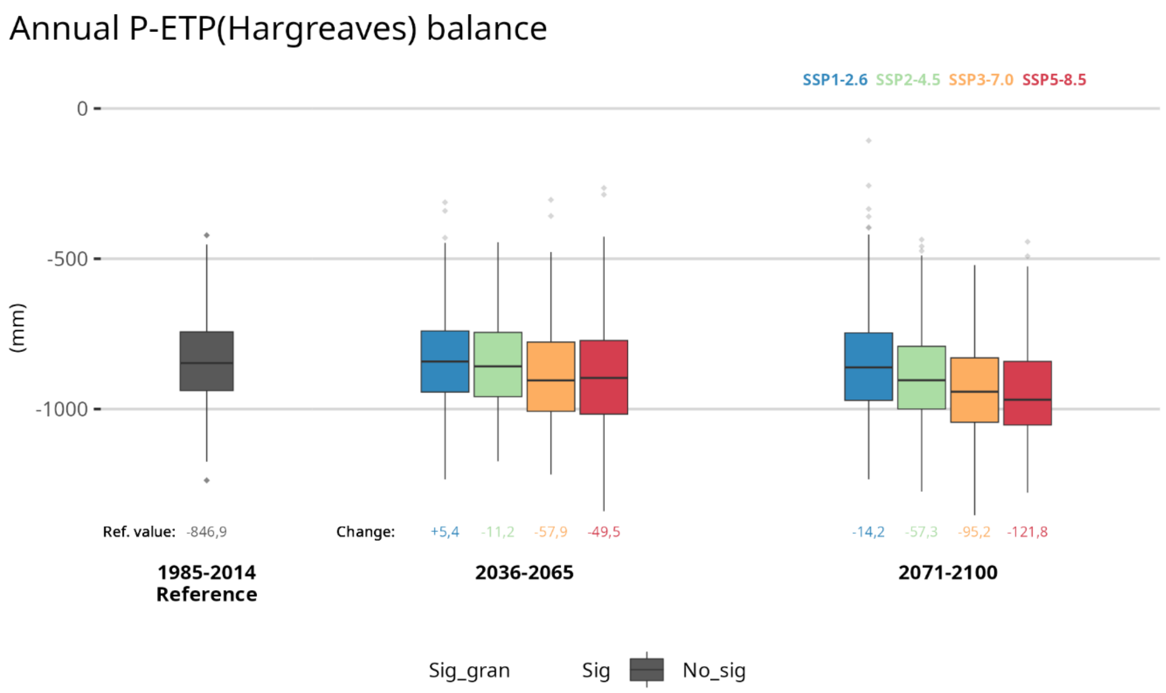

Figure 24.Expected evolution for the water balance evaluated as Precipitation minus ETP for Guadiana River.

Overall, the Guadiana River Living Lab is projected to experience a warmer climate with an upward shift across the temperature distribution and a substantial increase in hot-day frequency above key thresholds. Precipitation changes are dominated by a seasonal redistribution (relative winter gains versus spring–summer losses) and a rainfall regime with fewer wet days but higher intensity when precipitation occurs. For slow-hydrology processes, this implies increasing vulnerability to persistent warm-season deficits, reduced moisture persistence, and greater reliance on cool-season recharge opportunities, while intensifying rainfall characteristics may increase runoff- and erosion-related risks. The numerical results supporting these conclusions are provided in Table 6.

	RP	P1-RP	P2-RP
	Temperature Indicators (°C)		
T max	24	0.3-0.5	0.4-1.2
Winter Tmax	15.8	0.1-0.1	0.1-0.2
Spring Tmax	23.3	0.6-1	0.2-2.2
Summer Tmax	32.8	0.5-0.5	0.5-0.8
Autumn Tmax	23.7	0.5-0.8	0.8-1.5
Tmean	18.3	0.2-0.4	0.4-0.9
Winter Tmean	11.2	0-0.1	0-0.1
Spring Tmean	17.6	0.5-0.9	0.2-1.8
Summer Tmean	25.9	0.4-0.4	0.4-0.6
Autumn Tmean	18.5	0.4-0.6	0.6-1.2
Tmin	12.8	0.1-0.3	0.2-0.6
Winter Tmin	6.5	0	0.1
Spring Tmin	12	0.2-0.6	0.1-1.2
Summer Tmin	18.9	0.2-0.3	0.3-0.5
Autumn Tmin	13.3	0.4-0.5	0.5-0.9
T10	15.2	0.1-0.2	0.1-0.3
T25	17.4	0-0.2	0.2-0.7
T50	22.8	0.5-1.3	0.6-2.4
T75	30.4	0.4-0.8	0.4-1.5
T90	34	0-0.4	0.2-0.5
Days Tmax>25	155.3	7.8-13.5	8.8-29.2
Days Tmax>28	122.6	8.3-13.4	10-30.2
	Precipitation Indicators (mm or days)		
Prec	477.7	(-18)-15.6	(-51.3)-20.8
Winter Prec	160	7.2-29.3	12.6-20.7
Spring Prec	131.9	(-12.2)-(-2.1)	(-31.5) – 6.1
Summer Prec	18.9	(-6.7) –(-5.2)	(-9.5) –(-7.5)
Autumn Prec	149.5	(-20) – 0	(-32.5) –(-1.7)
Days P>1mm	61.6	(-5.3) – (-0.7)	(-13.3) – (-3.8)
Days P>5mm	26.4	(-1.7) – 0.5	(-5) - (-0.1)
Days P>10mm	12.9	(-1) - 0	(-1.9) – (-0.2)
Days P>15mm	5.7	0.9-1	0.3-1.1
Days P>20mm	2.4	0.5-0.6	0.3-0.6
Days P>30mm	0	0.1-0.3	0.2-0.5
Days P>P95	15.9	(-0.9) – (-0.2)	(-2.5) – 0.4
Max Prec in 1 day	26.2	2-3.1	2.6-3.9
Max Prec in 5 days	57.9	3.8-5.9	1.8-5.6
Max Prec in 10 days	79.1	2.7-5.9	(-2.9) - 5
P90	3.2	(-0.4) – (-0.1)	(-1.2) – (-0.3)
P99	17.1	1-1.2	0.9-1.3
	Water ability indicators		
AI	0.3	-	-
SDII	48.7	4.6-7	4.9-19.9
WD	52.7	(-3.9) – (-0.4)	(-11.2) – (-2.8)
ETP	226.9	(-16.3) – (14.5)	(-27.3) – (-0.5)
Prec-ETP	-846.9	(-57.9) – 5.4	(-121.8) – (-14.2)

Table 6. Summary of projected changes in temperature, precipitation and water-availability indicators for the Guadiana River Living Lab. Values are reported relative to the reference period RP (1985–2014). P1–RP represents the change for the mid-century period P1 (2036–2065) with respect to RP, and P2–RP represents the change for the late-century period P2 (2071–2100) with respect to RP. Temperature indicators (°C) include annual and seasonal Tmax, Tmean and Tmin, temperature percentiles (T10–T90), and the annual number of days above heat thresholds (Days Tmax > 25°C and Days Tmax > 28°C). Precipitation indicators (mm) include accumulated precipitation at monthly/seasonal/annual scales, maximum maximum accumulated precipitation over 1, 5 and 10 consecutive days, and frequency-based metrics (wet days and intensity-related indicators). Water-availability indicators summarise changes in SDII, wet days (WD), reference evapotranspiration (ETP) and the climatic water balance (P–ETP). For each entry, the table reports the P25 and P75 values of the projection ensemble (interquartile range) to summarise uncertainty across models and scenarios.

7.3.3 Implications for planned actions and resilience planning

The Guadiana River Living Lab exhibits a climate signal dominated by warming and a strong increase in heat-threshold exceedances, combined with a seasonal reorganisation of precipitation and reduced wet-day occurrence, while intensity-related indicators suggest that rainfall becomes more concentrated when it occurs. For slow hydrology in a Mediterranean setting, this combination is particularly relevant because it tends to increase the persistence of warm-season deficits, shorten soil-moisture recovery between events, and increase reliance on cool-season replenishment windows. Event-scale intensification also increases the potential for runoff- and erosion-dominated responses, which can further reduce the effectiveness of precipitation for recharge.

As with the other Living Labs, this deliverable does not prescribe measures; its role is to provide climate-driven evidence for resilience planning. For Guadiana, the primary stressors that planned actions should be tested against are (i) increasing warm-season demand and longer high-demand periods, (ii) fewer wet days and longer dry spells, and (iii) higher precipitation intensity when rainfall occurs. These stressors can be used by Living Lab teams to evaluate whether planned actions remain feasible and effective under the selected dry/median/wet futures, and to define monitoring indicators and adaptive management pathways where necessary.

7.4 Danube River Living Lab (Romania)

The Danube River Living Lab in Romania is located in a continental–riverine setting where hydro-meteorological conditions are shaped by pronounced seasonality and by the interaction between large-scale atmospheric circulation and basin-scale hydrology. The climate is typically characterised by cold winters and warm summers, with precipitation distributed throughout the year but with strong seasonal contrasts and a relevant contribution from convective rainfall during the warm season. These conditions influence slow-hydrology behaviour through seasonal soil moisture storage, groundwater recharge dynamics, and the persistence of baseflow contributions, while also making the system sensitive to shifts in temperature-driven evaporative demand and to changes in the frequency and intensity of precipitation events.

The baseline input data used to support the local-scale climate analysis consist of gridded daily series of precipitation and temperature extracted at 28 grid points distributed across the Living Lab area of influence (Figure 25). This set of grid points is designed to provide representative spatial coverage of the domain while capturing the main hydro-meteorological gradients relevant for catchment-scale aggregation and indicator computation. The daily temporal resolution is consistent with the project workflow and enables the derivation of both daily-based indicators (wet days, intensity metrics and threshold exceedances) and accumulated indicators at monthly, seasonal and annual scales used in the hydro-climatic assessment.

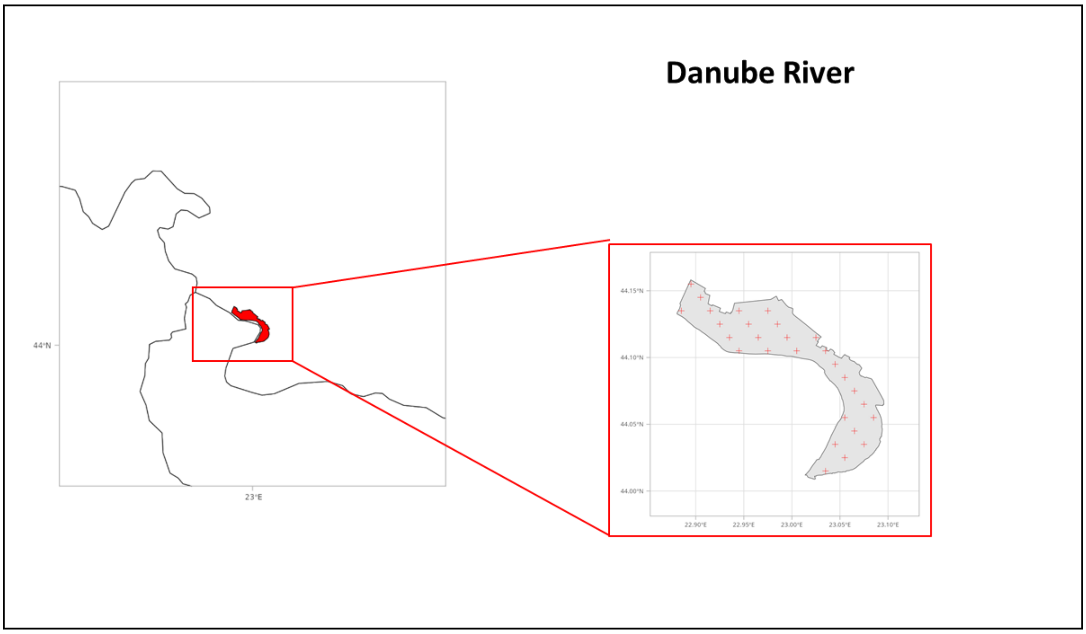

Figure 25. Location of the grid points with temperature and precipitation data used in the preliminary study for Danube River.

7.4.1 Selection of the three representative futures

For the Danube River Living Lab, three representative futures are selected from the ensemble and used consistently across all results and indicators. These futures are referred to as Scenario UKESM1-0-LL ssp585 (dry future), Scenario MPI-ESM1-2-HR ssp585 (median future) and Scenario CanESM5 ssp245 (wet future). Their position within the ensemble distribution and the corresponding selection are shown in Figure 26.

Model	Scenario	Difference
EC-EARTH3	ssp126	65.3
EC-EARTH3	ssp585	57.5
CanESM5	ssp585	54.6
EC-EARTH3	ssp370	46.2
CanESM5	ssp245	42.6
CanESM5	ssp370	33.8
EC-EARTH3	ssp245	32.4
CanESM5	ssp126	24.3
MPI-ESM1-2-HR	ssp245	19.3
MPI-ESM1-2-HR	ssp126	18.2
CMCC-ESM2	ssp126	17.9
MRI-ESM2-0	ssp245	16.8
ACCESS-CM2	ssp245	14.5
MRI-ESM2-0	ssp370	11.3
MRI-ESM2-0	ssp126	10.9
CNRM-ESM2-1	ssp370	10.4
MPI-ESM1-2-HR	ssp370	8.3
CNRM-ESM2-1	ssp126	7.9
UKESM1-0-LL	ssp126	4.6
MPI-ESM1-2-HR	ssp585	0.5
CNRM-ESM2-1	ssp585	-2
MRI-ESM2-0	ssp585	-7
ACCESS-CM2	ssp126	-13.1
BCC-CSM2-MR	ssp245	-13.2
BCC-CSM2-MR	ssp126	-13.8
UKESM1-0-LL	ssp245	-16.5
NorESM2-MM	ssp126	-20.5
CMCC-ESM2	ssp585	-21.6
BCC-CSM2-MR	ssp370	-23.7
UKESM1-0-LL	ssp370	-24.5
CMCC-ESM2	ssp245	-25.6
ACCESS-CM2	ssp370	-26.4
CNRM-ESM2-1	ssp245	-30.2
CMCC-ESM2	ssp370	-31.7
BCC-CSM2-MR	ssp585	-33.8
ACCESS-CM2	ssp585	-33.9
UKESM1-0-LL	ssp585	-39.7
NorESM2-MM	ssp370	-49.6
NorESM2-MM	ssp245	-52.3
NorESM2-MM	ssp585	-78.3

Figure 26.Ranked ensemble members (10 CMIP6 models × 4 SSPs) for the Danube River Living Lab based on the projected change in climatic water balance Δ(P–ETP) for 2071–2100 relative to 1985–2014. The three representative futures selected for the subsequent analysis are highlighted in red and correspond to positions 4 (wet future), 21 (median future) and 36 (dry future) in the ordered list.

7.4.2 Future climate projections and hydro-climatic interpretation

The projections for the Danube River Living Lab in Romania indicate a future climate characterised by strong warming and a marked intensification of heat-related conditions, combined with changes in precipitation that include both increases in accumulated amounts and shifts in event characteristics. Together, these changes modify the hydro-climatic conditions that matter for slow-hydrology processes such as soil moisture persistence, recharge dynamics and baseflow support. The results discussed below are reported relative to the reference period 1985–2014 and are summarised in Table 7. As in the other Living Labs, uncertainty is expressed as the interquartile range (P25–P75) across the ensemble, while the P10 and P90 values are used only to define the representative futures (Scenarios A and C) introduced in the scenario-selection subsection.

Temperature indicators show a consistent increase across annual and seasonal metrics already by mid-century (P1: 2036–2065), with a clear strengthening toward late century (P2: 2071–2100). The warming signal is broad, affecting mean, minimum and maximum temperatures as well as the percentile-based indicators, which implies an upward shift of the full temperature distribution.

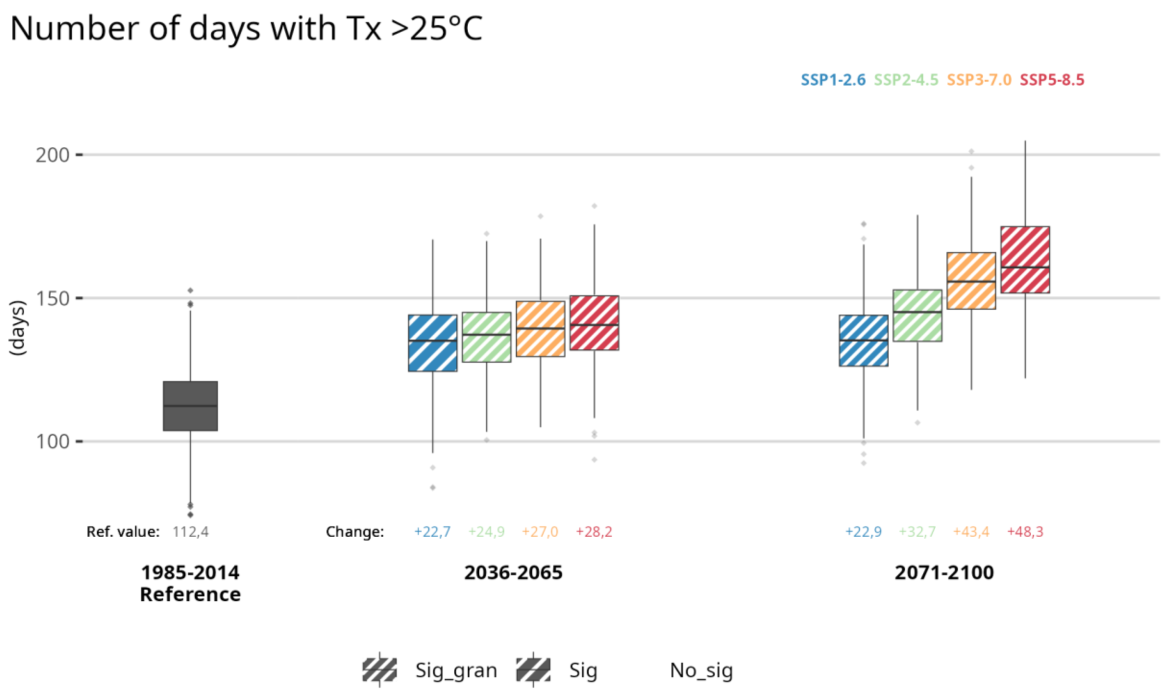

Figure 27.Expected evolution for the number of days with maximum temperature above 25ºC for Danube River.

Operationally, this shift translates into a pronounced increase in the frequency of hot days above key thresholds. The projected rise in days exceeding high-temperature thresholds indicates that warm-season heat stress becomes substantially more common, with a longer and more intense hot season by late century. In a continental setting, this also implies greater evaporative demand during summer and stronger depletion of soil moisture and storage, particularly during prolonged warm spells.

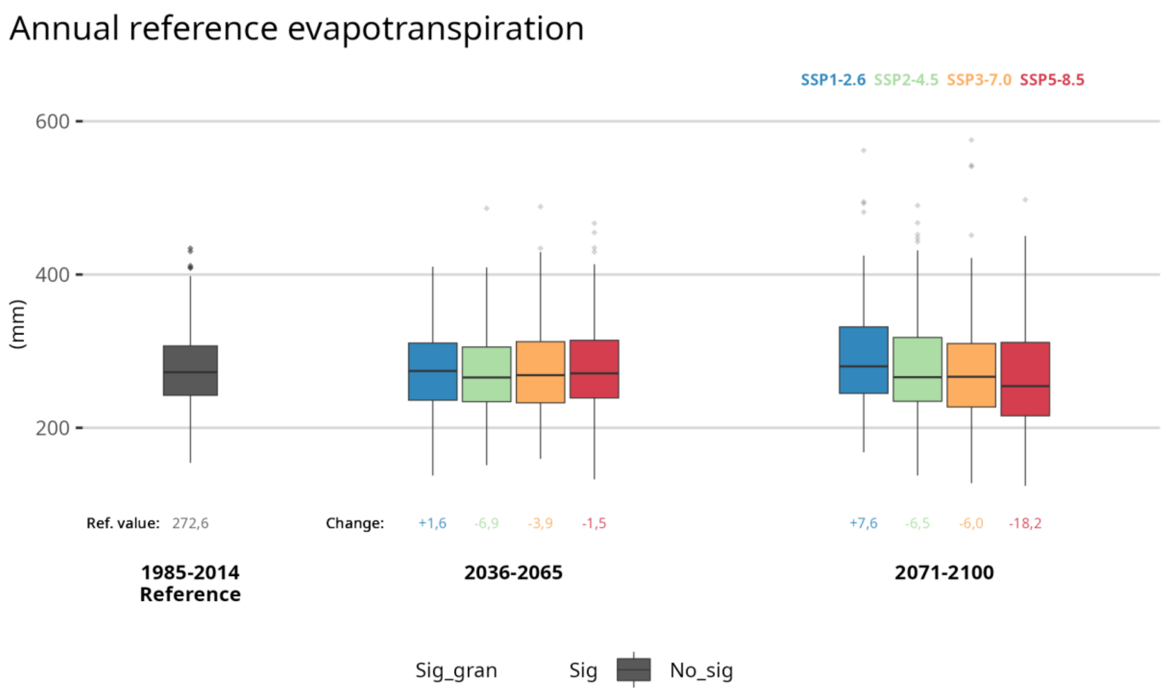

Figure 28.Expected evolution for the annual reference evapotranspiration for Danube River.

Precipitation indicators suggest an overall tendency toward higher accumulated precipitation, especially in the wetter parts of the year, but with important nuances in seasonality and event organisation. The increases in accumulated precipitation at annual and seasonal scales indicate the potential for enhanced water inputs, yet some seasonal components show negative changes, implying a redistribution in time rather than a uniform increase. This matters for slow hydrology because the effectiveness of precipitation for recharge depends strongly on the timing of inputs relative to atmospheric demand: increases during cooler months are more likely to contribute to storage and recharge, whereas changes during the warm season may be offset by higher evaporative losses.

Daily-scale precipitation metrics provide further insight into how rainfall characteristics may evolve. Indicators related to short-duration extremes and exceedance frequencies generally increase, suggesting a greater likelihood of intense events and higher multi-day maxima. This can have two competing implications. On the one hand, multi-day wet periods and higher extremes can produce episodic recharge opportunities, particularly outside the warm season. On the other hand, intensification of rainfall can increase runoff peaks and erosion risk and may reduce infiltration efficiency during the most intense episodes, especially in areas with limited infiltration capacity or strong hydrological connectivity. Therefore, the precipitation signal should be interpreted jointly through totals, frequency and intensity metrics.

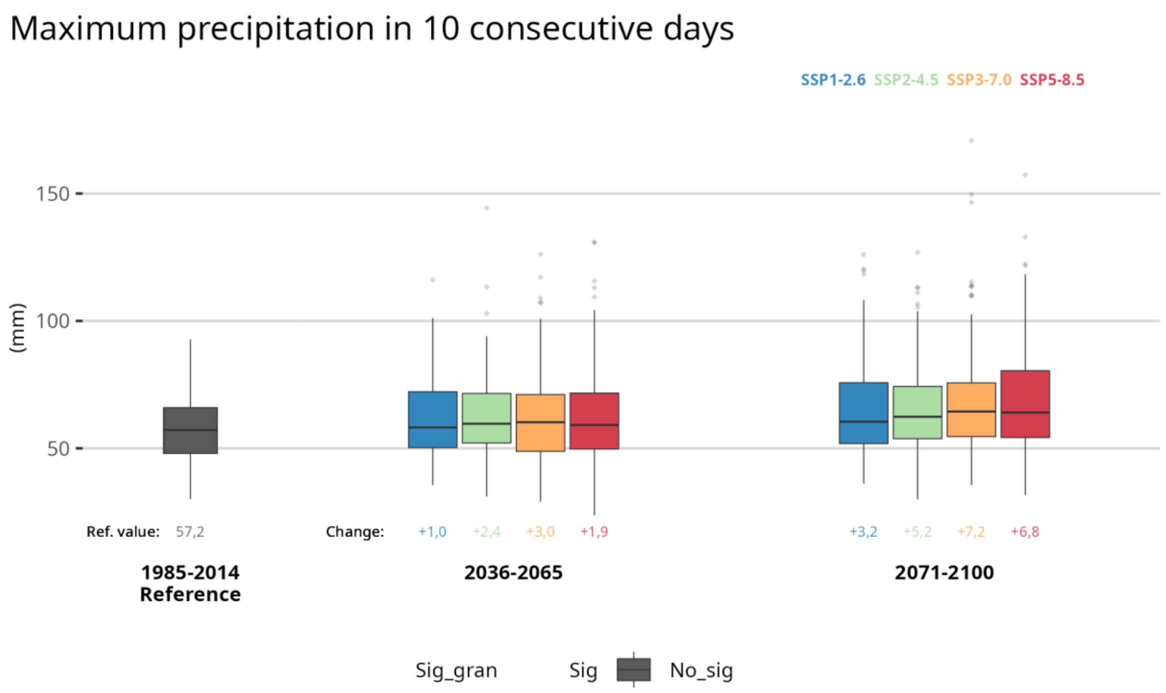

Figure 29.Expected evolution for the maximum accumulated precipitation in 10 consecutive days for Danube River.

The water-availability indicators integrate supply and demand into a single hydro-climatic perspective. In Table 7, intensity-related metrics (such as SDII) tend to increase, indicating more intense precipitation on wet days, while wet-day occurrence shows modest changes that can be negative in parts of the distribution, implying that precipitation may become less frequent but more intense. Most importantly for slow-hydrology interpretation, the climatic water balance P–ETP exhibits negative changes that become substantially larger by late century. This indicates that, despite precipitation increases in parts of the indicator set, the increase in atmospheric demand associated with warming is sufficient to drive a deterioration of the net climatic balance at catchment scale, shifting the system toward more deficit-prone conditions over longer time windows.

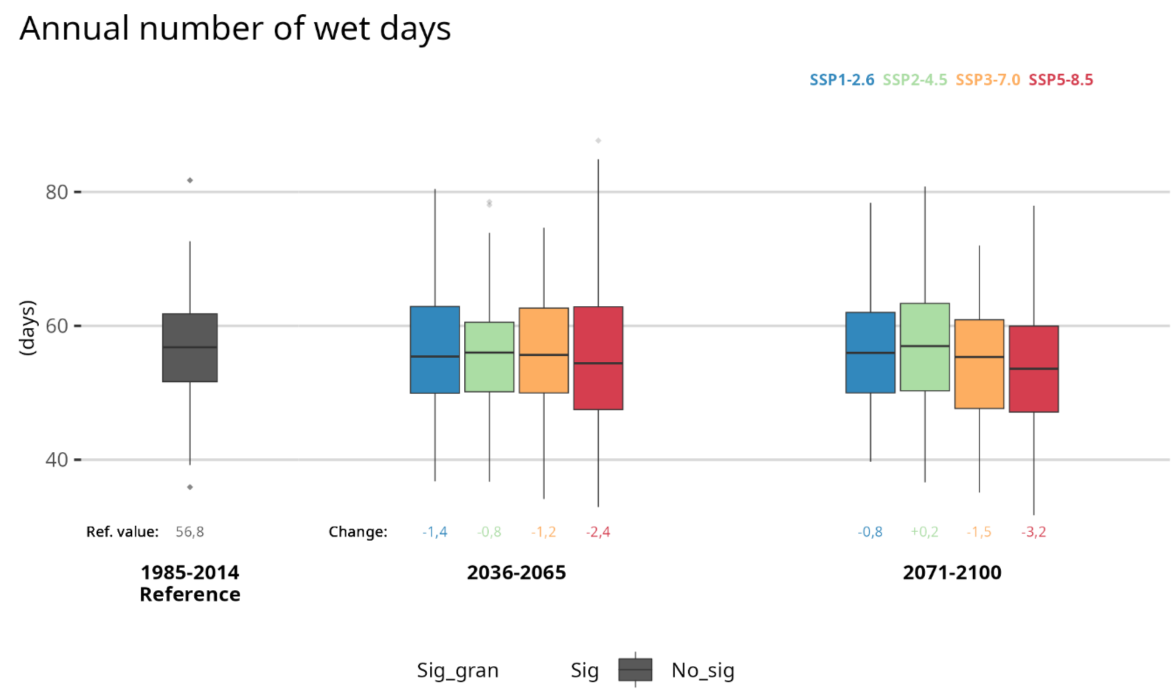

Figure 30.Expected evolution for the annual number of wet days for Danube River.

From a slow-hydrology perspective, this integrated signal suggests reduced climatic potential for recharge, lower persistence of soil moisture and storage, and increasing risk of sustained deficits affecting groundwater contribution and baseflow support, particularly by the end of the century. At the same time, more intense precipitation extremes imply that the system may experience a stronger contrast between short-lived wet extremes and longer periods of drying, which can increase both hydrological variability and the sensitivity of planned measures to event-scale impacts.

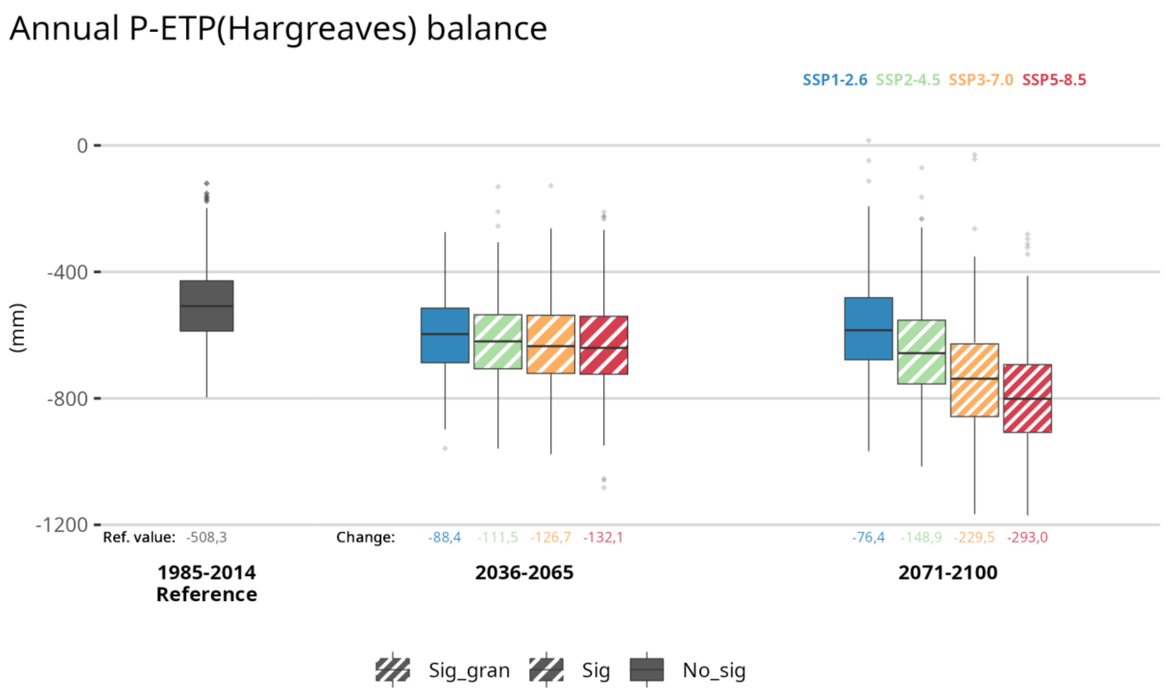

Figure 31.Expected evolution for the water balance evaluated as Precipitation minus ETP for Danube River.

Overall, the Danube River Living Lab in Romania is projected to experience substantial warming and a strong increase in heat-threshold exceedances, alongside precipitation changes that include increased accumulated inputs but also intensified event characteristics. The combined indicator evidence points toward increasing hydro-climatic stress and a more deficit-dominated balance by late century, with growing importance of both demand-driven drying and event-scale intensification for slow-hydrology processes and resilience planning. The numerical results supporting these conclusions are provided in Table 7.

	RP	P1-RP	P2-RP
	Temperature Indicators (°C or days)		
T max	17.7	1.9-2.9	2.1-5.8
Winter Tmax	5.2	1.4-2.5	1.6-4.7
Spring Tmax	16.9	1.5-2.2	1.8-4.5
Summer Tmax	30.7	2.7-3.9	2.8-8.1
Autumn Tmax	18.1	2-3.4	2.3-6.2
Tmean	12.5	1.6-2.6	1.9-5
Winter Tmean	1.5	1.3-2.4	1.6-4.2
Spring Tmean	11.7	1.3-2.1	1.6-4
Summer Tmean	24	2.3-3.4	2.5-6.8
Autumn Tmean	12.9	1.8-2.9	2-5.3
Tmin	7.4	1.4-2.2	1.6-4.2
Winter Tmin	-2.2	1.2-2.2	1.6-3.8
Spring Tmin	6.4	1.2-1.9	1.5-3.6
Summer Tmin	17.3	1.9-2.9	2-5.6
Autumn Tmin	7.8	1.5-2.2	1.6-4.4
T10	4.3	1.7-2.6	2.4-4.8
T25	8.7	1.5-2.5	2.2-4.8
T50	17.1	2.1-2.9	2.5-5.6
T75	27	2.6-3.7	3-7.5
T90	32.1	2.7-4.5	3.1-8.7
Days Tmax>25	112.4	22.7-28.2	22.9-48.3
Days Tmax>28	80.3	25.7-34.3	26.3-59.4
	Precipitation Indicators (mm or days)		
Prec	552.1	7.9-31.4	23.4-46.3
Winter Prec	114.9	7.7-14.1	13.8-18.7
Spring Prec	146.3	9.5-17.5	12.1-27.5
Summer Prec	148.5	(-11.6) –(4.3)	(-25.4) – (-6)
Autumn Prec	124.4	(-3.1)- 6	-(4.3) – 3.7
Days P>1mm	66.8	(-2.9) – (-1.5)	(-4.4) – 0.2
Days P>5mm	26.3	0.1-0.6	0.6 -1.6
Days P>10mm	11.3	0.6 -1.3	1.5 -2.3
Days P>15mm	5	0.8-1.4	0.9-2.1
Days P>20mm	2.1	0.7 -0.9	0.7 – 1.7
Days P>30mm	0	0.2-0.4	0.3-0.9
Days P>P95	112.4	22.7 -28.2	22.9-48.3
Max Prec in 1 day	27.9	0.1 -2	1.3-4.4
Max Prec in 5 days	46.1	2.9-5.1	(-7.7) – 8.3
Max Prec in 10 days	57.2	1 -3	3.2-7.2
P99	16.4	1.2 – 1.7	1.1 – 3
	Water ability indicators		
AI	0.5	-	-
SDII	43.2	2.8-4.1	3.1-10.3
WD	56.8	(-2.4) – (-0.8)	(-3.1) – 0.2
ETP	272.6	(-6.9) – 1.6	(-18.2) – 7.6
Prec-ETP	-508.3	(-132.1) – (88.4)	(-293) - (-76.4)

Table 7.Summary of projected changes in temperature, precipitation and water-availability indicators for the Danube River Living Lab. Values are reported relative to the reference period RP (1985–2014). P1–RP represents the change for the mid-century period P1 (2036–2065) with respect to RP, and P2–RP represents the change for the late-century period P2 (2071–2100) with respect to RP. Temperature indicators (°C) include annual and seasonal Tmax, Tmean and Tmin, temperature percentiles (T10–T90), and the annual number of days above heat thresholds (Days Tmax > 25°C and Days Tmax > 28°C). Precipitation indicators (mm) include accumulated precipitation at monthly/seasonal/annual scales, maximum accumulated precipitation over 1, 5 and 10 consecutive days, and frequency-based metrics (wet days and intensity-related indicators). Water-availability indicators summarise changes in SDII, wet days (WD), reference evapotranspiration (ETP) and the climatic water balance (P–ETP). For each entry, the table reports the P25 and P75 values of the projection ensemble (interquartile range) to summarise uncertainty across models and scenarios.

7.4.3 Implications for planned actions and resilience planning

For the Danube River Living Lab in Romania, projections indicate strong warming and a pronounced increase in heat-related conditions, alongside precipitation changes that include increases in accumulated inputs but also a tendency toward intensification of event characteristics. The integrated hydro-climatic interpretation suggests that increasing atmospheric demand plays a central role and can lead to more deficit-prone conditions over longer periods, particularly toward late century, even where precipitation increases. For slow-hydrology processes, this implies reduced persistence of soil moisture and storage, higher likelihood of sustained deficits affecting groundwater and baseflow support, and increasing variability due to a stronger contrast between intense wet events and longer drying phases.

This deliverable provides the climate and indicator evidence base for subsequent planning, without prescribing or implementing measures. The key stressors for robustness testing in this Living Lab are (i) demand-driven drying linked to strong warming and increased heat-threshold exceedances, and (ii) intensification of precipitation events, which may increase runoff peaks and reduce infiltration efficiency during extremes. These stressors provide an evidence-based input for Living Lab teams to assess action compatibility under the selected dry/median/wet futures and to identify adaptive management needs and monitoring priorities.

8. Conclusions

This deliverable provides the climate and hydro-climatic evidence base developed in INTERLAYER under WP4 / Task 4.2 “Future climate modelling and resilience” to support resilience planning and the assessment of the compatibility of planned Living Lab actions with future climate conditions. Building on the preliminary screening presented in D4.1, the work advances from a point-based representation to a spatially explicit, catchment/sub-catchment approach, enabling the analysis to reflect the full area of influence and upstream contributions that are critical for slow-hydrology systems.

A consistent workflow was implemented across all Living Labs to generate local-scale projections of temperature and precipitation from a CMIP6 ensemble (10 GCMs combined with four SSP pathways), using statistical downscaling/regionalisation supported by reanalysis-based reference fields. Reference evapotranspiration (ETP) and the climatic water balance (P–ETP) were derived to translate meteorological change into water-relevant information. To ensure operational usability while preserving uncertainty, the ensemble was reduced to three representative futures per Living Lab (dry, median and wet), and a comprehensive set of hydro-climatic indicators was computed to capture long-term availability, persistence and extremes at both monthly/seasonal/annual and daily scales.

Across the Living Labs, warming emerges as a robust signal that strengthens toward the end of the century. This is reflected not only in mean temperatures but also in distributional shifts and increases in heat-threshold exceedances, implying higher atmospheric demand and stronger warm-season pressure. Precipitation changes are more heterogeneous and season dependent, and several sites show signals consistent with changes in precipitation organisation and more energetic event characteristics, reinforcing the need to interpret totals jointly with frequency and intensity metrics rather than relying on totals alone.

When supply and demand are integrated through P–ETP and related indicators (including wet-day frequency and intensity metrics), clear contrasts emerge among Living Labs. Some sites maintain a relatively favourable climatic water-balance outlook at aggregated scale, while others show a shift toward more deficit-prone conditions due to the combined effect of rising demand and changes in precipitation occurrence and seasonality. These contrasts confirm the relevance of an indicator framework that captures both background conditions and event-scale processes, particularly for slow-hydrology systems where storage and persistence control water availability.

The Living Lab chapters provide locally grounded narratives and stressor-oriented interpretations that can be used to test the robustness of planned actions under uncertainty. Importantly, this deliverable does not prescribe or implement measures; instead, it delivers the climate projections, representative futures and indicator evidence required by Living Lab teams and subsequent project activities to evaluate action compatibility, define monitoring needs and identify where adaptive management or design refinements may be appropriate.

Overall, the deliverable establishes a coherent and traceable basis for translating CMIP6-driven local projections into catchment-scale, decision-relevant hydro-climatic information. By linking local-scale climate change, water-balance metrics and indicators of persistence and extremes, the project strengthens its capacity to support resilience planning in diverse slow-hydrology contexts across the Living Labs.

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