Interreg CENTRAL EUROPE

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MAURICE

Deliverable 2.4.1

Analysis of different scenarios and related adaptation measures

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Analysis of different scenarios and related adaptation measures

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A. Introduction

This deliverable outlines the two developed solutions referred in Output 2.3, developed thanks to the Pilot Actions implemented in Lombardy and Stuttgart-Feuerbach in the context of Work Package 2. The first section is thus presenting the first solution: relevant results from models and scenarios obtained in the two Pilot Areas, posing the basis for the integration of the tested measures into strategies and plans. Details on models' development and construction can be found in Deliverable 2.2.2 and 2.3.2, while details on the scenarios creation can be found in Deliverables 2.2.3 and 2.3.3. The second solution presented in this document is an interactive dashboard which collects the project results, available at: maurice.soft-water.it. This tool provides policy makers and stakeholders with an accessible platform where to compare possible implementations of the measures based on indicators and on the simulated scenarios.

The Annexes cover the practices used to obtain scenarios of meteorological and other relevant variables under climate change conditions in the two Pilot Actions. The methodology utilized in the two areas is explained and then the results are presented. The result of the work presented here is of crucial importance to plan and evaluate adaptation to climate change as done in Work Package 2.

B. Numerical models and scenarios: the basis for sound strategies and plans

The first solution developed within Output 2.3 consists of an integrated modelling and scenario-simulation framework designed to support evidence-based groundwater management and climate adaptation planning in the two MAURICE Pilot Areas: Lombardy and Stuttgart-Feuerbach. The solution combines numerical models, climate-informed scenarios, water balance assessments and the simulation of possible management measures, providing policy makers and technical stakeholders with a robust basis for integrating tested measures into strategies, plans and operational decisions.

The added value of this solution lies in its capacity to translate complex hydrogeological, hydrological and agro-hydrological processes into quantitative indicators. In both Pilot Areas, the models allow the assessment of how groundwater systems respond to climate variability, water use, irrigation practices, artificial recharge measures and anthropogenic pressures. They therefore represent not only a technical achievement, but also a decision-support instrument for evaluating adaptation pathways before their implementation.

1. A common modelling logic adapted to two different territorial contexts

The two Pilot Areas are characterised by very different groundwater systems and management challenges. In Lombardy, the pilot area west of Milan is an intensively irrigated agricultural plain, where groundwater recharge depends not only on precipitation and evapotranspiration, but also on irrigation methods, water allocation rules, seepage from canals and the interaction between agriculture and shallow aquifers. For this reason, the modelling framework integrates the distributed agro-hydrological model IdrAgra with the groundwater flow model MODFLOW-USG, coupling field-scale percolation and canal seepage with aquifer dynamics.

In Stuttgart-Feuerbach, the main challenge is the long-term decline of groundwater levels in a complex urban and hydrogeological setting. The modelling work therefore focused on reproducing past development of groundwater recharge groundwater recharge, surface-water/groundwater interactions, vertical exchanges between aquifers and possible management measures to compensate groundwater deficits. The framework combines a soil-water balance model, a hydrological runoff model and a calibrated multilayer numerical groundwater model representing both shallow and deep aquifer systems.

Despite the differences between the two contexts, the modelling activities share a common objective: to quantify groundwater availability under present and future conditions, identify critical pressures and simulate the effectiveness of possible adaptation measures.

2. Lombardy Pilot Area: modelling irrigation, recharge and groundwater response

In the Lombardy Pilot Area, the solution is based on an integrated agro-hydrological and groundwater modelling chain. IdrAgra was used to simulate irrigation water distribution and the daily hydrological balance at field scale, accounting for crop phenology, soil-crop water balance, irrigation systems and crop yield. The model was implemented on a 100 × 100 m grid and used to generate spatially and temporally distributed percolation fluxes, including both field-scale percolation and seepage losses from the irrigation canal network. These outputs were then used as recharge inputs for the MODFLOW-USG groundwater model. A key feature of the Lombardy modelling approach is the distinction between different simulation modes. The need mode estimates irrigation requirements assuming no water limitation, while the use mode reproduces actual water allocation using daily discharge time series, irrigation units and canal network information. This made it possible to represent not only theoretical crop water demand, but also the real constraints imposed by available water resources and distribution rules.

The calibrated MODFLOW-USG model further strengthens the solution by representing the groundwater system through eight layers corresponding to Aquifer Groups A, B and C. The model includes recharge from IdrAgra, lowland springs, pit lakes, surface-water bodies, canals and wells. Calibration was carried out using PEST-HP, with groundwater heads and lowland spring data as targets. The calibration achieved a strong fit, with an objective function reduction of 76%, head RMSE of 0.6 m and mass balance error of $6 \cdot 10^{-5}$%, confirming the suitability of the model for scenario analysis and management support. The future scenario simulations rely on regional circulation models downscaling and on water allocation rules derived from observed discharge data for the 2019–2025 period. These rules were then applied to projected Villoresi Canal discharges for the 2026–2050 period, enabling the simulation of future climate and water availability conditions. The methodology followed and results obtained are explained in Annex 2. The modelling chain can therefore compare reference and alternative scenarios by modifying climate inputs, water availability, land use, cropping patterns, irrigation methods, conveyance efficiency and management schedules.

The Lombardy model also provided relevant quantitative outputs on groundwater storage. During the simulated period, the model estimated a stored volume increase of approximately 8 Mm^3 in the first year and 7 Mm^3 in the second year, with more than 70% of the distributed volume stored in the aquifer and around 10% persisting from one year to the next. These results are particularly important for assessing the role of irrigation and recharge practices as potential adaptation measures. Overall, the Lombardy solution demonstrates how an integrated agro-hydrological/groundwater model can support the evaluation of adaptation strategies such as winter irrigation, improved conveyance management and alternative water allocation schemes, by quantifying their effects on irrigation requirements, evapotranspiration, runoff, percolation and groundwater recharge before implementation.

More details on the models development and implementation can be found in Deliverable 2.3.2.

3. Stuttgart-Feuerbach Pilot Area: modelling groundwater decline and compensation measures

In Stuttgart-Feuerbach, the developed solution addresses a long-term decline in groundwater levels affecting the shallow aquifer system and, to a lesser extent, the deeper system connected to the regional Muschelkalk aquifer and Stuttgart mineral springs. The modelling framework integrates hydrological modelling, conceptual hydrogeological framework, climate data analysis and groundwater flow simulation. The hydrological component combines the GWN-BW soil-water balance model and the HEC-HMS hydrological model. The northern, mainly urban part of the project area was simulated with the soil-water balance model, while the southern catchment required HEC-HMS to represent surface runoff processes. The models cover the period 1980–2024, with 1979 used for model initialization.

The combined water balance shows that, out of approximately 460 l/s of precipitation, almost 100 l/s infiltrate. Around half of this percolation contributes directly to groundwater recharge, while additional recharge occurs through infiltration from the Feuerbach creek. Direct groundwater recharge is estimated at approximately 43 l/s, indirect recharge from the creek at around 13 l/s, resulting in total groundwater recharge of approximately 56 l/s.

The groundwater model developed for Stuttgart-Feuerbach represents a complex 17-layer system, distinguishing the shallow aquifer units from the deeper Unterkeuper and Muschelkalk aquifers. This structure allows the model to simulate both local urban groundwater dynamics and broader regional interactions, including connections with the mineral water aquifer.

The model results confirmed that groundwater levels in the shallow aquifer system have been declining for approximately 20 years, with significant drops documented in several monitoring wells. The decline is superimposed on seasonal fluctuations and appears to have stabilised at a low level after 2017, with a moderate recovery observed since 2022/2024 due to wetter hydrological conditions. Similar, although not identical, trends were also identified in the deeper aquifer system and in the discharge of some mineral springs.

Climate and recharge analyses show that regional climate projections indicate a significant temperature increase, while precipitation and radiation trends remain less pronounced. However, KLIWA/LUBW analyses point to a clear decline in groundwater recharge since the early 2000s. In Feuerbach, calculated recharge decreased from around 62–65 mm/year before 2000 to approximately 53 mm/year after 2000.

A particularly important result of the scenario simulations is that the observed groundwater decline cannot be reproduced by the calculated 20% recharge reduction alone. Model calibration indicates that a local reduction of approximately 50% in recharge, or an equivalent reduction in groundwater turnover caused by leakage or increased losses, is needed to match the observed trends. This points to the combined influence of reduced recharge, possible vertical leakage through boreholes or construction-related connections, and local pump-and-treat operations.

The model-based water balance indicates a total groundwater turnover of approximately 80 l/s in the study area. The resulting groundwater deficit is estimated at 10–20 l/s, corresponding to the additional inflow required to restore groundwater levels to their historic range.

More information on the model development and implementation can be found in Deliverable 2.2.2.

4. Scenario simulation as a tool to compare adaptation measures

The main achievement of the solution is not limited to model construction; it also consists in the simulation of scenarios and management options.

In Stuttgart-Feuerbach, several compensation measures were assessed to determine whether they could reduce the groundwater deficit and support recovery of groundwater levels. Surface water retention using the Feuerbach creek was evaluated but found to be not feasible due to limited water availability, water quality issues, ecological constraints and limited infiltration capacity. The use of precipitation from sealed surfaces was also analysed. Unsealing alone would provide only limited additional recharge, while direct infiltration of collected rainwater could theoretically provide around 11 l/s per km², although practical implementation is constrained by the low permeability of shallow units. Artificial recharge via infiltration wells was identified as the most promising measure. Model simulations showed that infiltrating 10 l/s through five wells into the Bochinger Horizont could raise groundwater levels by approximately 0.5–2 m in shallow aquifers, with measurable effects also in deeper layers. A higher infiltration rate of 20 l/s would produce stronger effects but would require substantial external water sources.

The modelling work therefore provides a clear prioritisation of measures: promote rainwater infiltration where feasible, reduce surface sealing, reinfiltrate treated pump-and-treat water, make reinfiltration mandatory for construction dewatering, investigate and close possible vertical leakages, and improve the monitoring network to support adaptive groundwater management.

In Lombardy, scenario combinations were developed by varying climate projection, drought representation, field distribution, implementation strategy and emergency pumping assumptions. The tested adaptation measure was Agricultural Managed Aquifer Recharge, based on the winter distribution of water through canals and agricultural fields using surface/furrow irrigation. The measure was assessed both as a drought preparedness strategy, implemented before dry periods, and as a drought recovery strategy, implemented after drought events.

The results show that the measure can significantly increase groundwater storage. Considering a distributed winter volume of 27 Mm^3, the average stored volume at the end of the implementation period was about 61%, equal to 16.4 Mm^3, decreasing to 36%, or 9.7 Mm^3, by the beginning of summer. The average storage rate was broadly consistent across the three climate models, although RegCM4 showed slightly lower values.The scenarios also demonstrated the importance of implementation strategy. Drought preparedness and combined strategies produced, on average, around 7% more storage than drought recovery alone, mainly because they allow consecutive years of implementation. Around 10% of the infiltrated volume remained stored one year after implementation, showing that the measure can generate carry-over benefits across seasons. Field distribution strongly influenced the effectiveness of the adaptation measure. When infiltration was located north of the lowland spring and CSNO drainage area, the average stored volume reached 82% of the infiltrated water at the end of implementation. By contrast, the southern distribution, located closer to lowland springs and drainage features, stored only 38%, because a larger share of the infiltrated water was rapidly drained. Whole-area and canals-only distributions produced intermediate results, with average storage rates of 64% and 58% respectively.

Lowland springs play a dual role in the Lombardy scenarios. On one hand, they reduce the persistence of stored groundwater by draining part of the additional recharge. On the other hand, they are groundwater-dependent ecosystems that benefit from increased discharge. The model estimated an average increase of 2.4 l/s per spring following implementation of the measure. Concentrated infiltration near springs activates more springs immediately, while upstream or more diffused infiltration produces a more persistent effect over time. This highlights the need to balance groundwater storage, ecosystem support and the prevention of excessive groundwater level rise.

Extreme-period simulations, based on the repetition of the 2022–2023 drought conditions every seven years, showed that the measure can support both drought recovery and drought preparedness. As a recovery measure, it reduced the time needed for aquifer recovery after an extreme drought from 19 months to 9 months. As a preparedness measure, it helped the aquifer sustain the first year of emergency pumping without additional stress, although it was not sufficient to fully compensate pumping over two consecutive drought years. The combined strategy provided the most balanced performance, supporting both pre-drought resilience and post-drought recovery.

More details on the scenario construction and results can be found in Deliverable 2.2.3 and 2.3.3 for Stuttgart and Lombardy, respectively.

5. Contribution of the solution to strategies and plans

The numerical models and scenarios developed in the two Pilot Areas provide a technical foundation for sound strategies and plans. They allow decision makers to move from qualitative assumptions to quantified evidence, supporting the integration of groundwater adaptation measures into local and regional planning instruments.

In practical terms, the solution contributes to:

- identifying areas and periods where groundwater recharge is most vulnerable;
- quantifying the magnitude of groundwater deficits;
- assessing the expected effects of climate change on recharge and water availability;
- comparing alternative adaptation and management measures;
- estimating the groundwater response to artificial recharge, irrigation practices and water allocation changes;
- supporting the design of monitoring networks and adaptive management procedures.

The modelling activities also highlight that groundwater management under climate change cannot rely on single measures or simplified assumptions. In both Pilot Areas, groundwater availability is controlled by the interaction of climate, land use, infrastructure, water management and hydrogeological conditions. The models make these interactions visible and measurable, helping authorities and stakeholders to prioritise robust, site-specific and climate-resilient solutions.

As such, the first MAURICE solution represents a replicable approach for using numerical models and scenario simulations as the basis for adaptation planning. It provides the quantitative backbone for the second solution, the interactive dashboard, where results can be accessed, compared and communicated to policy makers and stakeholders.

In Deliverable 2.4.2 these aspects are investigated and guidelines are provided harnessing the solutions here presented.

C. Interactive what if analysis dashboard accessible to policy makers and stakeholders

6. Overview

The results of the Italian MAURICE pilot are interactively accessible via a web-based decision-support dashboard, publicly available at maurice.soft-water.it. The platform was designed and developed by SoftWater s.r.l. in collaboration with the Polytechnic University of Milan and with the support of the Consorzio Est Ticino Villoresi, as part of the Interreg Central Europe MAURICE project.

The primary objective of the dashboard is to communicate the scientific outputs of the Pilot Action to a broad audience that includes water managers, irrigation consortia, policymakers, and other stakeholders who may not have a technical modelling background. Targeting primarily Italian users, the entire platform was developed in Italian. Rather than providing raw model output, the platform presents synthesised and pre-computed results through an interactive visual interface, enabling users to explore how a winter Agricultural Managed Aquifer Recharge (Agri-MAR) measure can contribute to climate change adaptation in the Po Plain.

The dashboard is structured around three thematic sections (see Figure 1), accessible from the main navigation menu: Historical Period (Periodo storico), Future Projections (Proiezioni future), and Monitoring (Monitoraggio). An additional Documentation section provides supporting materials. All sections are protected by authentication, ensuring that access to sensitive model outputs is restricted to authorised users.

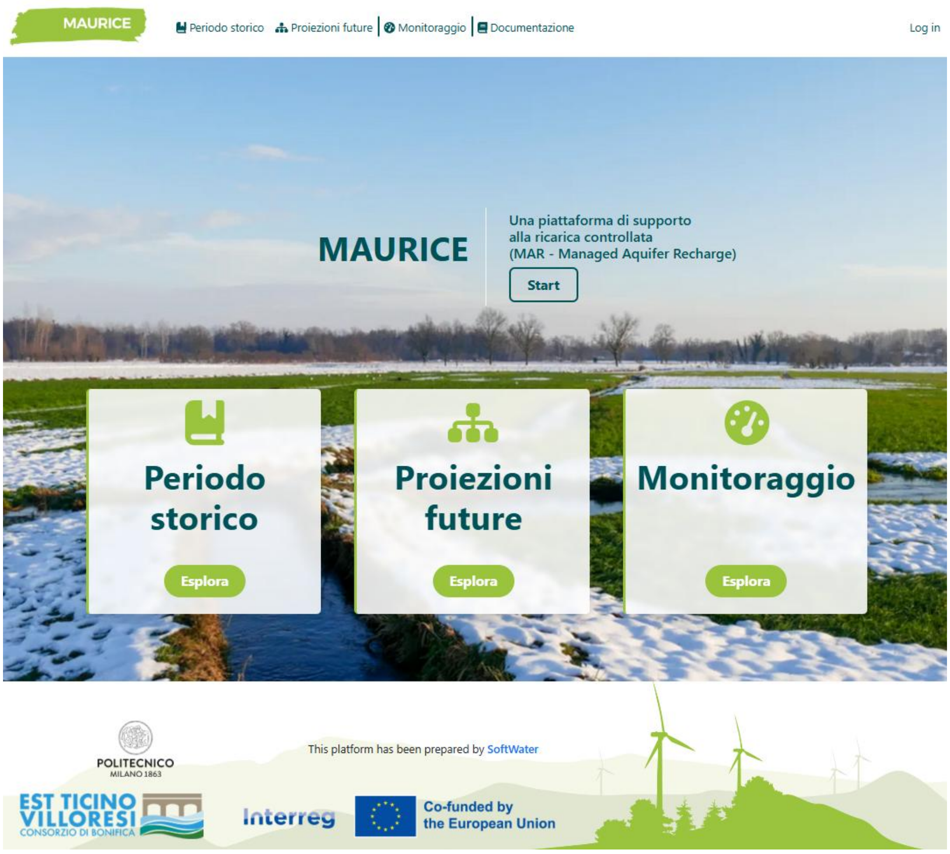


Figure 1. The landing page of Maurice Italian pilot demo site.

7. Content Description

7.1. Historical Period

This section presents observed and reconstructed hydro-climatic data for the study area covering the Lake Maggiore water basin and the Consorzio Est Ticino Villoresi territory. It includes time series of precipitation, temperature, and groundwater levels derived from historical measurements, as well as indicators computed from reanalysis datasets. These data constitute the reference baseline against which future projections and scenario simulations are compared. Interactive charts allow users to inspect seasonal patterns and inter-annual variability, and to contextualise the results of the 2022–2023 drought, one of the most severe recorded in the Po Plain over the past two centuries.

7.2. Future Projections

This section presents the results of over 200 groundwater simulations described in Section C of this report. The results are derived from three regional climate models (CNRM-ALADIN63, KNMI-RACMO22E, ICTP-RegCM4-6) combined with different field deployment configurations, deployment strategies, and emergency pumping scenarios, for the period 2023–2050. Users can interactively explore the projected groundwater dynamics and lowland spring discharge under climate change, with and without the application of the Agri-MAR measure. Key performance indicators, such as the volume stored in the aquifer at the end of the winter deployment period (March 1) and at the beginning of the summer irrigation season (June 1), and the increase in lowland spring discharge, are presented in the form of aggregated graphs and spatial maps. The visualizations allow stakeholders to compare the effectiveness of different field deployments (North, South, entire area, canals only) and implementation strategies (drought preparedness, drought recovery, and their combination) under different climate scenarios.

7.3. Monitoring

This section provides access to near-real-time and regularly updated observed data collected during the Pilot Project field trials conducted in selected areas served by the Villoresi Canal of the Est Ticino Consortium. It contains, among other things, estimates of percolation and groundwater level obtained by coupling the irrigation model with the groundwater dynamics model. Time-series graphs allow users to follow the temporal evolution of the aquifer's response to recharge events implemented in practice and those hypothesized as adaptation measures. Spatial visualizations on interactive maps contextualize the measurement points with respect to infiltration fields, the canal network, and the lowland spring system.

7.4. Documentation

This section collects project reports, methodological notes, and supporting datasets, making the scientific outputs of the Italian Pilot Action accessible for download and reference.

7.5. An example of interactive analytics tool

The figures below illustrate the main interactive view dedicated to analyzing the results obtained, which is also the most technically complex component of the dashboard. The view is organized into two overlapping parts and is designed to offer simultaneous access to three complementary analytical perspectives on the same data set: spatial point effects, spatial averages, and temporal distributions.

The upper layer (Figure 2) is divided into two panels. The left panel displays an interactive map of the pilot area, rendered on an OpenStreetMap base layer with Leaflet. The study domain is highlighted and overlaid with a color-coded raster layer showing the spatial distribution of a selected variable (in this case, groundwater level anomalies) at a specific point in time. The raster is dynamically provided by a custom TiTiler instance (described in Section D.4.2) and coloured according to a diverging palette with a user-adjustable range slider on the right edge of the map. Piezometer locations are displayed as interactive markers: clicking a marker highlights the corresponding time series in the graphs on the right. A time slider at the bottom of the map panel, with start/stop animation controls, allows users to animate the raster over time, observing the spatial evolution of the selected variable month by month.

The right panel contains two overlaid time series plots, generated by the Python/FastAPI backend. The upper plot shows absolute groundwater levels (in m above sea level) for three selected piezometers (Pz1, Pz2, Pz3, whose locations are indicated by pins in the left map), along with a spatially averaged percolation series, represented by a dashed reference line on the secondary y-axis. The lower plot shows the corresponding anomalies with respect to a reference period, allowing users to isolate the Agri-MAR measurement signal from underlying seasonal and interannual variability. Both plots share the same time axis and are displayed with a double y-axis to allow simultaneous reading of groundwater levels (left axis) and the percolation indicator (right axis). This layout was chosen to make the relationship between recharge and aquifer response immediately legible to non-specialist users.

Figure 2. Distributed result explorer dashboard: raster and spatial average timeseries visualizations.

The lower part (Figure 3) of the view is dedicated to temporal aggregation and spatial statistics. For each month of the year and for each of the three rows of displayed variables (change in groundwater storage, change in groundwater level, and recharge flow), a violin plot combined with a box-and-whisker plot shows the distribution of spatially averaged values across the study area. The rightmost column shows the aggregate distribution for all months. This layout allows users to read, at a glance, both the typical seasonal pattern of each variable and its spatial distribution across the pilot area. The relatively compact violin shapes in low-variability months and the broader, multimodal shapes in high-variability periods provide an immediate visual summary of when and where the measure has the most heterogeneous impact across the study area.

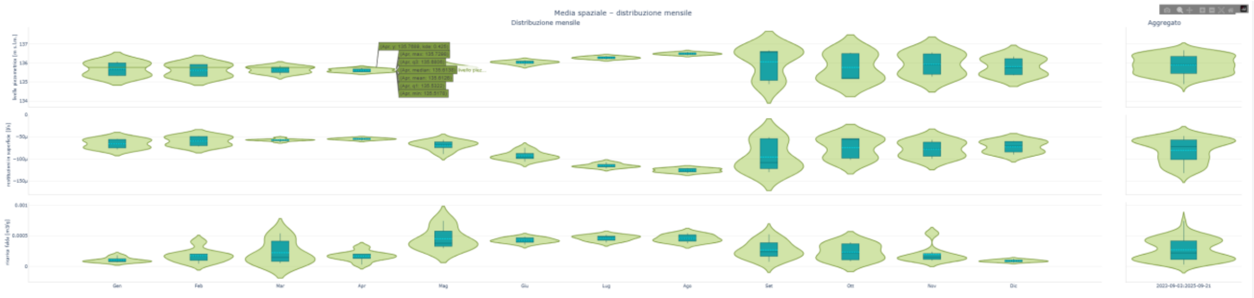


Figure 3. Distributed result explorer dashboard: temporal averages distributions.

Taken together, the three analytical layers of this visualization—the animated raster map (point/spatial effects), the time-series plots (temporal evolution at selected locations), and the box-and-violin matrix (temporal distributions of spatial means)—are designed to answer the key questions a water resource manager or policymaker would ask when faced with a dashboard: where does the aquifer respond most strongly to recharge measures, when does the effect peak, and how robust and spatially consistent is it?

8. Technology Stack

The platform is built on a fully open-source technology stack. The main components are described below. A summary table with links to the products used is present at the end of this chapter.

8.1. Content Management and Web Framework

The website is built on Drupal 10, an enterprise-grade open-source content management system (CMS). Drupal provides the overall page structure, navigation, user authentication, and content editing capabilities. Its modular architecture allows the integration of custom-built visualisation components alongside standard CMS pages. The platform is mobile-friendly and responsive, following accessibility best practices.

8.2. Scientific Computation Engine and Custom Charts

The most computationally intensive visualisations are generated by a Python-based computation engine served as a REST API via FastAPI, a modern asynchronous web framework. Model outputs are stored in the Zarr format, a cloud-optimised array storage format designed for large multi-dimensional datasets. When a user requests a specific combination of scenario parameters, the FastAPI backend reads the relevant Zarr arrays on demand, computes the requested indicators, and returns the chart data dynamically. This architecture avoids the need to pre-generate all possible chart permutations, keeps storage requirements manageable, and provides sub-second response times thanks to Zarr's efficient chunking and compression.

8.3. Spatial Raster Visualisation

Spatial outputs from the IDRAGRA irrigation model and the MODFLOW groundwater one, are served as dynamic map tiles using a customised instance of TiTiler, an open-source cloud-native raster tile server built on FastAPI and GDAL. In its standard configuration, TiTiler reads Cloud Optimised GeoTIFF (COG) files. For the MAURICE dashboard, TiTiler was extended with a custom endpoint that reads multi-band Zarr arrays directly, replacing the conventional multi-band GeoTIFF workflow entirely. This architectural choice was driven by two complementary requirements. First, efficiency: the model outputs comprise hundreds of time steps and multiple variables, resulting in large multi-band raster datasets. Storing these as GeoTIFF files would require either a large number of individual files (one per time step and variable) or very large multi-band files, both of which are poorly suited to the on-demand, user-driven navigation pattern of the dashboard. Zarr's chunked storage format, by contrast, allows the server to read only the spatial and temporal subset actually needed for each tile request, minimising I/O and memory usage. Second, user experience: the animated time slider on the map requires that transitions between consecutive time steps be rendered with minimal latency. Because Zarr chunks are aligned with the array's time dimension, loading a new frame requires reading a single compact chunk rather than seeking through a large file, resulting in smooth animations even for high-resolution spatial outputs. The custom TiTiler endpoint also handles on-the-fly re-projection, dynamic colour mapping, and the application of the user-defined range filter, all of which are computed server-side before the tile is returned to the browser.

8.4. Interactive Maps

Raster tiles produced by the customised TiTiler instance are displayed in the browser using Leaflet, a widely adopted open-source JavaScript library for interactive web maps. Leaflet also handles all vector overlays, including piezometer markers, infiltration field boundaries, canal network lines, and lowland spring locations. User interactions on the map (marker clicks, zoom, pan) are connected to the time series charts via JavaScript event listeners, enabling coordinated views across the spatial and temporal components of the dashboard.

8.5. Standard Charts and Maps via Redash

A significant portion of the visualizations are provided through Redash, an open-source business intelligence and data visualization platform. Redash connects directly to a PostgreSQL database extended with the PostGIS geospatial module, which stores the entire set of observational time series used for model calibration and validation, including data from weather stations, stream flow gauges, lake level measurements, and groundwater levels. Redash queries are defined in SQL, and the resulting charts and maps are embedded in Drupal pages via iframes. This approach allows subject matter experts to update visualizations and add new data sources without modifying the application code, and to leverage PostGIS spatial functions to prepare inputs for geospatial queries.

A representative example of this component is shown in Figure 4, which illustrates the explorer of the measured data used for model calibration. The left panel of the figure shows a general map of the Lake Maggiore basin and the Po Valley, created with Leaflet, on which the meteorological and hydrological stations used for model calibration are displayed as grouped markers, color-coded by station type. Clicking on a group expands it to show the individual sensors; clicking on a station marker opens a pop-up summarizing the station's metadata—type (e.g., METEO_STATION), available variables (in the example shown: prev precipitation and tavg mean temperature), and the number of scenarios for which the station data were used—and provides a direct link (Go to Dashboard →) to access the station-specific Redash dashboard.

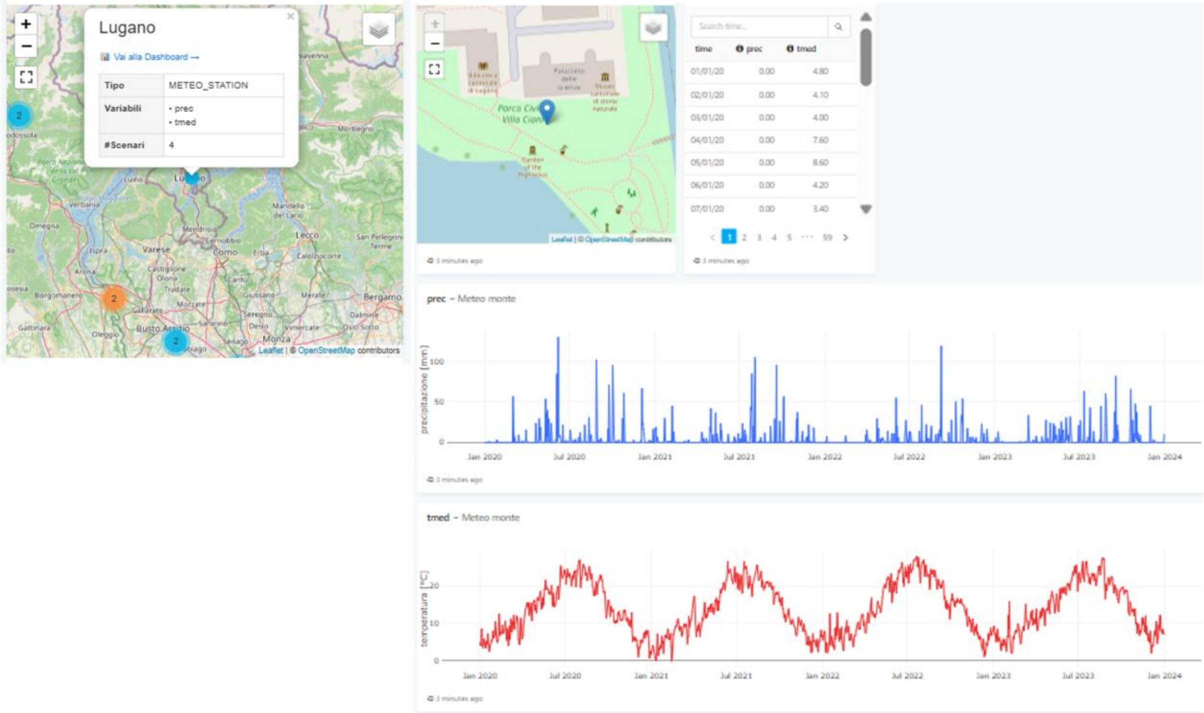


Figure 4. An example of Redash embedded dashboards: the measures map explorer.

The station-specific dashboard, shown on the right side of the same figure, combines three conveniently integrated Redash widgets side by side: a detailed map centered on the selected station location (rendered via Redash's Leaflet integration), a paginated data table that allows users to review or export raw daily data, and two time series charts showing the entire available time series for each variable. In this example, the Lugano station provides daily precipitation (blue bar chart, 2020–2024, mm) and daily average temperature (red line chart, 2020–2024, °C). All these charts are also interactive: users can zoom in on specific periods, hover over individual data points to see exact values, and export the underlying data.

This two-level navigation scheme (overview map → station pop-up → station dashboard) is consistently applied to all sensor types in the calibration network, including flow values input into the Ticino River and the Villoresi Canal, as well as groundwater level data. It provides stakeholders with a transparent and verifiable view of the measured data underlying the modeling work, without requiring any specialized software other than a web browser.

8.6. Summary of the Technology Stack

The table below summarises the main components of the platform:

Component	Technology	Link	Role
CMS / Web framework	Drupal 10	https://www.drupal.org	Page structure, navigation, authentication, content management
Computation engine	Python / FastAPI	https://fastapi.tiangolo.com	On-demand computation of scenario indicators from Zarr arrays
Model output storage	Zarr	https://zarr.dev	Cloud-optimised multi-dimensional chunked array storage
Raster tile server (customised)	TiTiler + Zarr backend	https://developmentseed.org/titiler/	Dynamic rendering of groundwater rasters; Zarr replaces COG for efficiency
Interactive maps	Leaflet	https://leafletjs.com	Browser-side display of raster tiles and vector overlays; coordinated views
BI / standard charts	Redash	https://redash.io	SQL-driven charts and maps for historical and documentation sections
Observational database	PostgreSQL / PostGIS	https://postgis.net	Storage of monitoring time series and geospatial data

All software components used in the platform are released under open-source licences, in line with the open-science principles of the Interreg Central Europe programme. The platform is hosted on infrastructure maintained by SoftWater s.r.l. and will remain accessible for the duration of the project and beyond, subject to the data governance arrangements agreed by the consortium.

Annex 1: Pilot Action Stuttgart future scenarios

Methodology

Considerations on future climate change scenarios are based on the 5th IPCC (Intergovernmental Panel on Climate Change) assessment report. It presents future climate scenarios as “representative concentration pathways” (RCPs). The numbers in the RCP’s names refer to radiative forcing, measured in watt per square meter. Four “representative” scenarios (Representative Concentration Pathways RCPs) were selected, describing possible climate futures based on radiative forcing values, measured in watt per square meter (W/m^2), by the year 2100 (Figure 5).

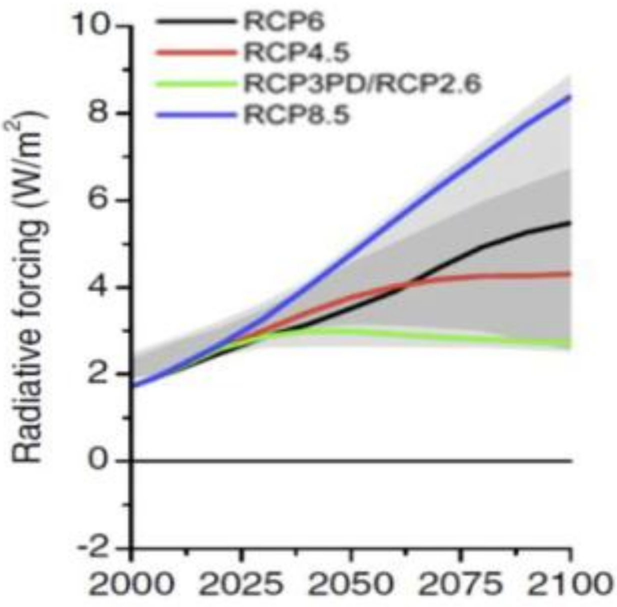


Figure 5. Representative Concentration Pathways

The most consolidated method to assess the impacts of changing drivers on water resources systems is through the downscaling of global scenarios to the local scale. The Top-Down strategy involves a downscaling of the climate variables from Global Climate Models (GCMs), under a range of possible emissions scenarios, to the local scale through the Regional Climate Models (RCMs).

A set of techniques is available to downscale the global models’ variables to higher resolution. Particularly used for their accuracy and availability of variables are the products obtained from EURO-CORDEX (Coordinated downscaling experiment - European Domain). They refine the results of the Global Climate Models using various methods for higher resolutions (grid size ~2 to 5 km) no longer for the entire earth, but for smaller regions, such as southern Germany. CORDEX Data are bias-corrected and made available by the German National Climate Agency (Deutscher Wetterdienst DWD).

With regard to global climate modeling, a next generation of models has been available since 2021 with the 6th IPCC Assessment Report. However, no reliable results are yet available for the regional area.

The federal states Baden-Württemberg, Bavaria and Rheinland-Pfalz in Southern Germany joined forces in the KLIWA cooperation, to determine and evaluate the future effects of climate change. One result of this cooperation is the predicted impact of climate change on the soil water balance and groundwater recharge.

KLIWA uses the worst case (RCP8.5) with the highest assumed amount of greenhouse gas emissions. It corresponds to a world in which no climate protection measures are taken. Nine projections based on dynamic climate models have proven to be suitable for southern Germany. In the groundwater sector, the KLIWA ensemble is supplemented by four statistical climate projections. They are the basis for current water balance modeling.

Results

Climate variables

Key drivers from a water budget perspective are past and future evolution of air temperature and precipitation.

Temperature

Air temperature has a significant influence on evaporation and thus also on precipitation. The warmer the air mass, the more water it can absorb. This increases the maximum possible amount of precipitation. On the other hand, rising air temperature leads to longer vegetation periods, thus increasing evaporation, leading to a lower seepage water rate and consequent decrease in groundwater recharge. The air temperature considered in KLIWA describes the temperature measured at a height of 2 m above the ground.

Analysing the past evolution already shows distinctly rising temperatures since 1990 with a further intensifying trend after 2000 (Figure 6).

According to KLIWA climate projections for southern Germany (worst case scenario RCP8.5), temperature can increase by an average of 3 to 4.4°C until 2100 compared to the timeline 1971-2000.

In **Figure 7**, forecasted temperature changes are shown for the upcoming future until 2100 for the KLIWA federal cooperation states BW (Baden-Württemberg, hosting the Maurice pilot), BY (Bavaria) and Rheinland-Pfalz (RP).

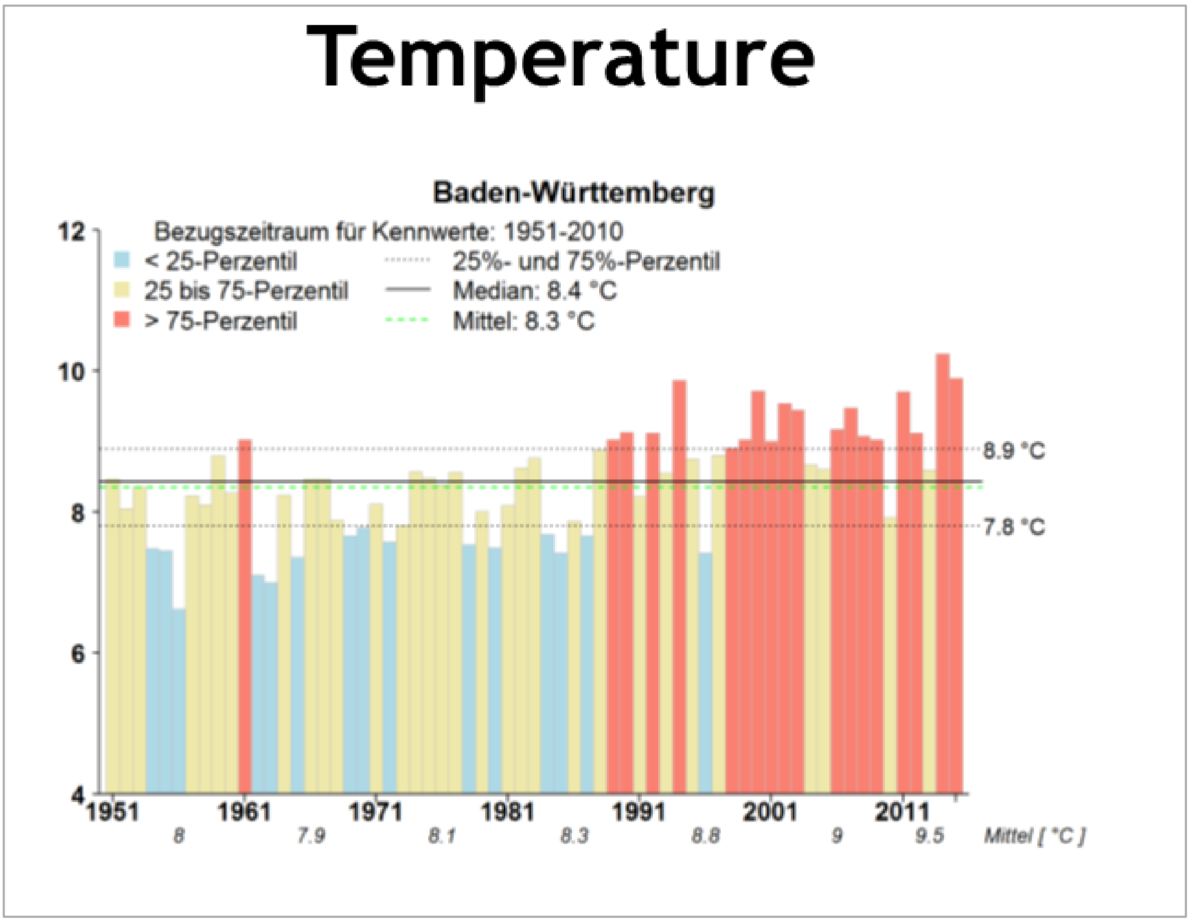


Figure 6. Air Temperature Evolution in Baden-Württemberg since 1951

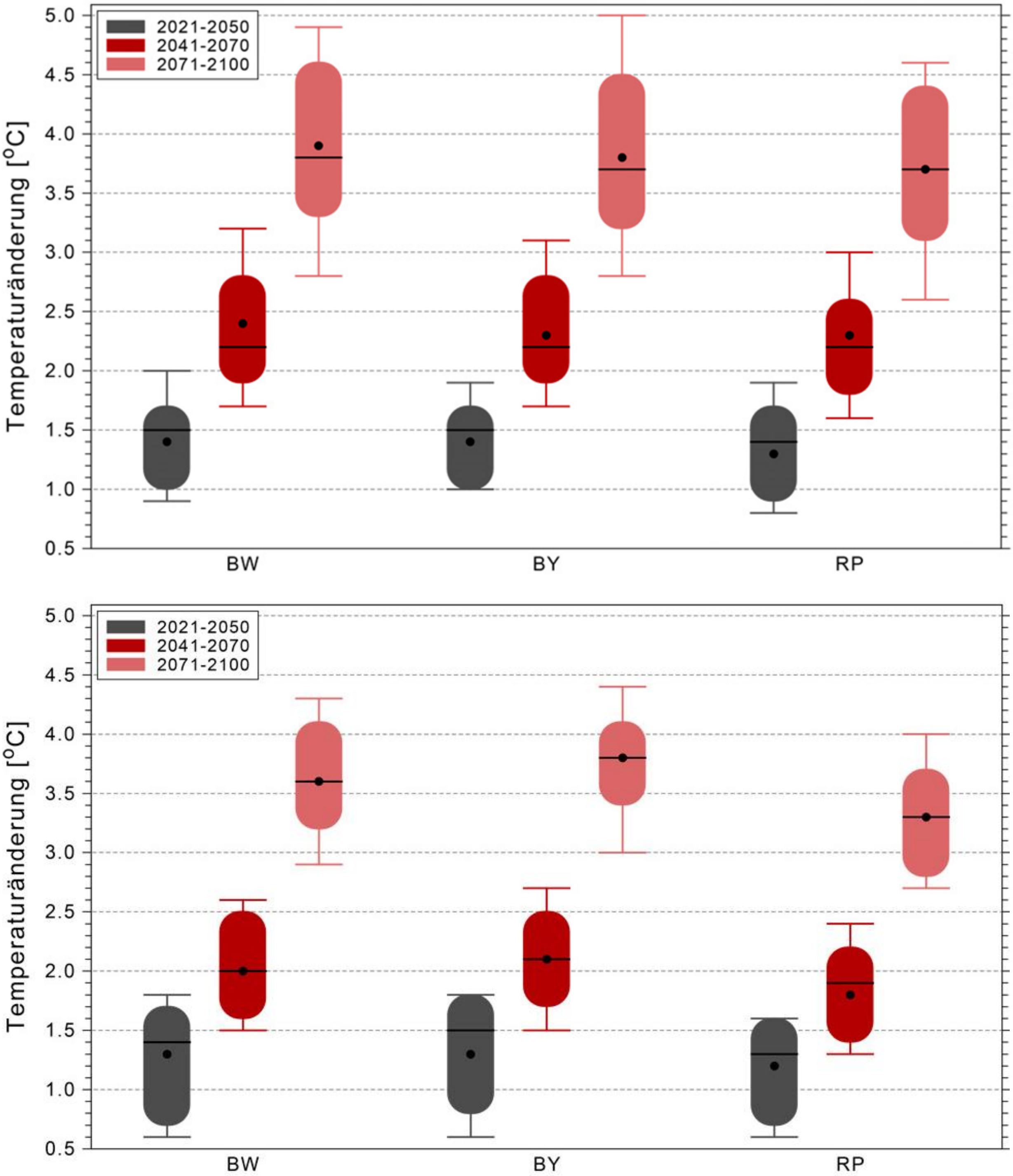


Figure 7. The diagrams show the development of air temperature in the hydrological summer (top) and winter half-year (bottom) for three future periods compared to 1971-2000. The range of the KLIWA ensemble for the KLIWA countries is shown. The boxes are the 15th and 85th percentile, minimum and maximum are given over the range. The line is the median and the dot is the mean value of the ensemble.

Precipitation

The amount of precipitation and its temporal variability have a central effect on all other variables in the water balance. The trend towards more frequent and more intense heavy precipitation events increases the proportion of rapid lateral runoff components and thus simultaneously reduces infiltration and groundwater recharge. On the other hand, European cities increasingly strive for implementing sponge city concepts, with a perspective for mitigation in the long term.

Analysing the past evolution already shows a distinctly decreasing tendency with hardly any years above average (green line, **Figure 8**) after 2003.

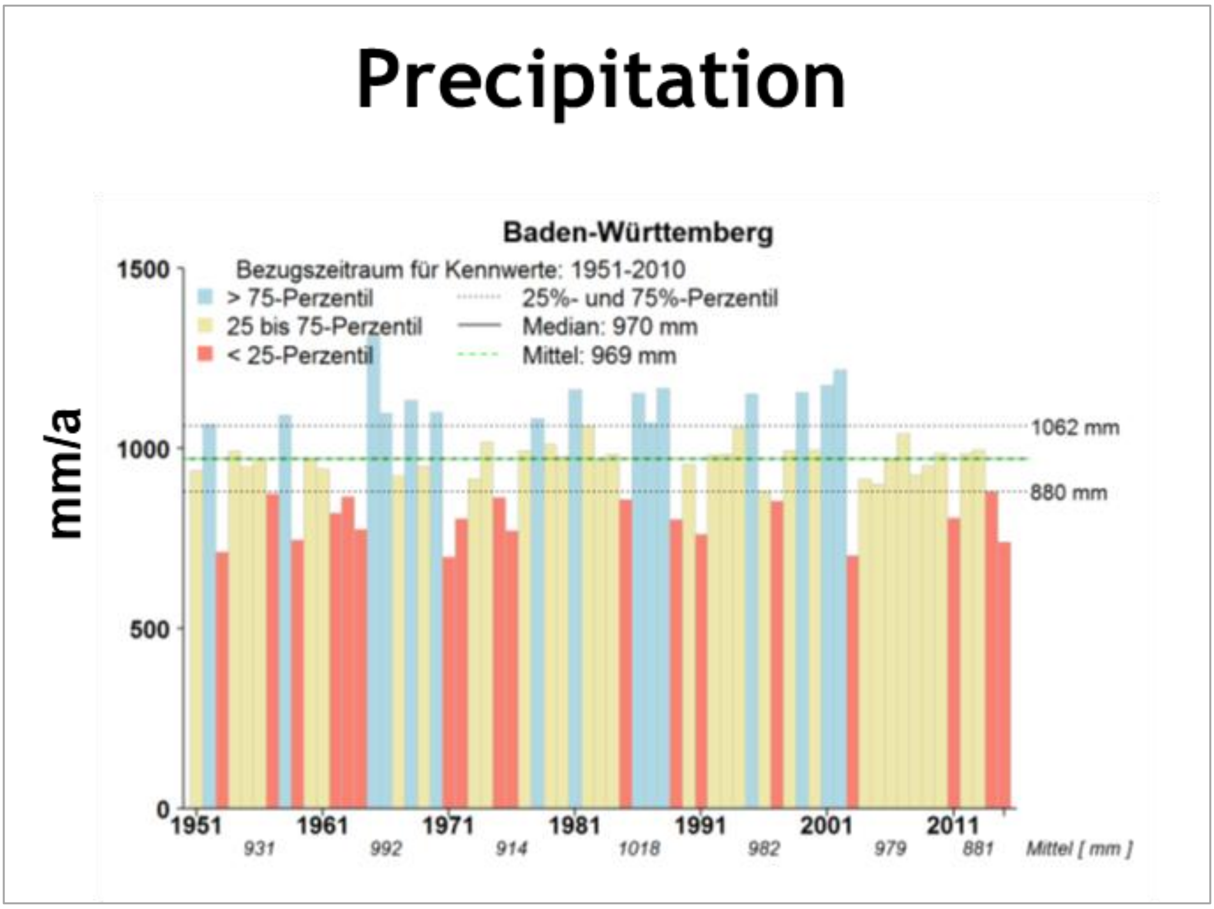


Figure 8. Evolution of precipitation in Baden-Württemberg since 1951

Figure 9 shows forecasted changes in precipitation for the upcoming future until 2100 for the KLIWA federal cooperation states BW (Baden-Württemberg, hosting the Maurice pilot), BY (Bavaria) and Rheinland-Pfalz (RP). Projections were done according to worst case scenario RCP8.5, generally applied in KLIWA. According to these predictions, the current trend of wetter winters and drier summers will continue.

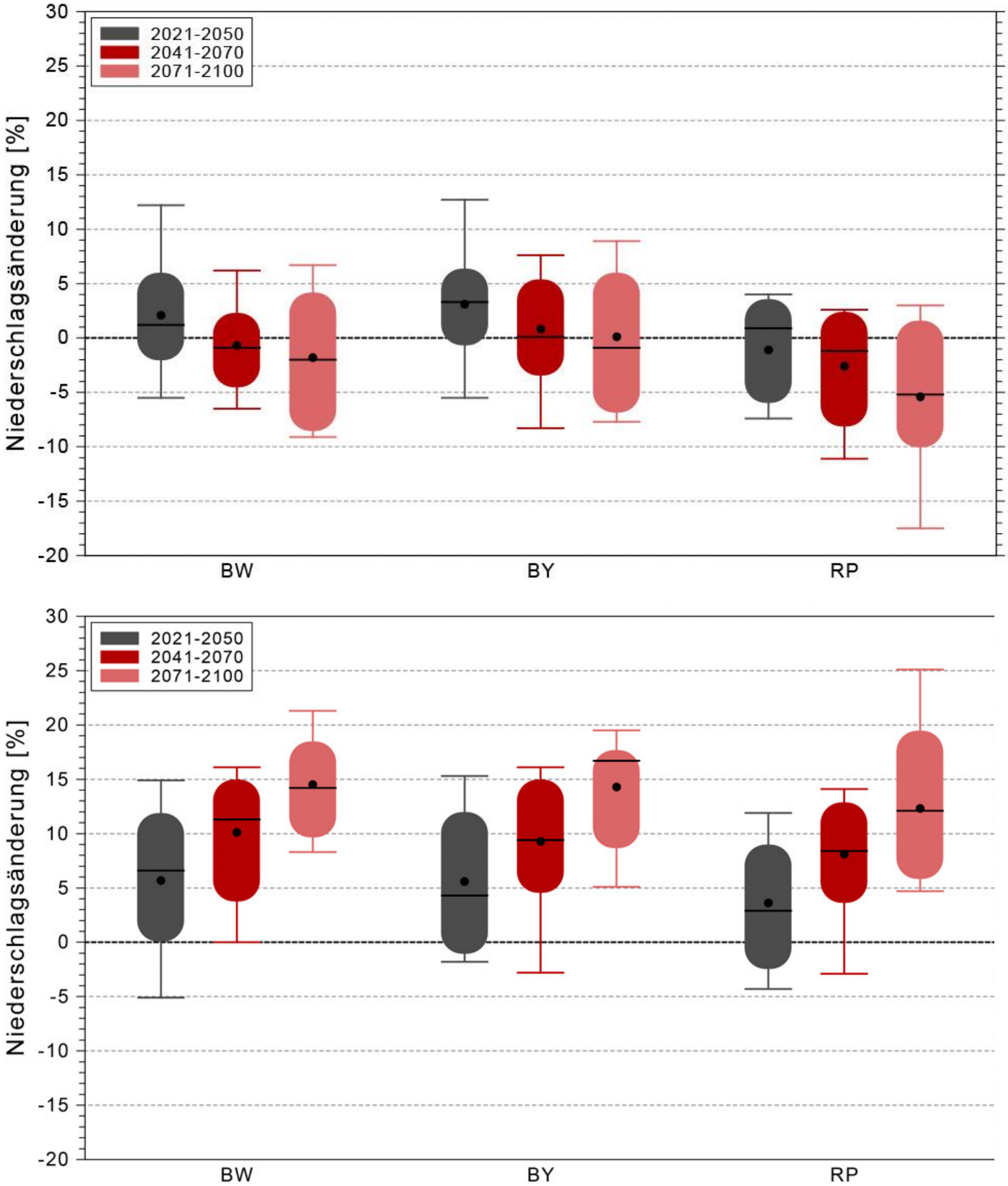


Figure 9. The diagrams show the relative change in areal precipitation for three future periods compared to 1971-2000 The range of the KLIWA ensemble for the KLIWA countries is shown. The boxes are the 15th and 85th percentile, minimum and maximum are given over the range. The line is the median, and the dot is the mean value of the ensemble.

Groundwater recharge

Groundwater recharge represents the balance of precipitation minus evaporation and surface runoff. As a "balance residual", it therefore reacts particularly sensitively to changes in the climate and decreases in precipitation. Figure 10 shows the principles of interaction between these influencing factors.

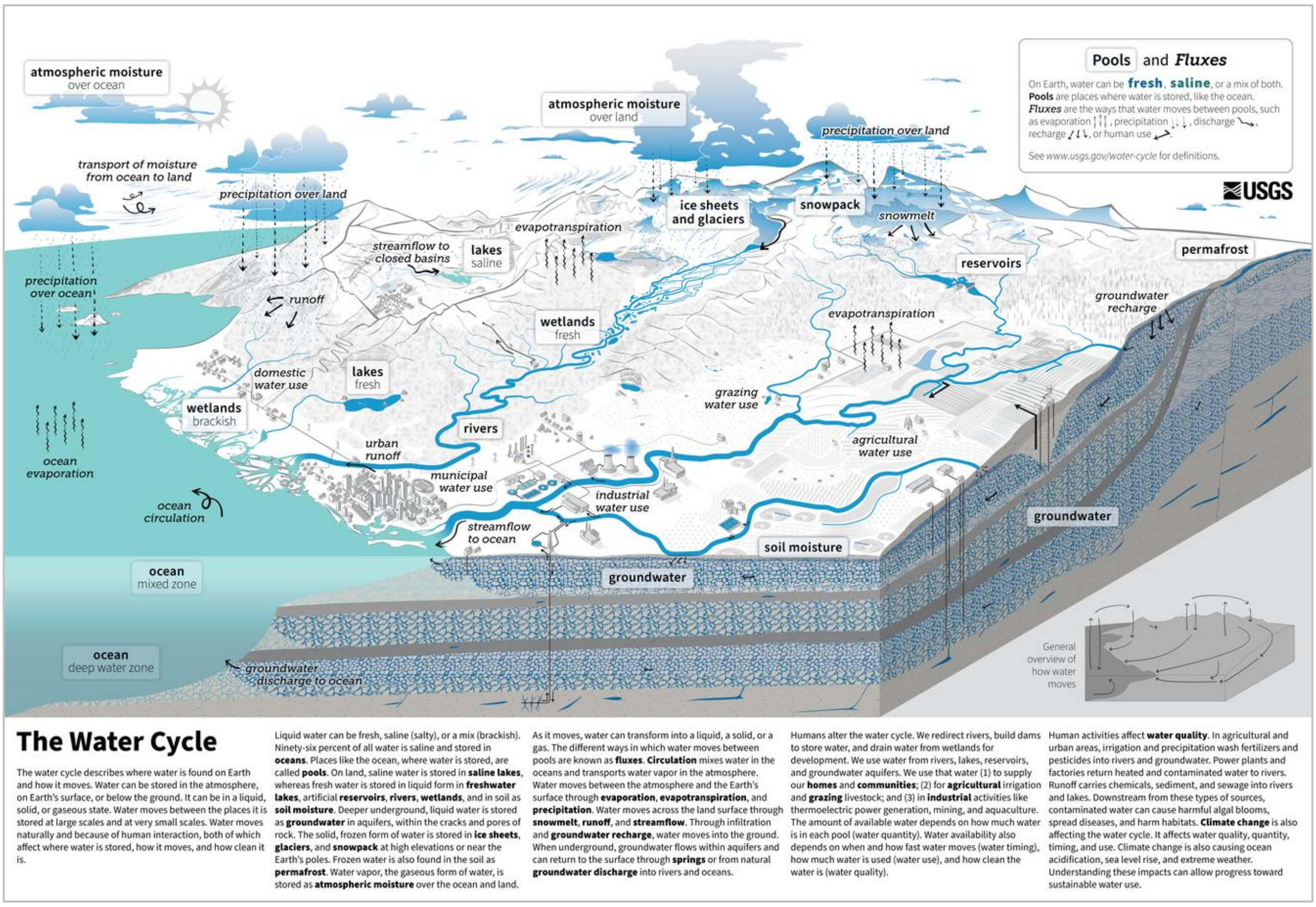


Figure 10. Schematic representation of the water cycle, including the groundwater balance

Scenario simulations based on the KLIWA ensemble were carried out to investigate the question of future changes in groundwater recharge due to climate change. A soil water balance model was established to determine long term mean groundwater recharge rates on the basis of measured values. WETTREG is a statistical regionalization procedure that generates results (realizations) on the basis of station data for those stations where measurement series are available.

The WETTREG forecast for groundwater recharge (Figure 11) shows the long term past evolution in combination with 13 selected future projections. They were selected by KLIWA on basis of an audit process. They are all based on the RCP 8.5 (worst case) scenario with the aim of providing a good reflection of the range of possible developments in soil water balance dynamics.

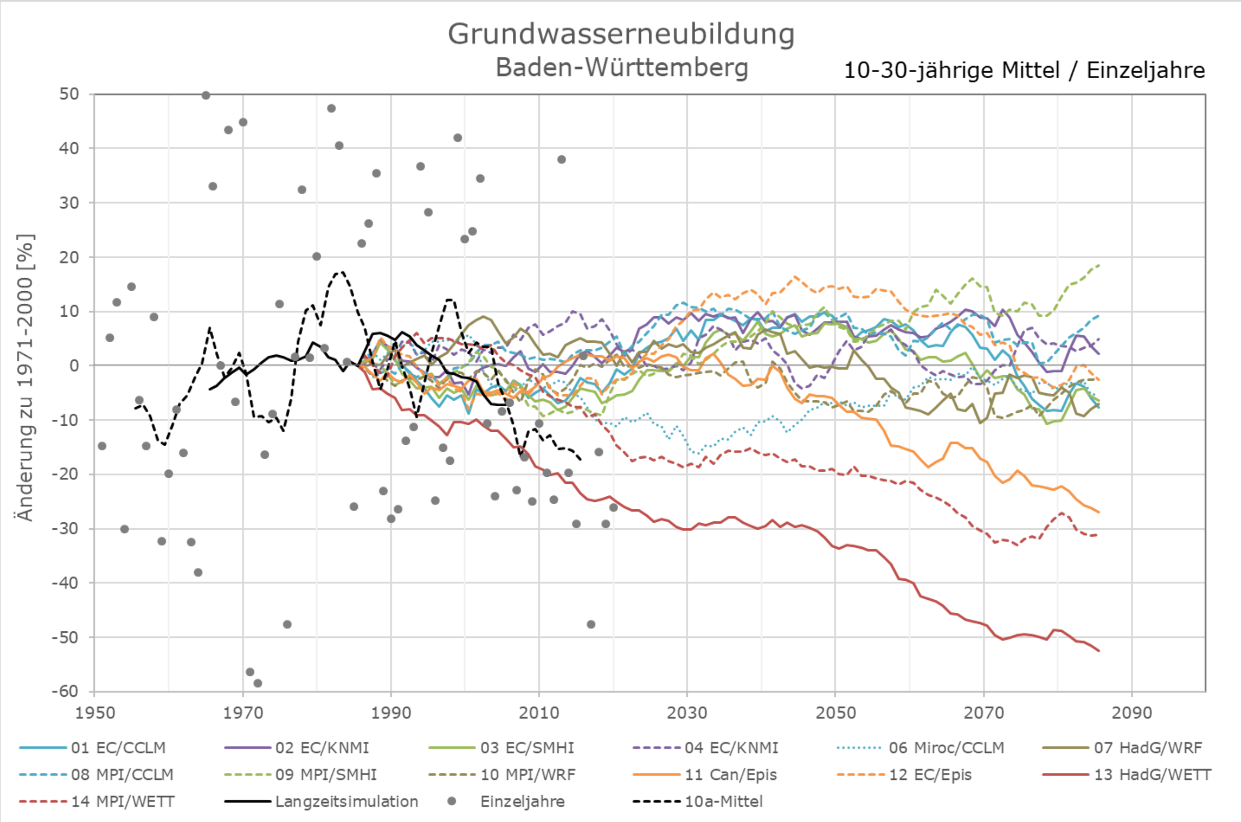


Figure 11. 30-year moving average of the relative change to the reference period 1971-2000 of past (black line, long-term simulation based on measured data) and projected groundwater recharge of the various projections of the KLIWA ensemble, for state Baden-Württemberg. Grey dots show the individual annual mean values from the long-term simulation to illustrate the high annual variability of groundwater recharge from precipitation

According to the past long-term simulation a deficit in groundwater recharge has built up since 2003. Combining soil water balance simulations, based on measured data, with climate projections, it becomes clear that the development of groundwater recharge in recent years is currently tending towards the dry, lower edge of the extended KLIWA ensemble.

Figure 12 shows the regional distribution of expected groundwater recharge reductions in the state of Baden-Württemberg for the years 2036-2065 compared to 1991-2020. For the Stuttgart region, a decrease of 25% is expected.

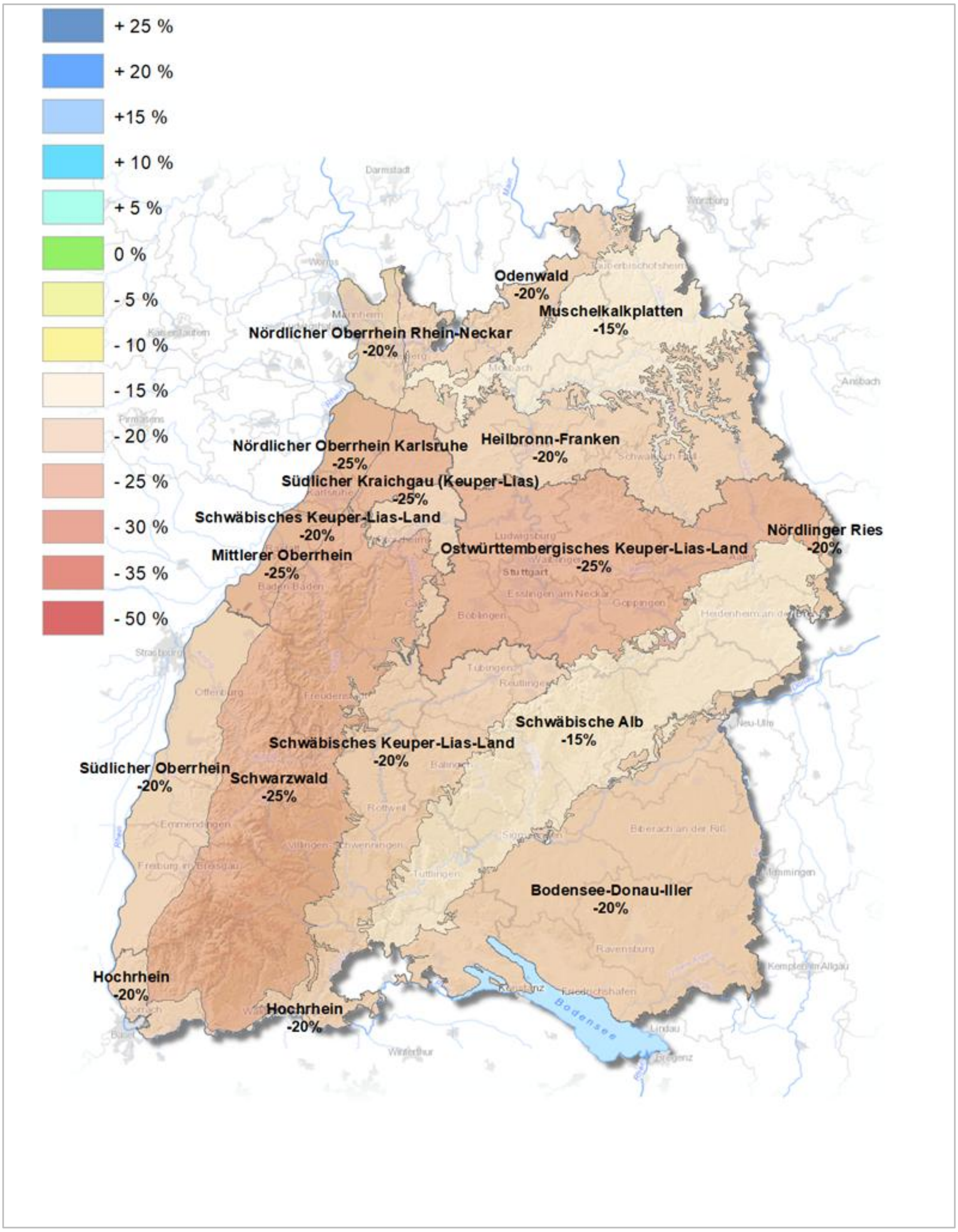


Figure 12. Expected Regional Distribution of Groundwater Recharge Reductions in Baden-Württemberg for the years 2036-2065 compared to 1991-2020, according to KLIWA worst case scenario

Pilot Area Stuttgart Feuerbach

To analyse past evolution, the water balance for the project area was calculated using a soil water balance model and a hydrological model. The northern part of the project area (mainly urban area of Feuerbach) was simulated with a soil water balance model (GWN-BW, GIT HydroS Consult GmbH, 2014), used to estimate grounwater recharge and evaporation rates, since no relevant surface runoff could be expected. For a hydrological assessment of the southern project area, where surface runoff had to be included, the soil another hydrological model was developed using the HecHMS 4.11 software (U.S. Army Corps of Engineers, 2023) within the extents of the southern Feuerbach basin.

Figure 13 shows the past evolution of groundwater recharge in the Stuttgart Feuerbach area. as annual totals, mean value and moving average over 10 years. Since 2000 the ten years moving average shows a decrease of approximately 20%.

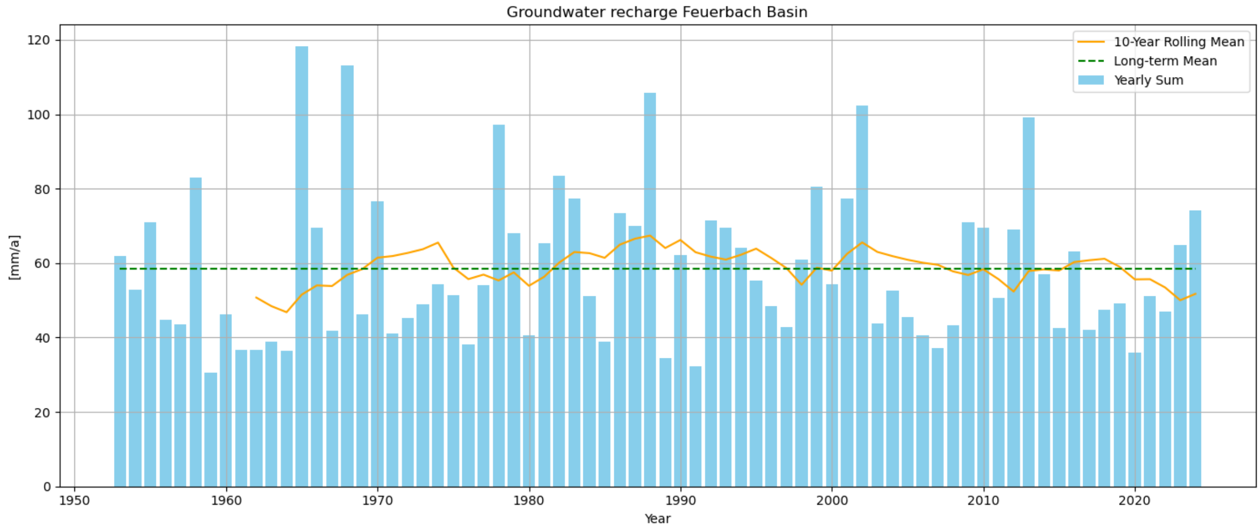


Figure 13. Past development and statistical evaluation of groundwater recharge in the project area. Total annual amount (dark blue line), average (light grey line) and moving average over 10 years (orange line)

Scenario calculations for future development were based on WETTREC prognosis (Figure 14). Corresponding with our project area past evolution we decided to choose the worst-case scenario (13 HadG/WETT) with a decrease of groundwater recharge of around 25% in the period 2036-2065 (compared to the period 1990-2020, see Figure 14).

10 shows an extrapolation from past evolution to future development based on a statistical evaluation according to WETTREC scenario 13. We used this assumed evolution as input parameter for scenario calculations in the groundwater model.

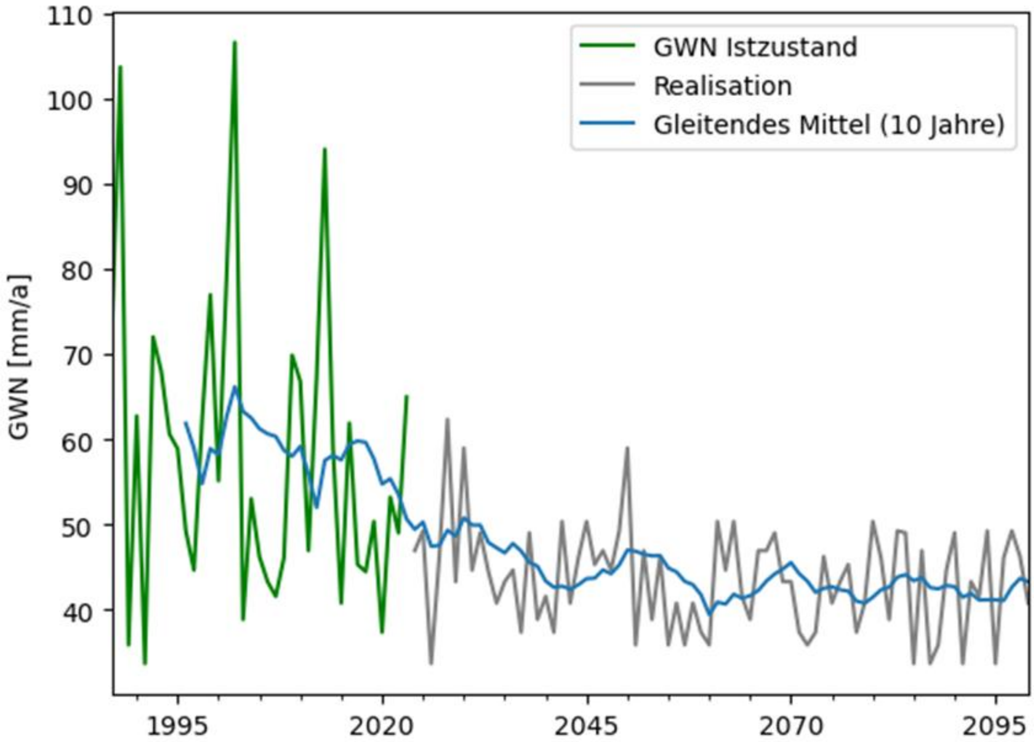


Figure 14. Past evolution and assumed future development of groundwater recharge according to WETTREC scenario 13 with past development (green line), future prognosis (grey line) and moving average over 10 years (blue line).

Annex 2. Pilot Action Milan future scenarios

Methodology

The simulation of the aquifer and the irrigation system dynamics in the area under study requires knowledge of the meteorological and climate context as well as the surrounding conditions, specifically the flow rates taken at the Panperduto dam toward the Villoresi Canal, and the flow rates passing downstream of the same dam towards the Ticino.

The average daily values of these flow rates have been known since the construction of the Miorina dam, regulating the Lake Maggiore and was built in the 1940s. This dam modulates the flow rates entering the Panperduto node, and it is therefore crucial to consider its behaviour within the proposed model.

The study does not limit itself to reconstructing what happened historically but aims to provide elements to estimate what the effects could be in the future, considering the current climate evolution. It is therefore necessary to identify relationships that allow estimating the previously mentioned flows, starting from the formation of the inflow to Lake Maggiore, which collects the waters that fall on a catchment area of about 6600 km^2, partly in Italy and partly in Switzerland.

It was decided to use a pair of cascade models: the first, to estimate the values of the inflow to Lake Maggiore starting from temperature and precipitation data, representative of the conditions of the catchment area; the second, to obtain the two flows of interest starting from the inflow estimated by the first. These models, once identified, were fed with the projections of the climatic variables obtained as described in Deliverable 1.3.1 to which reference is made.

From a methodological point of view, the models were designed using machine learning techniques and recurrent neural networks (RNN) and Long Short-Term Memory (LSTM). Traditionally, hydrological modelling has relied on physically based models, which represent hydrological processes through differential equations derived from physical laws. Although these models provide a deep understanding of the underlying mechanisms, their application can be challenging due to the large number of parameters to be calibrated, their dependence on the availability of detailed physical data, and their difficulty in capturing the extreme nonlinearity and spatial and temporal variability of hydrological systems (Beven & Freer, 2001).

Unlike physically based models, RNNs and LSTMs are data-driven models, meaning they learn input-output relationships directly from observed historical data. Their inherently recurrent architecture makes them particularly well suited to modelling time series, such as those typical of hydrological data. RNNs are able to maintain a “memory” of previous inputs, allowing them to capture temporal dependencies in the data (Elman, 1990). However, standard RNNs suffer from the well-known “vanishing/exploding gradient problem”, which limits their ability to learn long-term dependencies. LSTMs are a variant of RNNs that solve this problem by introducing a “memory cell” and “gates” (input gate, forget gate, output gate) that regulate the flow of information. This allows LSTMs to learn and maintain long-term dependencies more effectively, making them extremely powerful for complex time series forecasting (Hochreiter & Schmidhuber, 1997).

LSTMs are emerging as promising tools for hydrological simulations such as river flow forecasting, runoff simulation, evapotranspiration estimation, and other applications (Kratzert et al., 2018; Hu et al., 2019; Hunt et al., 2022; Liu et al., 2024; Hosseini et al., 2024). Recent papers highlight how the use of LSTM networks has improved water flow forecasts in complex basins, highlighting the ability to capture nonlinear temporal dynamics (Zhang et al., 2022). In cases of poorly structured data, it has been shown (Li et al., 2023) how deep learning models, including recurrent ones, are more effective than traditional methods, feeding more reliable forecast scenarios. Innovative techniques have also been proposed to improve the performance of these models to accurately reproduce flood peaks (Martel et al., 2024a).

Some studies have suggested hybrid approaches, where data-driven models are coupled with physically based models to combine the strengths of both approaches (e.g., to improve forecasts or to inform machine learning with physical knowledge). Recent studies (Kumar et al., 2024, Maity et al., 2024) highlight for example how physical-empirical models can be integrated with machine learning techniques to improve forecasts and reduce interpretability limits.

In summary, the choice of model depends on the specific goals of the simulation, the availability of the data, and the level of interpretability required. The comparison between data-driven models (such as RNN/LSTM) and physically based models is an active research topic (see e.g. Lei et al., 2023; Fuente et al., 2024; Martel et al., 2024b). While physically based models offer greater interpretability and can be generalized to unobserved scenarios (if the physical processes are well understood and represented), they require in-depth knowledge of the system and can be computationally expensive. In contrast, LSTM models excel at prediction based on historical data, are faster to run once trained, and can capture complex relationships that would be difficult to express in physical equations. However, their "black-box" nature can make it difficult to interpret the "why" of a specific prediction, and their performance is highly dependent on the quality and quantity of the training data.

Results

Climate variables

This chapter presents all the time series of the climatic variables produced, both those needed to feed the models described previously, which simulate the Lake Maggiore upstream system, and those used to feed the model of the valley irrigation downstream system, for the case study area. In both cases, the EURO-CORDEX dataset was used, in particular the projections provided by the Aladin, RegCM4 and RACMO models in correspondence with the RCP8.5 scenario. For the methodological description of the techniques used and for the related bibliographic references, see D1.3.1.

Climate variables in the upstream system

Precipitation and temperature time series were obtained for the stations of Domodossola and Crodo, in Italy, and Lugano, Locarno and Magadino, in Switzerland, considered overall representative of the catchment area of Lake Maggiore.

For temperature, the statistical correction between the chosen EURO-CORDEX projections and the ground data was performed by comparing two different techniques: Empirical Quantile Mapping (EQM) and Detrended Quantile Mapping (DQM) bias-adjustments. For example, for the Domodossola station, corresponding to the 3 models, the daily cyclostationary means shown in Figure 15. are obtained, from which the differences between the two approaches are negligible.

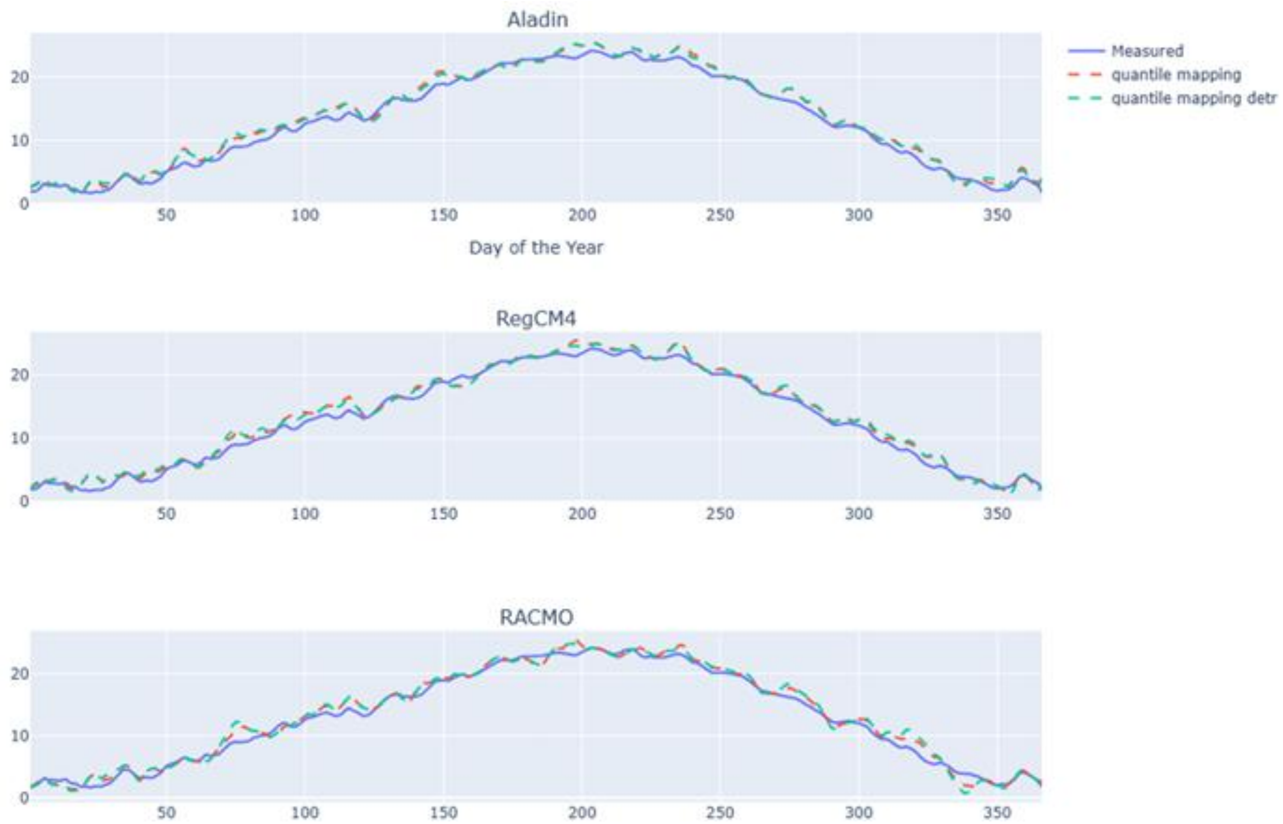
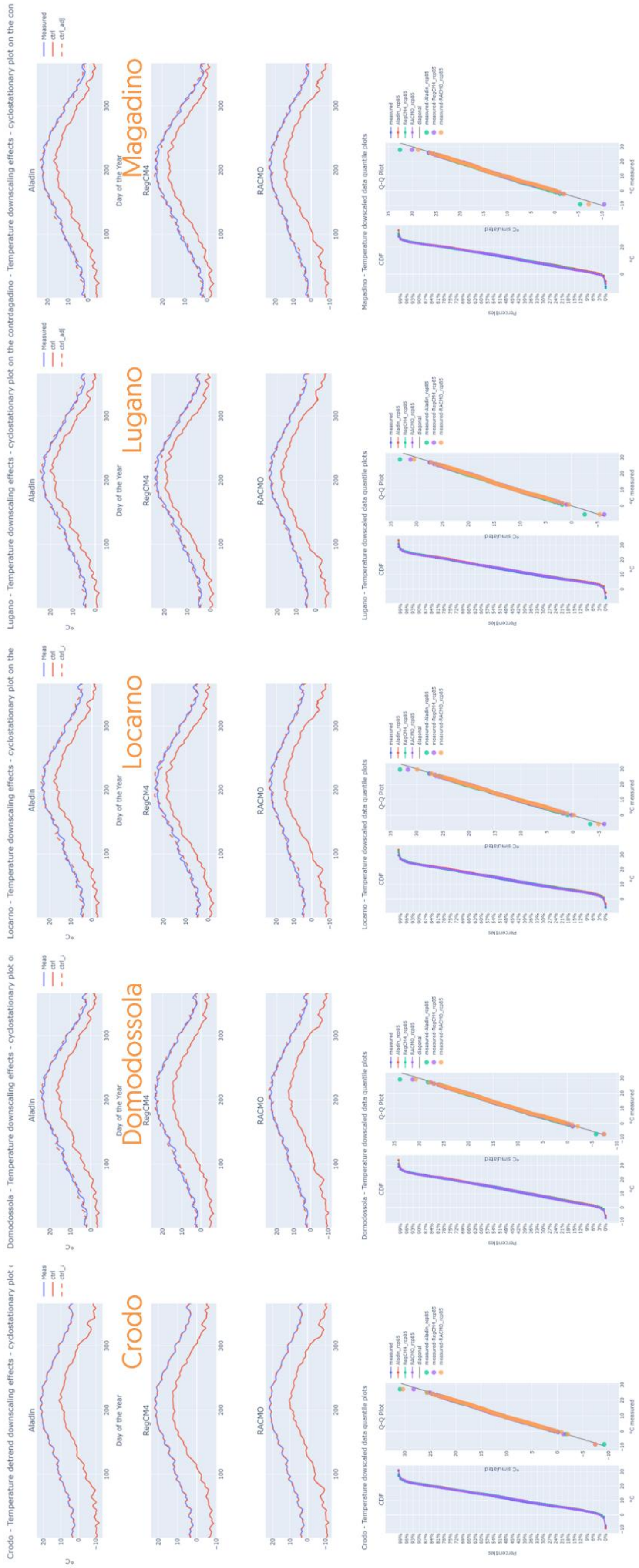


Figure 15. An example of the daily cyclostationary temperature average, corresponding to each of the models used, after the downscaling operation with the EQM and DQM methods.

It was therefore opted to use EQM for all stations, obtaining the results shown in Figure 16, in which, in addition to the cyclostationary means, there are also the q-q plots, with which the alignment of the quantiles of the projections is judged with respect to the ground data, after the adaptation operation.

Also, in the case of precipitation, the classic EQM was compared without and with a previous adjustment phase called Local Intensity Scaling (LOCI) bias-adjustment. It is known in fact that EQM is not able to faithfully reproduce the frequency of dry days, in which precipitation can be considered zero. The consequence is that if the total amount of precipitation, for example in a year, is statistically homogeneous between projection and ground data in the control period, this volume is often made up of a greater number of days with moderate rain. This result would lead to underestimating the effects of climate change, favouring for example agriculture and in general making the management task less problematic. The application of LOCI before EQM allows to alleviate this phenomenon, as shown in **Figure 17**, where the number of days without rain in the control period before and after the application of LOCI + EQM is shown.

Figure 16. Daily cyclostationary temperature averages (top figure) and quantile distributions with q-q plots (bottom figure) for all downstream used stations corresponding to each of the models used, after he downscaling operation with the EQM and DQM methods.



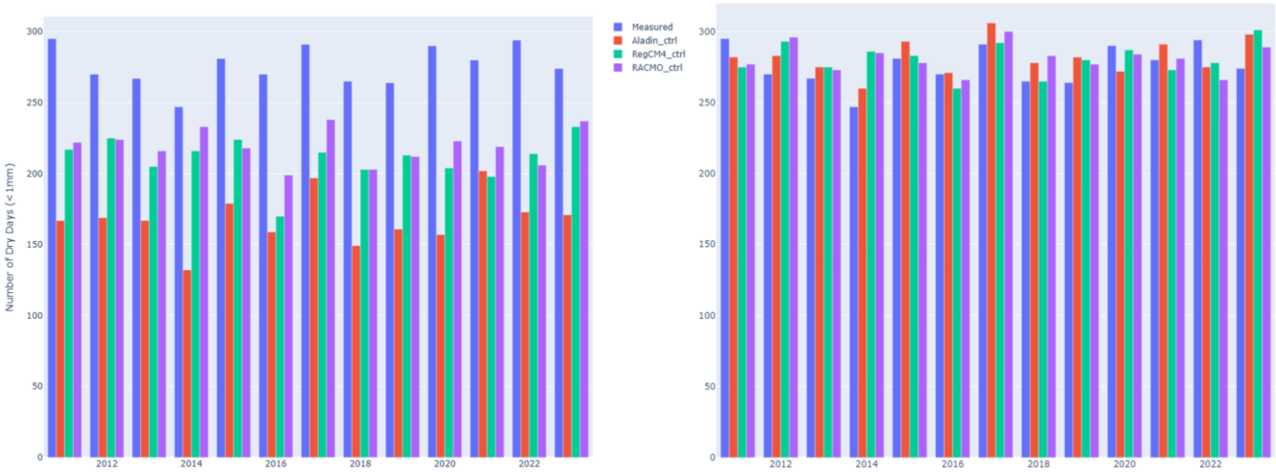


Figure 17. Comparison of number of dry days in the control period (left side) and in the future horizon (right side) corresponding to each of the models used, after the downscaling operation with the LOCI + EQM methods.

The application of these two methods to all five stations considered led to the result shown in the following **Figure 18** and **Figure 19**. Figure 18 shows the cumulative daily precipitation [mm] after downscaling, always in the control period, while Figure 19 shows the annual values [mm/year] before and after downscaling until 2050.

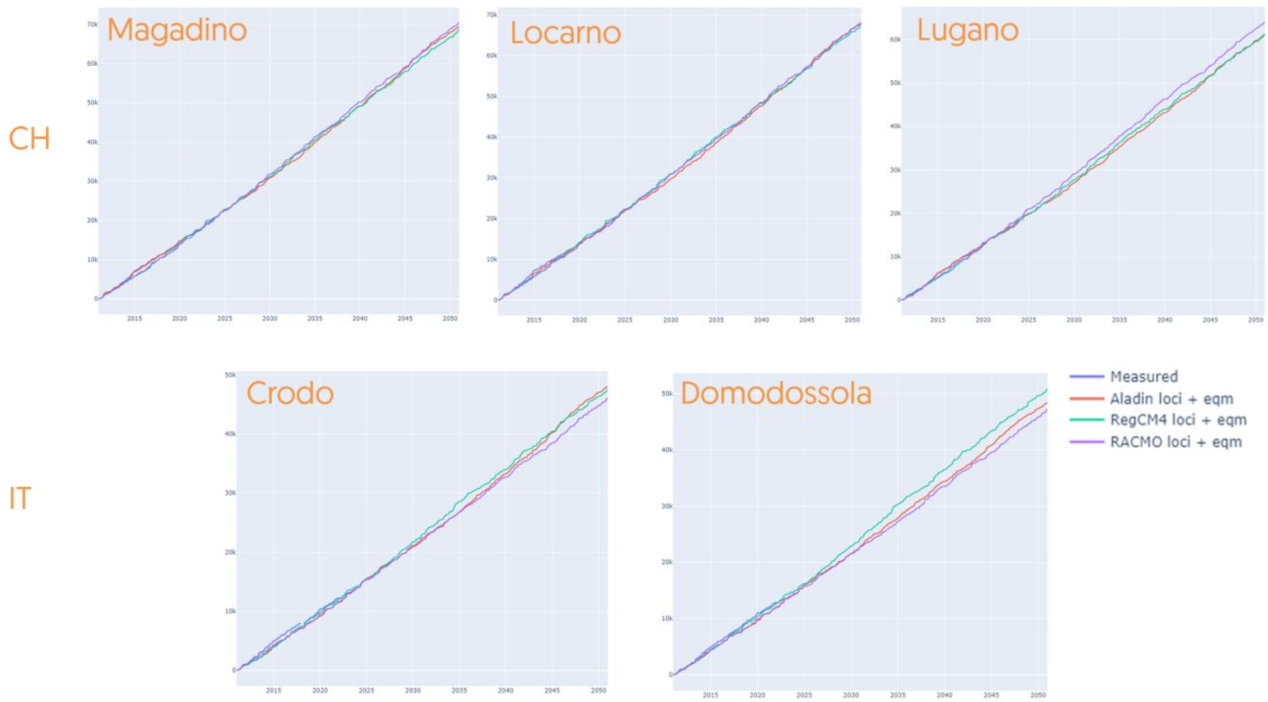


Figure 18. Cumulative daily precipitation in the future horizon for all downstream used stations corresponding to each of the models used, after the downscaling operation with the LOCI + EQM methods.

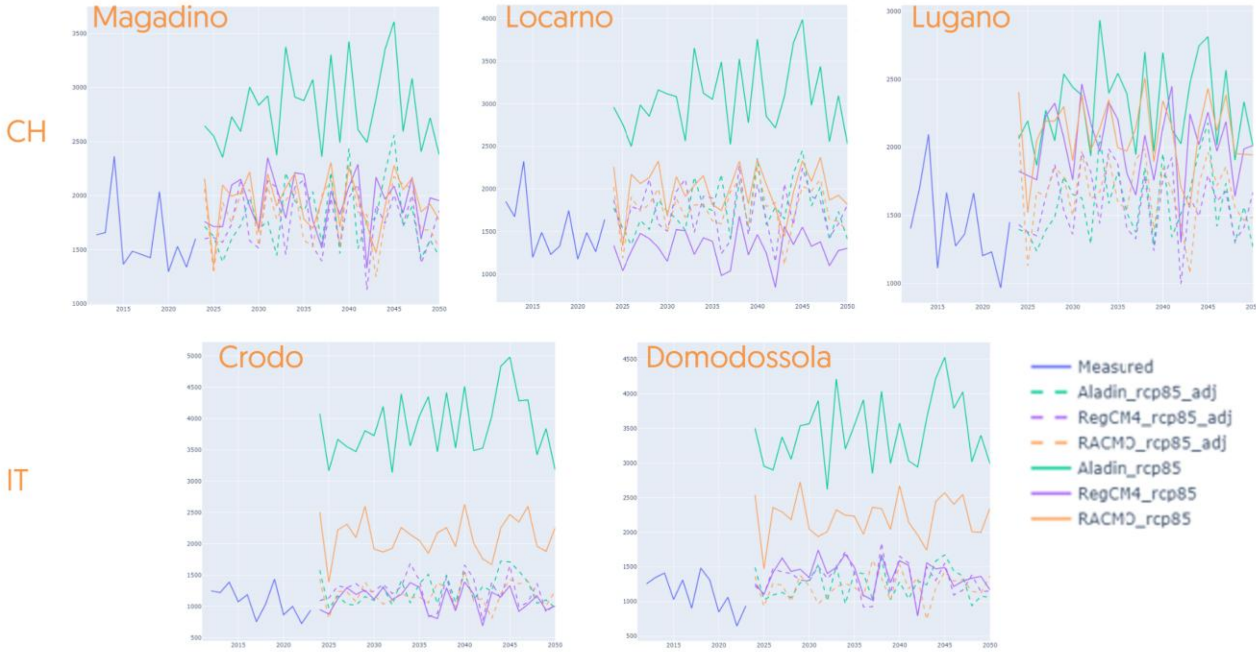


Figure 19. Yearly total precipitation in the future horizon for all downstream used stations corresponding to each of the models used, before and after the downscaling operation with the LOCI + EQM methods compared with the measured values.

Climate variables in the downstream system

The valley irrigation system model requires the production of time series for 7 variables (minimum and maximum temperature and humidity, precipitation, irradiance and wind speed) for 7 stations (Landriano Cascina Marianna, Cinisello Balsamo Parco Nord, Arconate SMR, Corsico v.le Italia, Rescaldina, Pogliano Milanese, Rho Scalo Fiorenza – Prato). In the case of temperature and humidity, the maximum value and the daily delta were produced, subsequently calculating the minimum value by difference.

The effect of downscaling is visible, in Figure 20. where, for a certain station, the daily averages of maximum and minimum relative humidity are shown before and after downscaling, comparing them with the observed data.

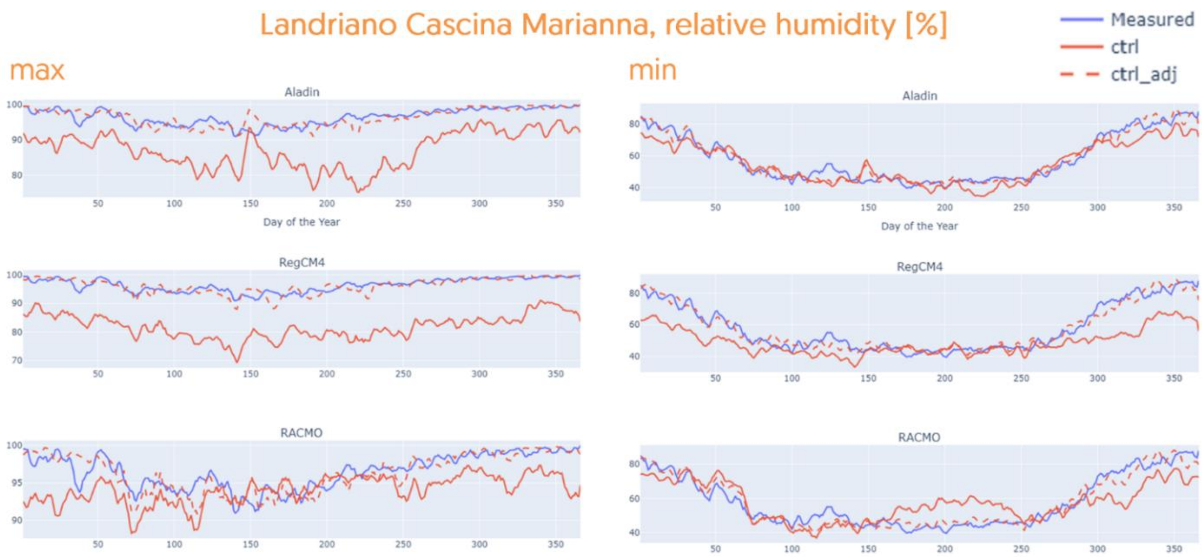


Figure 20. An example of the daily cyclostationary relative humidity (max on the left, min on the right) corresponding to each of the models used, before and after the downscaling operation.

To produce the precipitation time series, the same method described previously was adopted, utilizing the LOCI + EQM pipeline in order to adjust the frequency of days with no rain between projections and ground measurements. The synoptic result containing also the trend of the cumulative precipitation for a station and for the 3 models is shown in **Figure 21**. Finally, for both the irradiance and for the wind speed the EQM method was used, obtaining the daily averages shown in **Figure 22**.

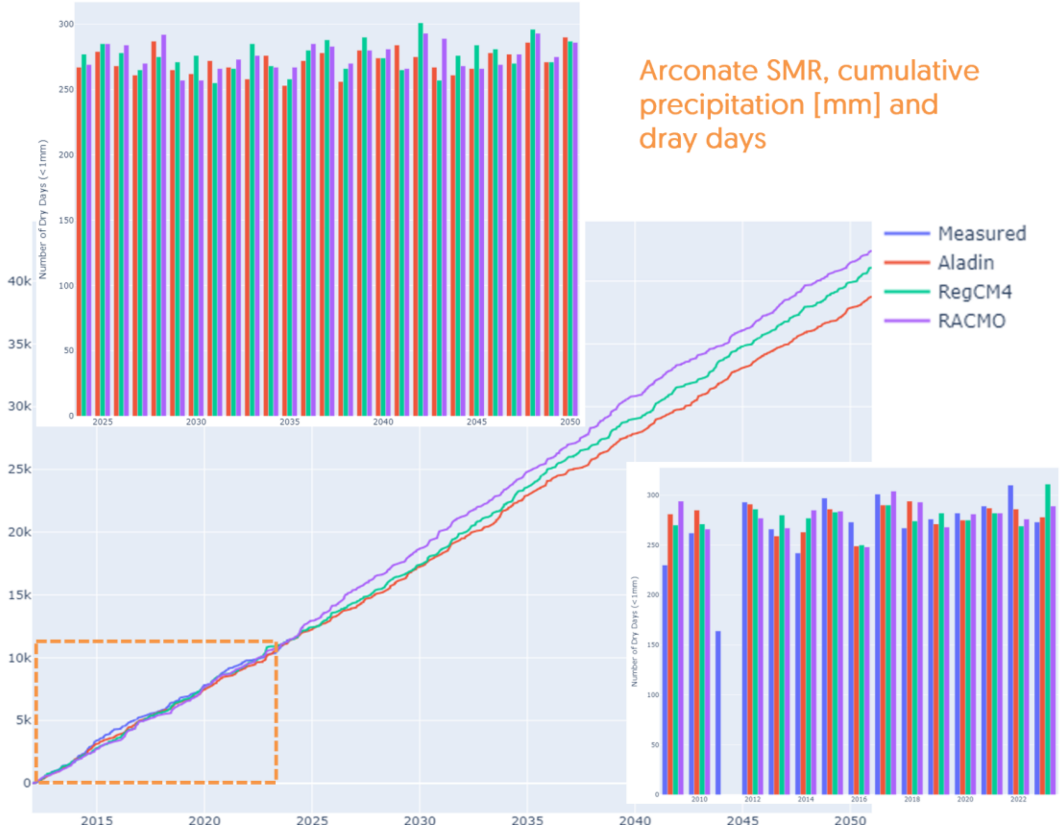


Figure 21. An example of the cumulative daily precipitation in the future horizon (main plot), comparison of number of dry days in the control period (small plot on the bottom-right) and in the future horizon (small plot on the top-left side) corresponding to each of the models used, after the downscaling operation with the LOCI + EQM methods.

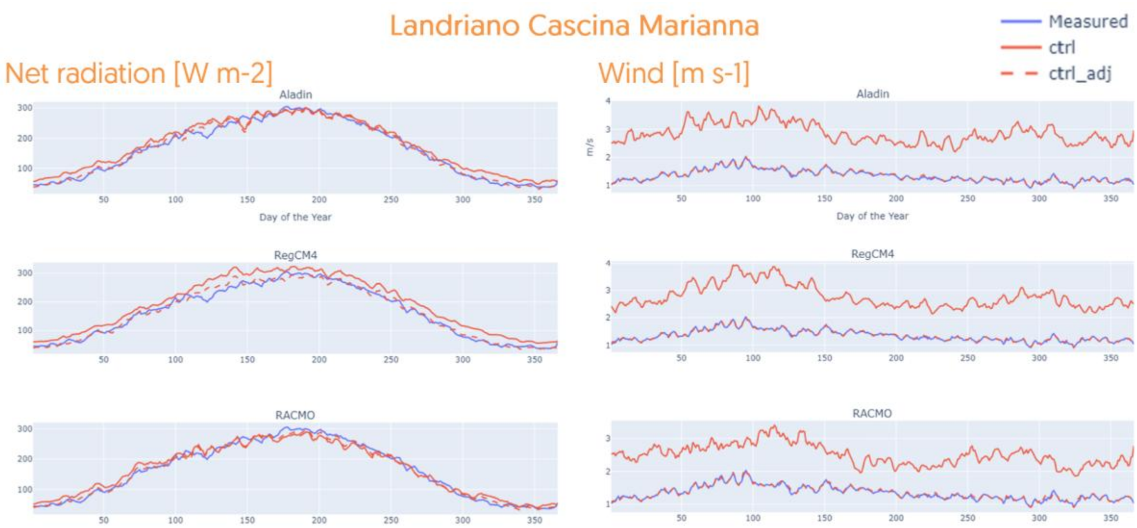


Figure 22. An example of the daily cyclostationary net radiation (on the left) and wind velocity (on the right) corresponding to each of the models used, before and after the downscaling operation.

Lake Maggiore, Ticino river and Villoresi diversion

Lage Maggiore inflow

The first time-series described in the previous chapter were used to feed the rainfall-discharge model, implemented with the LSTM architecture introduced in the methodological part. For example, the daily averages considering ten-year intervals (MASH plot) up to 2050, corresponding to the RegCM4 model, are shown in Figure 23. Daily values used in the plot are obtained as a spatial average of the daily downscaled values considering all upstream stations.

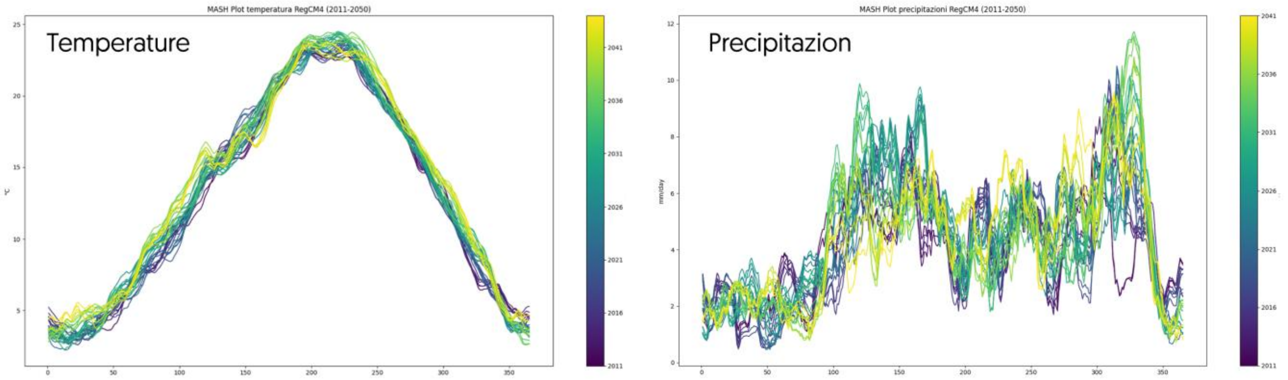


Figure 23. Moving daily cyclostationary averages considering ten-year intervals of the RegCM4 inputs after the downscaling operations: temperature (on the left) and precipitation (on the right).

For greater control of the results, the discharges estimated by this model were compared with those produced by a physically based model with lumped parameters, HBV, appropriately calibrated by coupling it to a state-of-the-art genetic optimization engine.

The comparison shown in **Figure 24** is merciless, by looking at both the cumulative and annual volumes, the underestimation produced by HBV is decidedly high. On the contrary, LSTM provides acceptable values, more than satisfactory considering the objective of the work.

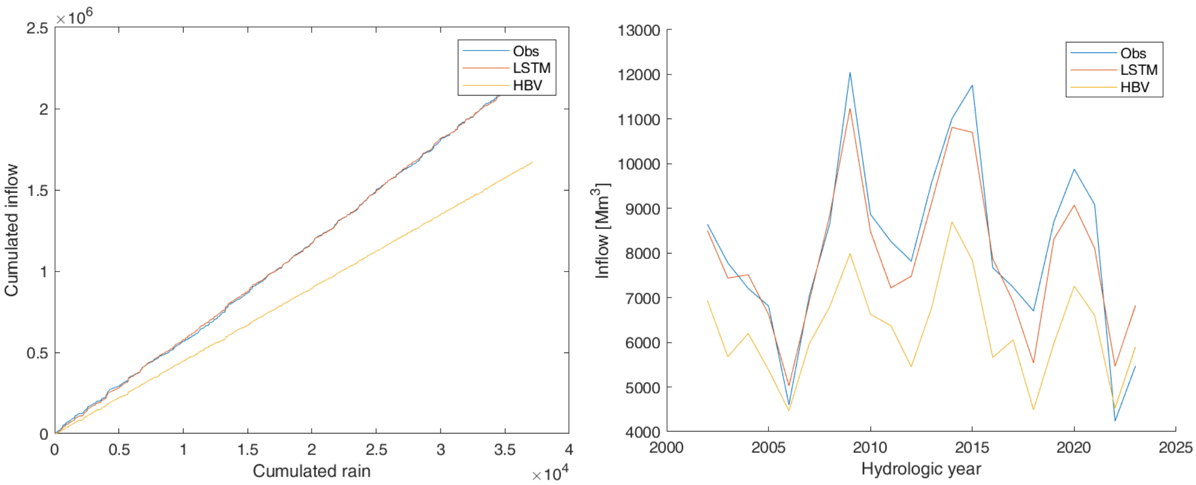


Figure 24. Comparison between observed inflow (obtained by daily water balance), and LSTM and HBV estimations, considering their cumulative values respect the cumulative precipitation (on the left) and the yearly volume (on the right).

Overall, the daily averages obtained considering the same ten-year intervals used to describe the inputs (always corresponding to the RegCM4 model), are shown in **Figure 25**. Moving from the past decades to the most recent ones and those more distant in the future, a significant reduction in high flows is expected, both due to the disappearance of part of the contributions deriving from the melting of the glaciers, and due to a reduction in the intensity of autumn rains. At the same time, a shift between one to two months in local maximums is observed, expecially those usually observed in spring, and those in autumn. A third local maximum also appears to be consolidating, corresponding to the late summer period.

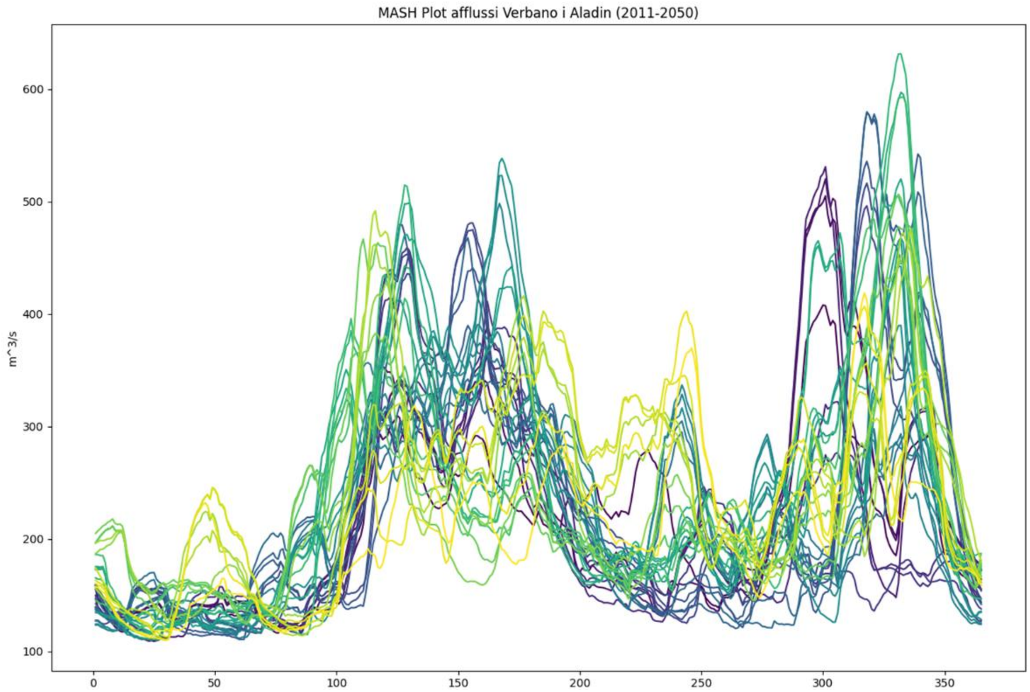


Figure 25. The moving daily cyclostationary average considering ten-year intervals of the LSTM estimated inflow considering Aladin inputs.

Ticino river and Villoresi canal flows

The outputs of the previous model, produced in correspondence with the three models considered, represent the inputs of a two-output model that simulates both the dynamics of Lake Maggiore and the regulation operations of the Miorina dam and the Panperduto dam to obtain the derived flow in Villoresi and the residual flow in Ticino.

The comparison of the monthly averages of the Villoresi flows, obtained in the control period in which the measured data are available, highlights an excellent adaptation of the model (left graph of **Figure 26**), demonstrating the reliability of the projections up to 2050, always represented at monthly frequency, in the right graph.

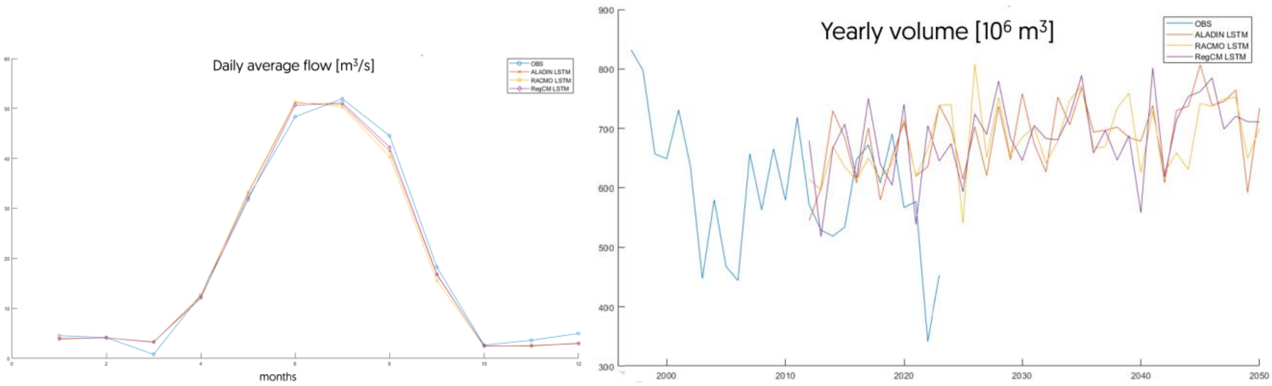


Figure 26. The overall monthly average (on the left) and the yearly volume (on the right) of the LSTM estimated Villoresi flow downstream Panperduto dam corresponding to each of the models used.

Overall, the daily average calculated on the usual ten-year intervals up to 2050, highlights the tendency to flatten the curve, not allowing the same maximum values historically measured to be reached (reduction of 4 to 5 m^3/s), but at the same time managing to support the diversions even in the final part of the irrigation season.

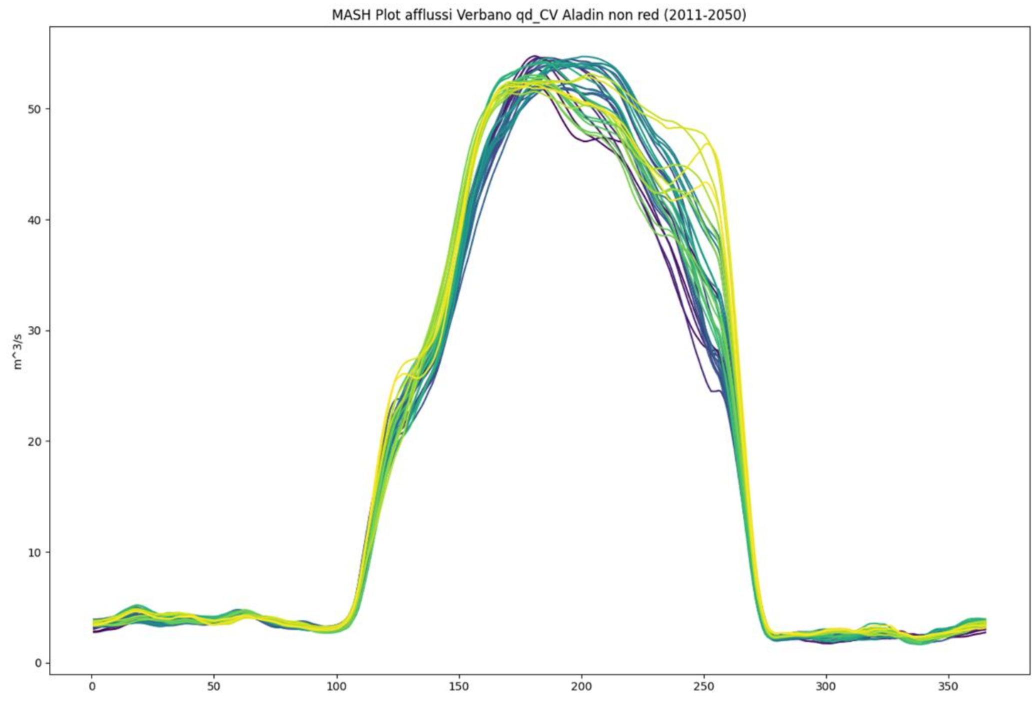


Figure 27. The moving daily cyclostationary average considering ten-year intervals of the LSTM estimated Villoresi flow downstream Panperduto dam considering Aladin inputs.

The residual flows in Ticino are characterized by a much higher variability, and the model systematically underestimates the flood peaks recorded historically, as can be seen from the graph on the left of **Figure 28**. The training has also favored the behavior in correspondence with the low and medium flows, considering the purpose of the project, as can be seen from the scatter reported on the right in the same Figure. The final behavior of the model is shown by the daily average calculated on the usual ten-year intervals up to 2050 reported in the Figure 25. The pattern in this case is less recognizable, from one decade to another there can also be very significant deviations. However, it seems evident that a significant flattening of the flow rates, obviously partly reflecting the trend of the inflows to the lake as described above.

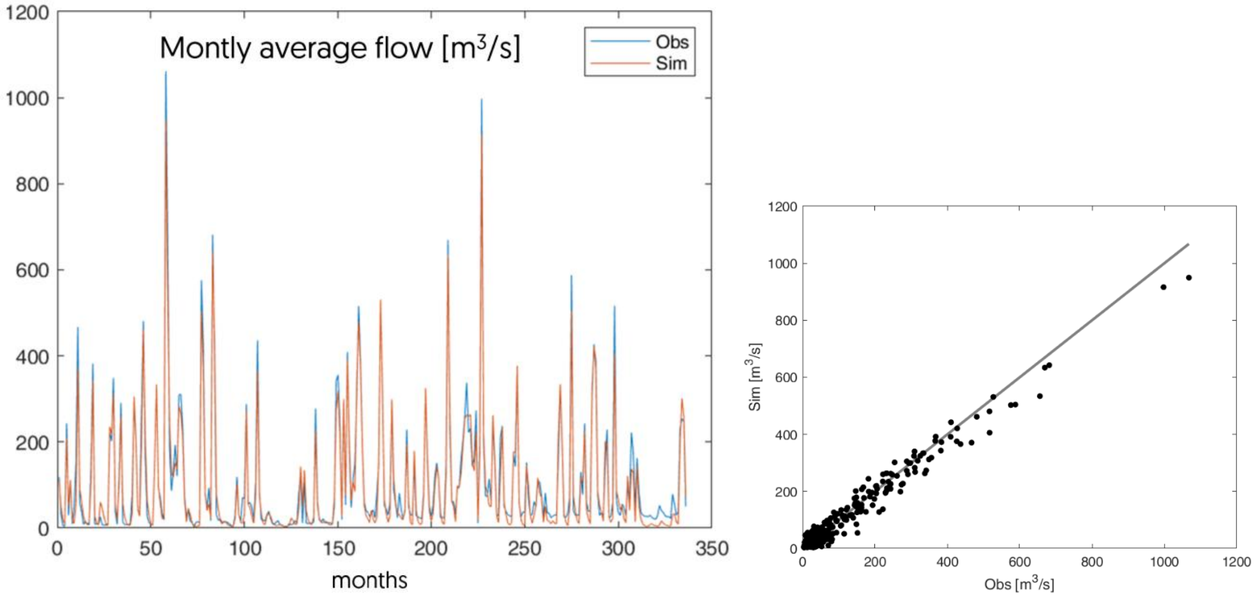


Figure 28. The comparison between monthly average in the time (on the left) and as a scatter (on the right) of the LSTM estimated Ticino flow downstream PanPerduto dam considering the control period.

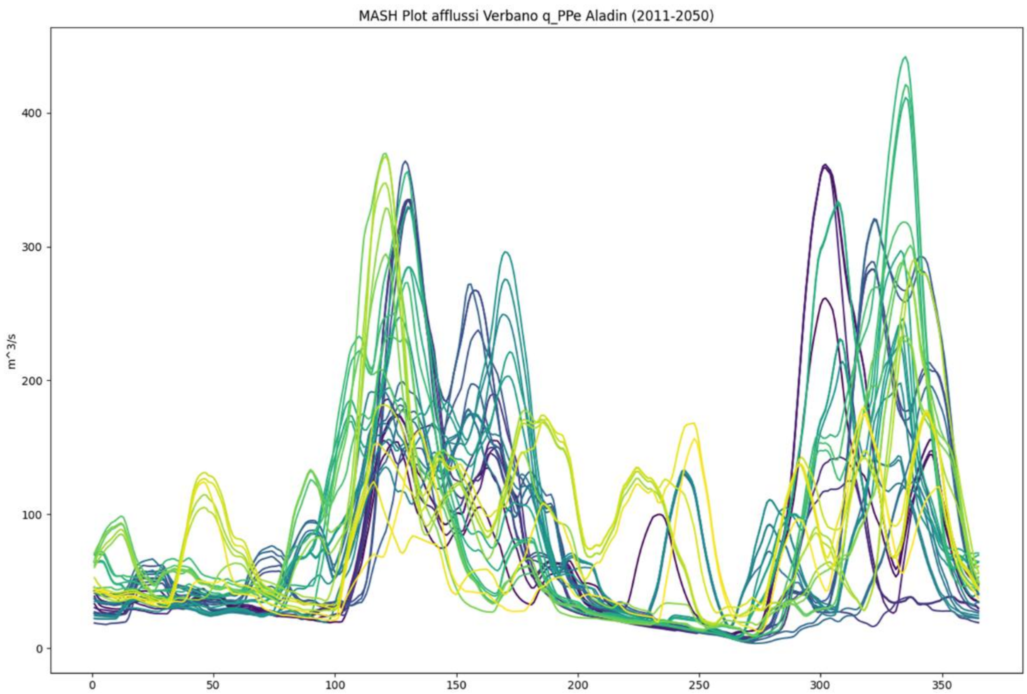


Figure 29. Moving daily cyclostationary average considering ten-year intervals of the LSTM estimated Ticino flow downstream PanPerduto dam considering Aladin inputs.

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