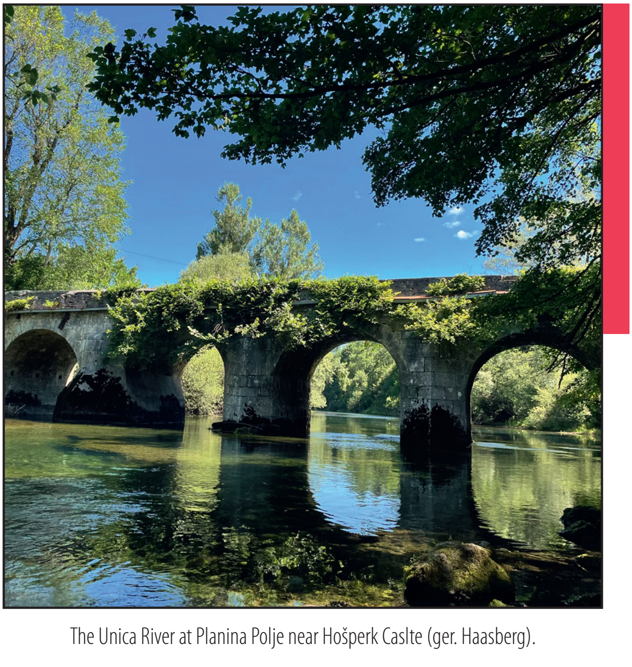
Acta geographica Slovenica, 66-1, 2026, 121–146

# NATIONAL-SCALE WATER BALANCE IN SLOVENIA (1972–2024): LONG-TERM TRENDS AND VARIABILITY IN WATER BALANCE COMPONENTS

Peter Frantar, Frank Herrmann, Mišo Andjelov



FRANK HERRMANN

The Unica River at Planina Polje near Hošperk Caslte (ger. Haasberg).

DOI: https://doi.org/10.3986/AGS.14632
UDC: 556.1(497.4) "1972/2024"

**Peter Frantar[1], Frank Herrmann[2], Mišo Andjelov[3]**

# National-scale water balance in Slovenia (1972–2024): Long-term trends and variability in water balance components

ABSTRACT: Climate change is altering hydrological processes and water availability, requiring robust long-term analyses based on consistent data and models. In the article, the main components of the hydrological water balance – precipitation, evapotranspiration, and runoff – in Slovenia for the period 1972–2024 are analysed. The analysis is based on results from a verified national-scale mGROWA water balance model. The objective of study is to identify trends that could be relevant for water resources management in a changing climate. A key finding is that evapotranspiration has increased significantly in large parts of the country. However, above-average precipitation in recent years has so far compensated for this increase, preventing a country-wide decline in average runoff. Finally, a hydro-climatological trend indicator is proposed as a future element for monitoring the water balance components in Slovenia.

KEYWORDS: hydrology, water balance modelling, mGROWA, climate change, hydro-climatological trend indicator, water resources management, Slovenia

# Vsedržavni vodno bilančni model Slovenije (1972–2024): dolgoročni trendi in spremenljivost komponent vodne bilance

POVZETEK: Podnebne spremembe spreminjajo hidrološke procese in razpoložljivost vode, kar zahteva robustne dolgoročne analize na podlagi konsistentnih podatkov in modelov. V članku so analizirane glavne komponente hidrološke vodne bilance – padavine, evapotranspiracija in odtok – v Sloveniji za obdobje 1972–2024. Analiza temelji na rezultatih verificiranega modela vodne bilance mGROWA za območje Slovenije. Cilj študije je prepoznati trende, ki bi lahko bili pomembni za upravljanje vodnih virov v spreminjajočem se podnebju. Ključna ugotovitev je, da se je evapotranspiracija v velikem delu države znatno povečala, vpliv tega povečanja pa je bil manjši zaradi nadpovprečnih padavin v zadnjih letih, zato se povečanje ni izrazilo v manjšem povprečnem odtoku. Avtorji predlagamo hidro-klimatološki kazalnik trendov kot element spremljanja vodnobilančnih komponent v Sloveniji.

KLJUČNE BESEDE: hidrologija, modeliranje vodne bilance, mGROWA, podnebne spremembe, hidro-klimatološki kazalnik trendov, upravljanje vodnih virov, Slovenija

The article was submitted for publication on August 29th, 2025.
Uredništvo je prejelo prispevek 29. avgusta 2025.

---

[1] Slovenian Environment Agency, Ljubljana, Slovenia; Faculty of Environmental Protection, Velenje, Slovenia
[2] Forschungszentrum Jülich, Agrosphere Institute (IBG-3), Jülich, Germany
[3] Slovenian Environment Agency, Ljubljana, Slovenia

peter.frantar@gov.si, peter.frantar@fvo.si (https://orcid.org/0000-0003-0501-4930), f.herrmann@fz-juelich.de (https://orcid.org/0000-0003-4939-0479), miso.andjelov@gov.si (https://orcid.org/0009-0009-4383-7939)

# 1 Introduction

The global hydrological cycle is undergoing significant changes due to current climate change affecting regional water balance components. Rising temperatures and altered precipitation regimes influence evapotranspiration, snow cover duration, runoff distribution, and groundwater recharge, leading to shifts in water availability and hydrological extremes (e.g., Huntington 2006; Milly et al. 2008; Intergovernmental Panel on Climate Change 2023; Xiong et al. 2023). These climatic developments necessitate continuous regional water balance assessments to support water resources management and water security planning (European Commission 2015; Bevacqua et al. 2024).

Slovenia is located in Europe in the transition zone between the Alps, the Mediterranean, the Dinaric Alps, and the Pannonian Basin (Figure 1, top). In Slovenia previous national-scale water balance studies analysed the mean conditions for the periods 1961–1990 and 1971–2000 (Kolbezen and Pristov 1998; Frantar 2007; Frantar 2008), providing an important basis for the water resources management. More recent assessments have employed grid-based GROWA model to analyse annual water balance components at high spatial resolution (Tetzlaff et al. 2015; Andjelov et al. 2016). The latest development of this modelling is the mGROWA model (Herrmann et al. 2015), which provides the water balance at daily resolution.

This study applies the national-scale mGROWA model to analyse precipitation (P), evapotranspiration (ET) and runoff (Q) in Slovenia for the period 1972–2024. The objectives are to (i) assess long- and mid-term changes in the main water balance components, (ii) identify regions with significant recent changes that may require adaptation in water resources management, and (iii) propose a hydro-climatological trend indicator for continuous monitoring of the national water balance. Results are analysed at national level and at the level of the five major Slovenian hydrological regions (Figure 1).

The study presents a novel national-scale, high-resolution assessment of long-term and seasonal changes in water balance components in Slovenia. It is integrating mGROWA simulations with an enhanced hydro-climatological trend framework that combines LOESS-based continuous trend indicators, raster hydrograph visualisation, and spatially explicit statistical testing of regime shifts and trends.

# 2 Hydrological regions of Slovenia

Slovenia is hydrologically divided into two major river basin districts (RBDs): the Danube RBD and the Adriatic RBD, separated by the main topographic watershed. Approximately 81% of the national territory belongs to the Danube RBD, which includes the Sava, Drava, and Mura river basins, while the remaining 19% drains into the Adriatic Sea, primarily via the Soča River and smaller coastal rivers (Figure 1, subareas 3 and 4).

The Danube RBD is characterised by a strong east–west gradient in climate, topography, and water availability. Mountainous alpine and pre-alpine areas in the west receive higher P, while lower elevations in the east, particularly in the Drava and Mura basins, experience more continental conditions and lower P. This gradient is reflected in runoff formation and regional water availability, with major urban centres such as Ljubljana and Maribor located within the Sava and Drava basins, respectively.

The Adriatic RBD extends from the Alps in the north to the Mediterranean coast. P and Q generally decrease from the mountainous regions towards the south, resulting in a pronounced north–south gradient in water availability.

Large parts of Slovenia are characterised by karst hydrogeology with scarce surface water flows. Major structural depressions in Slovenia are filled with unconsolidated alluvial sediments that form productive aquifers with complex surface–groundwater interactions and highly heterogeneous flow paths of national importance, while smaller hydrogeological units, such as flysch formations, play a key role at the local scale. Detailed descriptions of Slovenian hydrology are provided by Kolbezen and Pristov (1998) and Frantar (2008). These pronounced physiographic and hydrogeological contrasts are reflected in distinct water balance regimes and justify the spatially differentiated analyses applied in the following sections.

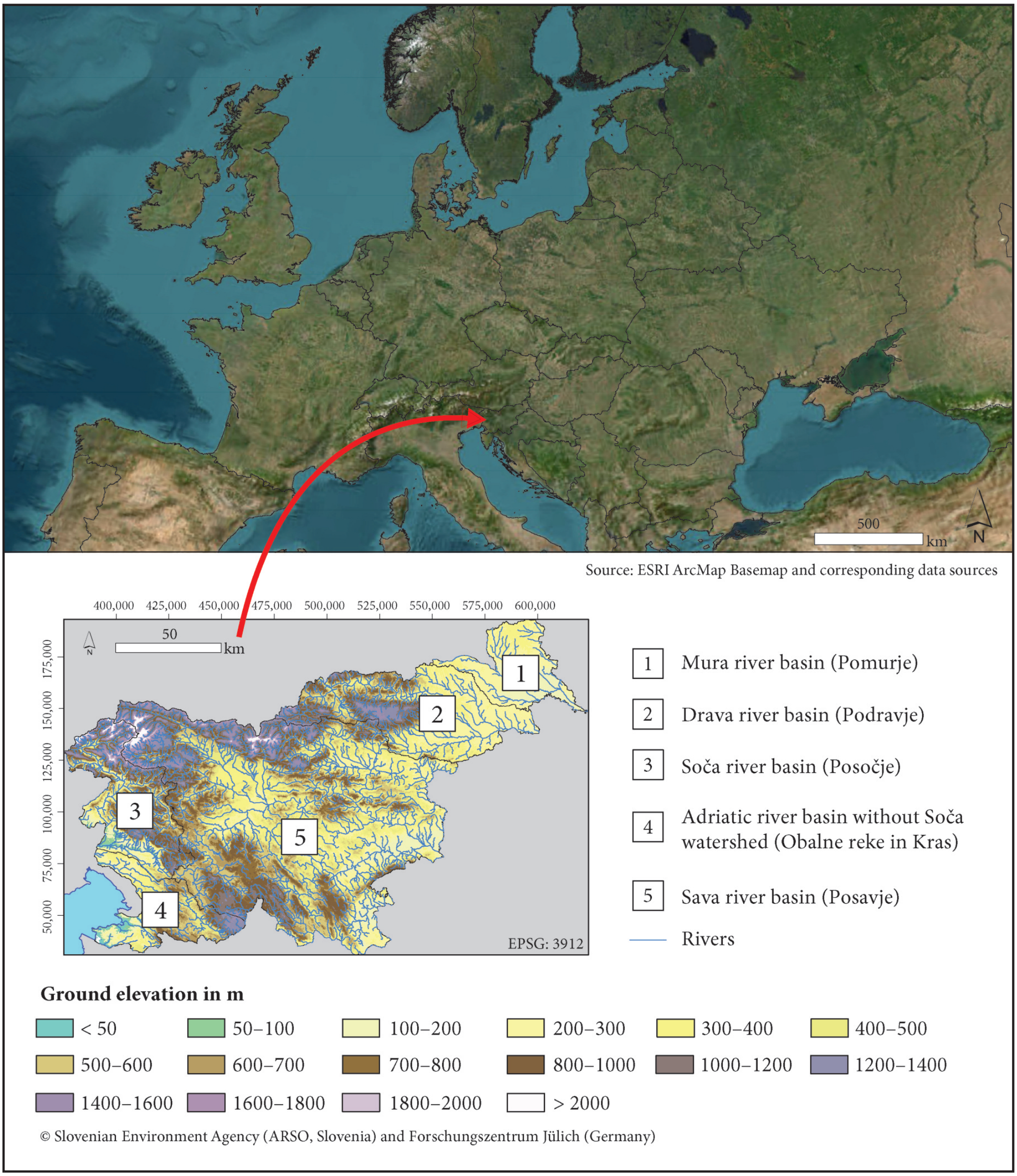


Figure 1: Location of Slovenia in Europe (top) and location of river basins and districts within Slovenia (bottom). In addition, the bottom map shows the nationwide ground elevation and the river network. The geographic coordinate system of the map of Slovenia is MGI 1901 / Slovene National Grid (EPSG: 3912), axis labels show metres.

# 3 Methodology

## 3.1 mGROWA modelling methodology and data basis in Slovenia

In previous national-scale water balance studies in Slovenia, the grid-based GROWA model was applied. This model solves the hydrological water balance equation P = Q + ET ± ΔS for high-resolution spatial grids, where P denotes precipitation, Q runoff, ET evapotranspiration, and ΔS changes in water storage. Earlier applications in the GROWA model focused on annual totals, but subsequent developments improved the representation of soil water storage dynamics and their varying contribution to evapotranspiration.

As a result of these developments, the deterministic, grid-based water balance model mGROWA (Herrmann et al. 2013; Herrmann et al. 2015) has been available for several years. It can be applied to assess the impact of climate variability and change on water resources at the scale of large river systems and entire countries (Herrmann et al. 2017; Herrmann et al. 2021). Figure 2 provides an overview of the main input data, simulated variables, and derived statistics, while detailed equations and algorithms are documented in the cited literature. In the following, the mGROWA model is described from a generic perspective, focusing on elements relevant for interpreting the results presented in this study.

Climatic input to the model includes air temperature, P, and reference evapotranspiration (ETo). These variables are typically provided by national meteorological services or derived from regional weather forecast and climate models. Adapted methods can be used to interpolate or downscale these variables and country-specific ETo methods can be used. The mGROWA model operates on daily time step; accordingly, meteorological inputs are prepared at daily resolution. Daily variability in P and ETo is derived from station-based observations, and these temporal patterns are internally transferred from spatially interpolated monthly grid data.

Geospatial input data (left column of Figure 2) describe land use, topography, soil properties, and surface imperviousness. They are used to parameterise the land surface and the rooting zone of vegetation and are essential for calculating soil water content and ET as a function of vegetation type, soil water storage capacity, slope, sealings and exposition. Additional geodata are used to characterise subsurface conditions relevant for Q generation. In particular, the depth to the groundwater table provides an important boundary condition and can serve as an interface to numerical groundwater models.

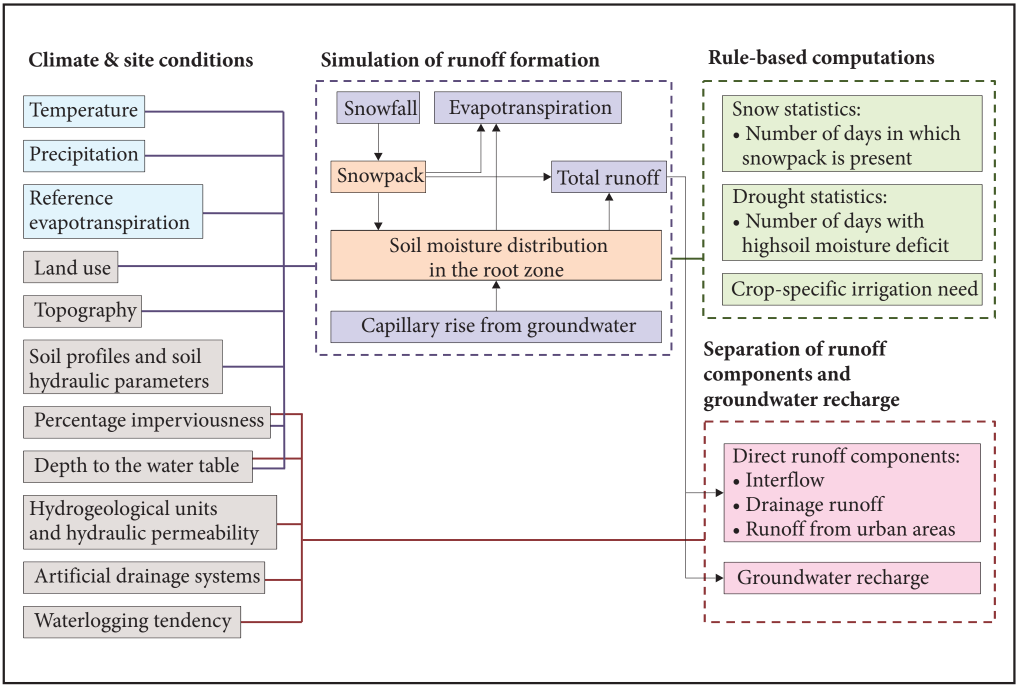


Figure 2: mGROWA modelling diagram. Cyan indicates the climatic input data, light brown indicates the geodata on site conditions, violet indicates the simulated hydrological variables, orange indicates the water storages considered, red-brown indicates simulated runoff components and groundwater recharge, light green indicates rule-based computations and statistics, lines indicate dependencies.

Runoff formation (central column in Figure 2) in mGROWA is simulated using physically based representations of snow processes, soil water dynamics, ET, and percolation. Snow accumulation and melt are primarily temperature-controlled and are simulated using methods originally implemented in the WaSiM-ETH model (Schulla 1997), including a temperature-index approach for snow melting, also considering the temperature – elevation dependency. Soil moisture dynamics are calculated using the multi-layer soil water balance model BOWAB (Engel et al. 2012), with the daily change in soil moisture representing the storage term of the water balance equation. Actual evapotranspiration is computed as a function of soil moisture using the Disse-function (Disse 1995) in combination with evapotranspiration coefficients analogous to the FAO crop coefficient concept (Allen et al. 1998). Capillary rise from groundwater into the root zone depends on groundwater depth and may occur under conditions of soil moisture deficit (conversion is performed by functional relationship of van Genuchten's equation (van Genuchten 1980) in combination with tabulated capillary rise rates). When soil water storage exceeds field capacity, excess water contributes to total runoff.

Total runoff simulated at daily time steps is aggregated to monthly values and subsequently separated into groundwater recharge and direct runoff components (right column bottom in Figure 2). Groundwater recharge is calculated in monthly time steps using the base flow index approach, which has been previously evaluated for Slovenia (Tetzlaff et al. 2015), while direct runoff components are obtained as residual terms. By simulating snow and soil water dynamics, the model can also provide spatiotemporal statistics such as snow cover duration or soil moisture deficit (right column top in Figure 2), which may be used as indicators of agricultural drought. The irrigation water requirements for specific crops can also be derived from this model (McNamara et al. 2024). These outputs are not analysed further in this study.

The data basis used for the mGROWA application in Slovenia is listed in Table 1. All datasets were transferred to a 100 m model grid using standard geographic information system methods, resulting in 2,027,330 active grid cells, each representing one hectare of the national territory. Monthly P and ETo fields

Table 1: Data basis used for the mGROWA water balance modelling in Slovenia.

| Theme | Database / format / resolution | Source |
|---|---|---|
| **Observed climate** | Station-based, daily time steps (1972–2024):<br>• Precipitation (P)<br>• Reference evapotranspiration (ETo)<br>• 2 m air temperature<br><br>Grid-based 100 m, monthly time steps (1972–2024):<br>• Precipitation (P)<br>• Reference evapotranspiration (ETo) | Slovenian Environment Agency (ARSO) |
| **Land use** | • CORINE land cover layer (2006), grid-based 100 m<br>• Imperviousness layer (2012), grid-based 20 m | European Environment Agency (EEA) |
| **Soil** | • Slovenian soil map (polygons) and over 10,000 soil profiles<br>• European Soil Database derived data layers for gap filling | • Biotechnical Faculty, University of Ljubljana<br>• Hiederer (2013) |
| **Topography** | Grid-based 100 m, Digital elevation model (DMV 100) | Surveying and Mapping Authority of the Republic of Slovenia (GURS) |
| **Geology** | • Geological map 1:100,000<br>• Hydrogeological map 1:500,000 | Geological Survey of Slovenia (GeoZS) |
| **Groundwater** | Depth to groundwater table 1:25,000, grid-based | Slovenian Environment Agency (ARSO) |
| **Artificial drainage** | Artificially drained farmland 1:25,000, grid-based | • Slovenian Ministry of Agriculture, Forestry and Food (MKGP)<br>• Tetzlaff et al. (2009) |
| **Hydrology** | • Catchment boundaries 1:25,000, polygons<br>• Daily discharge (1981–2020), gauge-based | Slovenian Environment Agency (ARSO) |
| **Base maps** | River network, political boundaries, towns, digital elevation model | Surveying and Mapping Authority of the Republic of Slovenia (GURS) |

were reconstructed at the Slovenian Environment Agency (ARSO) using ordinary kriging based on relative anomalies, which exhibit lower spatial variability than absolute values and are therefore better suited for interpolation. This geostatistical approach, originally proposed by Matheron (1963), has been established as standard practice for climatological data mapping at ARSO (Dolinar 2009).

## 3.2 Methods for assessing changes and trends

From a water resources management and planning perspective, long-term changes in the mean values of the water balance components P, ET, and Q are of primary importance. Therefore, the assessment begins with an analysis of interdecadal variability between the decades from 1972 to 2020 relative to the current World Meteorological Organization (WMO) reference period 1991–2020.

In addition to interdecadal changes, inter-annual and seasonal changes and shifts have gained increasing attention in regional water resources assessments (e.g., Ertl et al. 2018; Ertl et al. 2022). For the high-resolution mGROWA simulations, a standard visualisation was therefore used that combines area-specific time series of monthly and annual totals with a long-term trend line. In this study, this visualisation was extended by a hydro-climatological trend indicator enabling continuous monitoring of recent trends. Figure 6 shows this standard visualisation for P, ET, and Q for Slovenia. The upper panels display annual totals and a LOESS-42 trend line (Scherrer et al. 2024), representing a smooth nonlinear climate trend calculated using local linear regression (1st-order LOESS with a 42-year window; grey shading denotes 95% confidence limits). The main advantage of this filter is that extreme values are strongly smoothed while still influencing the trend direction. The 42-year window proved suitable for approximating a 30-year moving average. Unlike moving averages, LOESS-42 also provides unbiased values at the beginning and end of a time series, which is particularly important for monitoring. The difference between the latest LOESS-42 value and the 30-year average is used as a deficit or surplus indicator, describing whether recent trends deviate positively or negatively from the long-term reference.

As a second component of the visualisation, monthly totals are displayed as a raster hydrograph (following Strandhagen et al. 2006), allowing seasonal variability to be interpreted together with longer-term trends (Ehlers et al. 2016). Seasonal patterns and their shifts can thus be quickly compared and evaluated.

Visual interpretation of time series raises the question of whether statistically significant changes or trends have occurred in recent decades. This was addressed using statistical tests. Mauget (2003) applied the non-parametric Mann–Whitney–Wilcoxon test (MWW; Wilcoxon 1945; Mann and Whitney 1947) to detect multi-decadal regime shifts in water balance components, and this approach is recommended for evaluating changing climate signals (Pfeifer et al. 2015). The test examines two segments of annual time series for significant differences in mean values and distributions. In addition, the Mann–Kendall trend test (MK; Kendall 1938; Mann 1945) was used to detect monotonic trends (Helsel and Hirsch 1992).

Both tests were implemented in a grid-based manner, yielding spatial patterns of the probability of the alternative hypothesis, i.e., evidence of significant change or trend. For the MWW test, two time-span pairs were analysed: 1999–2024 versus 1973–1998 (26 years each, covering nearly the entire simulation period) and 2001–2020 versus 1981–2000 (20 years each), representing conditions before and after the year 2000, which often marks a more significant shift in climatological time series. For the MK test, the tail of the simulation from 1995–2024 was evaluated to assess the direction and significance of recent monotonic trends.

## 3.3 Methods for the evaluation of the runoff simulation

Before results of the mGROWA simulation are used for long-term water resources management, the quality of the calculated runoff balance must be evaluated. This evaluation is generally performed in suitable catchments based on measured discharge data. The long-term mean observed runoff for a 30-year hydrological period is calculated from stream-gauge hydrographs by averaging daily mean discharges. The simulated counterpart is obtained by zonal analysis of the total runoff grids produced by mGROWA for the areas contributing to each gauge.

Identifying suitable river catchments is a key step in this evaluation. Several criteria must be fulfilled: (i) long-term, gap-free discharge measurements must be available; (ii) catchment boundaries must be delineated with sufficient certainty, which is often challenging in karst areas; (iii) human influence on runoff regimes and water use should be low; and (iv) gauges should be relatively evenly distributed across the country. Additional technical factors may also affect discharge measurements, but these are not discussed further here.

Agreement between observations and simulations for the selected catchments is assessed using objective performance measures. For the country-wide evaluation of long-term mean values, the area-weighted variants of the Nash–Sutcliffe efficiency (NSE; Nash and Sutcliffe 1970) and PBIAS (percent bias; Gupta et al. 1999) have proven useful (Herrmann et al. 2015). NSE describes how well observed and simulated values fit the 1:1 line, with a maximum value of 1.0. Values between 0.75 and 1.00 indicate very good performance, and values between 0.65 and 0.75 indicate good performance (Moriasi et al. 2007). PBIAS quantifies the overall tendency of a model to over- or underestimate observations. The optimal value is 0.0, with low-magnitude values indicating high simulation quality. Positive values indicate underestimation and negative values indicate overestimation. According to Moriasi et al. (2007), values within ±10% are considered very good, ±10% to ±15% good, and ±15% to ±25% satisfactory.

# 4 Results

## 4.1 Long-term water balance and interdecadal deviations

The water balance components P, ET, and Q are listed in Table 2 for the reference period 1991–2020, their deviations in the five decades from 1972 to 2020, and the five hydrological regions. During 1991–2020, Slovenia received an average annual P of 1455 mm/a. The dependence of P on topography and along a west–east gradient is visible in Figure 3A. The highest mean values, exceeding 3200 mm/a, occur in the Julian Alps (Soča River basin), while the lowest P, below 900 mm/a, is found in the northeastern plains of the Mura River basin. Almost nationwide, P was above the reference value (+33 mm/a) in 1972–1980, particularly in the northwest and southwest. In the following decades, 1981–1990 and 1991–2000, declines of −24 mm/a and −17 mm/a occurred, respectively. The decade 2001–2010 was also slightly below the reference level (−10 mm/a). In contrast, 2011–2020 was characterised by an average anomaly of +27 mm/a. During this period, the Drava River basin represented the driest region (Figure 3). Deviations in the hydrological regions vary in magnitude between decades, but the large-scale spatial gradients of P remain evident.

For 1991–2020, the average annual ET, simulated with mGROWA was approximately 710 mm/a (Table 2, Figure 4). ET exhibits pronounced spatial variability related to vegetation cover, soil physical properties, and topography (slope and exposition). Highest values (>850 mm/a) occur in lowland areas with dense vegetation and favourable climatic and soil-moisture conditions, especially in southwestern and central Slovenia. Lowest values (<500 mm/a) are found in alpine regions, where low temperatures, short growing seasons, and vegetation-free areas constrain ET. Because summer P regularly replenishes soil moisture across Slovenia, spatial P patterns are not directly reflected in ET patterns. The influence of rising temperatures is already visible in the persistent increase of ET anomalies over the five decades. In 2011–2020, a nationwide anomaly of +21 mm/a was reached relative to the reference period, indicating the need for the more detailed trend analyses presented in the following chapter.

Spatial and temporal patterns of runoff result from the combined effects of P and ET and are simulated accordingly in mGROWA. During 1991–2020, the average annual Q in Slovenia amounted to 741 mm/a (Table 2). The highest Q values (>2000 mm/a) occur in parts of the Julian Alps, whereas the lowest values (<100 mm/a) are found in the northeastern lowlands of the Mura River basin (Figure 5A). Q patterns are primarily controlled by P, consistent with previous studies (Kolbezen and Pristov 1998; Frantar 2008). Owing to above-average P, the first decade shows the highest Q almost nationwide. In the subsequent decades, interpretation becomes more complex. With increasing ET (Figure 4), deviations of Q (Figure 5) diverge more strongly from those of P (Figure 3). Thus, as climate change progresses, runoff correlates less directly with P. The strength of this decoupling varies regionally, reflecting the combined effects of changing P patterns and Slovenia's geodiversity, ranging from the Alps to the Dinaric karst, Mediterranean, and Pannonian regions. Consequently, country-level generalisations are more uncertain than basin-scale interpretations, which highlights the importance of regional trend analyses presented in the following section.

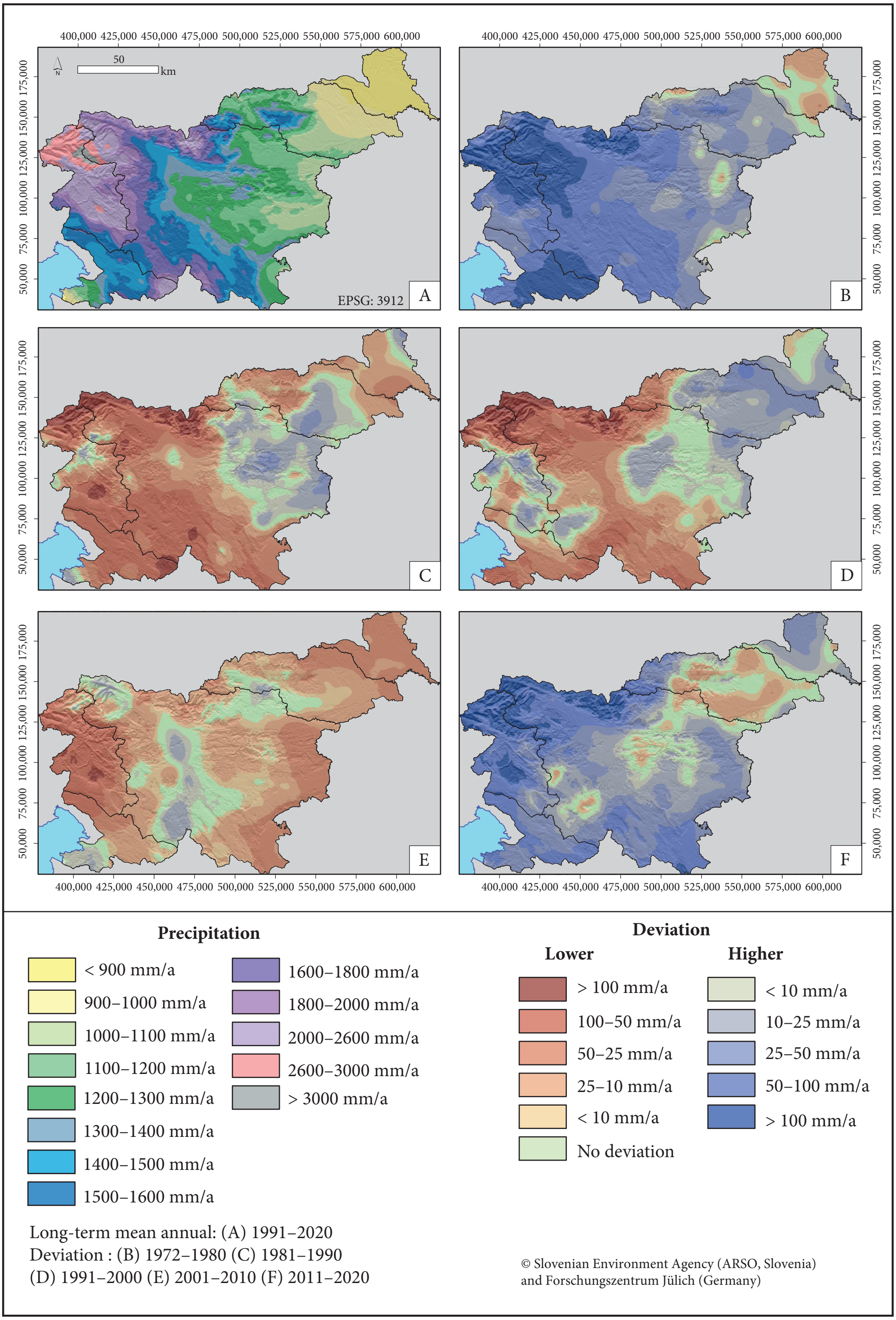
Table 2: mGROWA model results for the major water balance components precipitation (P), evapotranspiration (ET) and runoff (Q) in Slovenia and in the five major hydrological regions in the period 1991–2020 and corresponding interdecadal deviations. The interdecadal deviations have been calculated as decadal average minus long-term average. All values are in mm/a.

| Region | | Long-term average 1991–2020 | Deviation 1972–1980 | Deviation 1981–1990 | Deviation 1991–2000 | Deviation 2001–2010 | Deviation 2011–2020 |
|---|---|---|---|---|---|---|---|
| Slovenia | P | 1455 | +33 | −24 | −17 | −10 | +27 |
| | ET | 712 | −38 | −21 | −14 | −7 | +21 |
| | Q | 741 | +71 | −2 | +2 | −10 | +8 |
| (1) Mura river basin (Pomurje) | P | 827 | −19 | −7 | +10 | −21 | +10 |
| | ET | 693 | −42 | −18 | −18 | −2 | +20 |
| | Q | 132 | +21 | +14 | +30 | −25 | −5 |
| (2) Drava river basin (Podravje) | P | 1130 | +1 | +3 | +10 | −5 | −5 |
| | ET | 688 | −50 | −24 | −17 | −5 | +21 |
| | Q | 441 | +49 | +31 | +31 | −8 | −23 |
| (3) Soča river basin (Posočje) | P | 2222 | +58 | −47 | −17 | −53 | +70 |
| | ET | 751 | −45 | −30 | −14 | −2 | +16 |
| | Q | 1468 | +104 | −17 | +2 | −53 | +51 |
| (4) Adriatic river basin without Soča watershed (Obalne reke in Kras) | P | 1491 | +71 | −57 | −28 | −12 | +40 |
| | ET | 730 | −19 | −5 | −7 | −12 | +20 |
| | Q | 759 | +90 | −55 | −16 | −6 | +22 |
| (5) Sava river basin (Posavje) | P | 1463 | +39 | −24 | −26 | −2 | +27 |
| | ET | 711 | −36 | −20 | −13 | −9 | +22 |
| | Q | 750 | +74 | −3 | −7 | −1 | +7 |

Figure 3: Observed long-term precipitation (P) patterns and interdecadal deviations in Slovenia from 1972 to 2020. The geographic coordinate system of the map of Slovenia is *MGI 1901 / Slovene National Grid (EPSG: 3912)*, axis labels show metres. ➤ p. 130

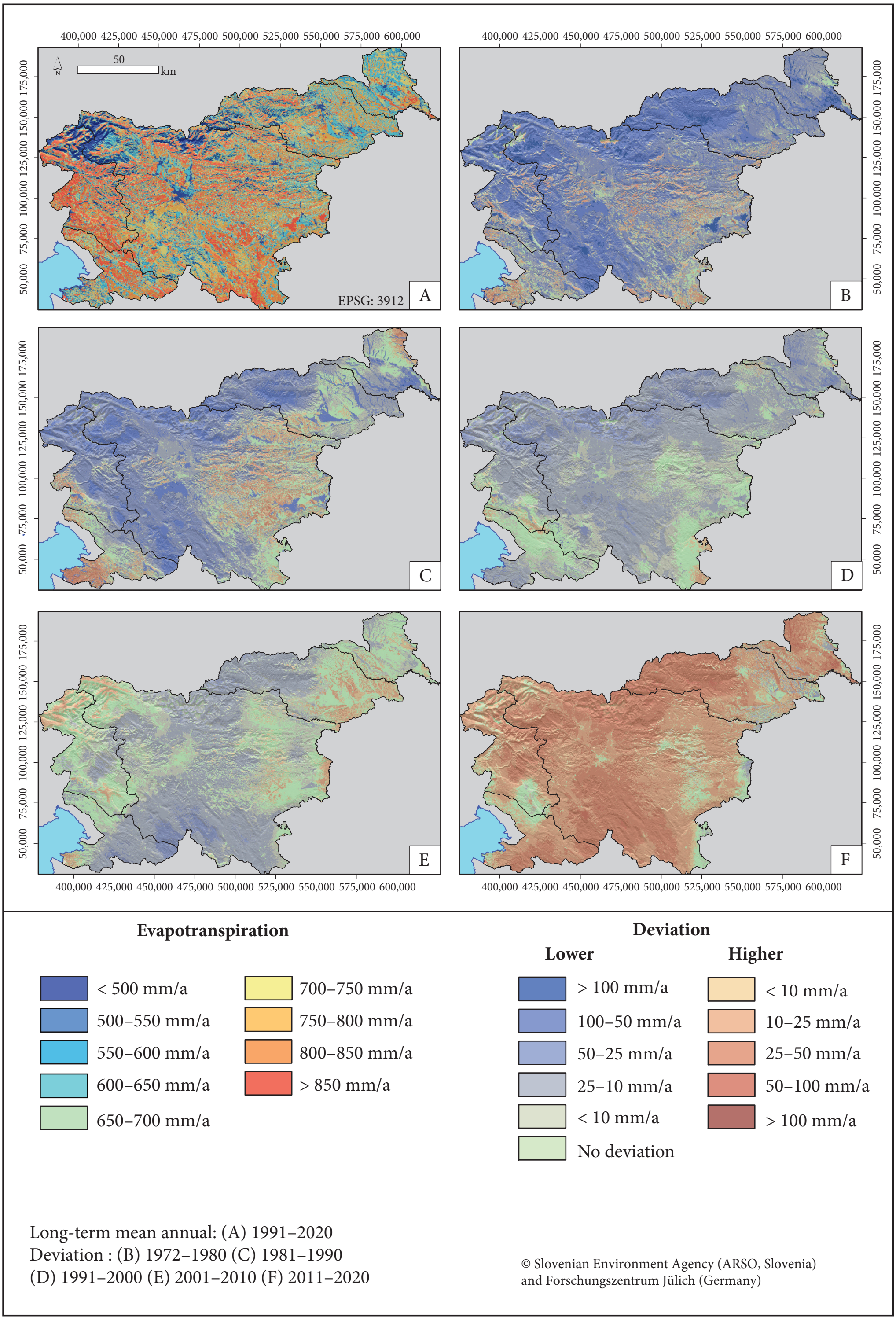
Figure 4: Modelled long-term evapotranspiration (ET) patterns and interdecadal deviations in Slovenia from 1972 to 2020. The geographic coordinate system of the map of Slovenia is *MGI 1901 / Slovene National Grid (EPSG: 3912)*, axis labels show metres. ➤ p. 131

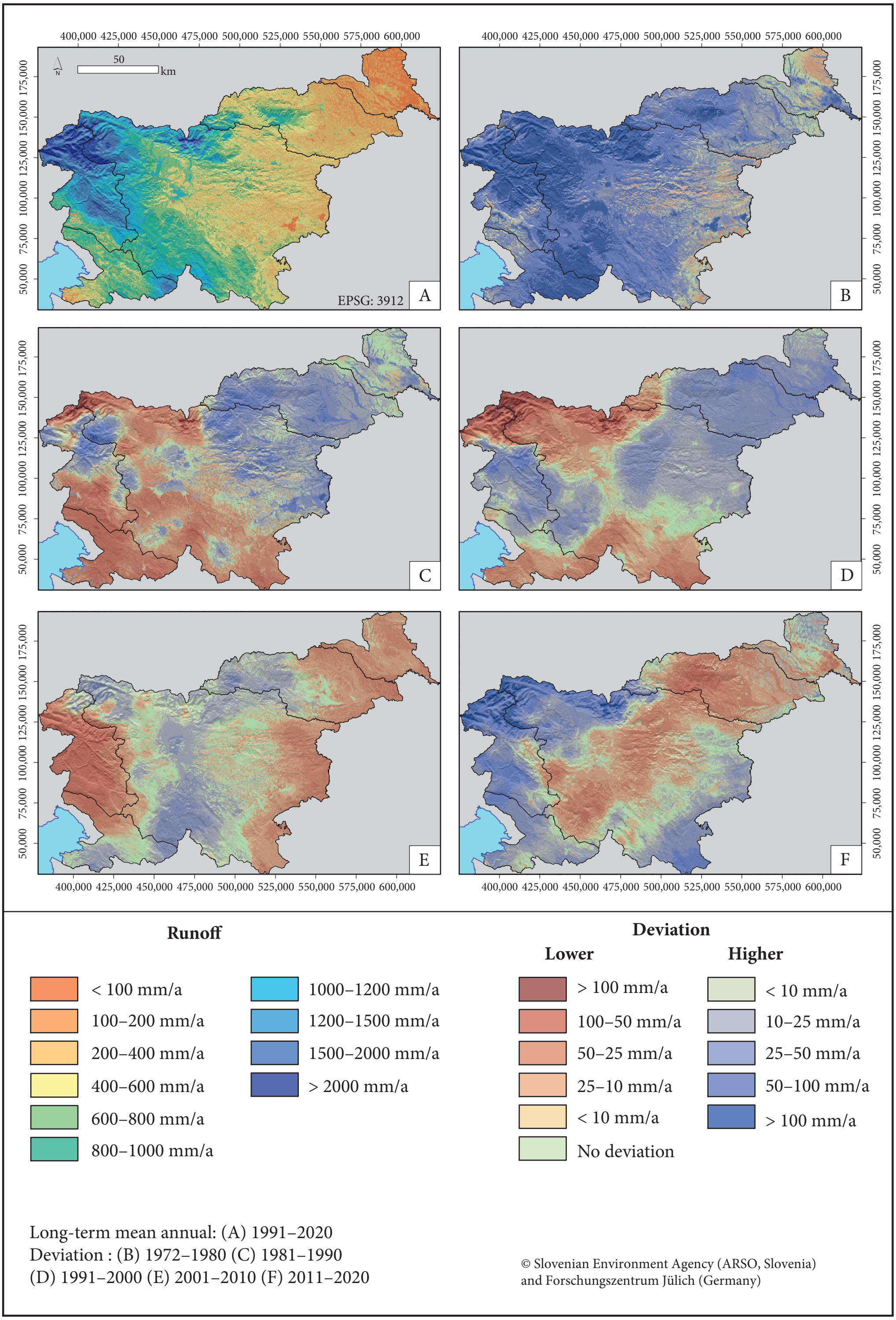
Figure 5: Modelled long-term runoff (Q) patterns and interdecadal deviations in Slovenia from 1972 to 2020. The geographic coordinate system of the map of Slovenia is *MGI 1901 / Slovene National Grid (EPSG: 3912)*, axis labels show metres. ➤ p. 132



Long-term mean annual: (A) 1991–2020
Deviation : (B) 1972–1980 (C) 1981–1990
(D) 1991–2000 (E) 2001–2010 (F) 2011–2020

© Slovenian Environment Agency (ARSO, Slovenia)
and Forschungszentrum Jülich (Germany)


400,000 425,000 450,000 475,000 500,000 525,000 550,000 575,000 600,000
50,000 75,000 100,000 125,000 150,000 175,000
N
50
km
EPSG: 3912
A
B
C
D
E
F
Evapotranspiration
< 500 mm/a
500–550 mm/a
550–600 mm/a
600–650 mm/a
650–700 mm/a
700–750 mm/a
750–800 mm/a
800–850 mm/a
> 850 mm/a
Deviation
Lower
> 100 mm/a
100–50 mm/a
50–25 mm/a
25–10 mm/a
< 10 mm/a
No deviation
Higher
< 10 mm/a
10–25 mm/a
25–50 mm/a
50–100 mm/a
> 100 mm/a
Long-term mean annual: (A) 1991–2020
Deviation : (B) 1972–1980 (C) 1981–1990
(D) 1991–2000 (E) 2001–2010 (F) 2011–2020
© Slovenian Environment Agency (ARSO, Slovenia)
and Forschungszentrum Jülich (Germany)



Long-term mean annual: (A) 1991–2020
Deviation : (B) 1972–1980 (C) 1981–1990
(D) 1991–2000 (E) 2001–2010 (F) 2011–2020

© Slovenian Environment Agency (ARSO, Slovenia)
and Forschungszentrum Jülich (Germany)

## 4.2 Temporal variability and trends in Slovenia's water balance

In Slovenia, months with unusually high P occur most frequently in September, October, and November (Figure 6), whereas months with below-average P are more common in winter. Annual P currently exhibits an upward trend (+87 mm). However, comparison of individual years with the trend line indicates that a small number of dry years could substantially weaken or even offset this trend. Monthly ET displays a pronounced seasonal cycle, with high values during summer when sufficient soil moisture is available and low values during winter. In response to global warming, annual ET totals show a relatively continuous upward trend that has intensified since year 2000 (+42 mm). The temporal behaviour of Q again reflects the superposition of P and ET. High winter P is transformed into high Q, in some cases delayed by temporary storage as snow, whereas low Q typically occurs during summer when ET is high. The current increase in annual P is largely compensated by rising ET, resulting in only a small net increase in Q (+42 mm).

Figures 7 to 11 show that general temporal patterns are similar across the five Slovenian hydrological regions, while trend magnitudes differ substantially. For example, Q in the alpine Soča River basin (area 3 in Figure 1) exhibits a clear increasing trend (Figure 9), whereas in strongly karstified areas near the Mediterranean coast (area 4 in Figure 1) virtually no substantial trend is detected (Figure 10). A more precise evaluation of the significance of identified changes and trends is provided by the two statistical tests.

Grid-based results of the MWW and MK tests (Figures 12 and 13) indicate that statistically significant changes and trends in water balance components occur with varying frequency across Slovenia's river basins and districts. The maps display probabilities of the alternative hypothesis for the MWW test (Figures 12A–12F) and for monotonic trends in the MK test (Figures 13B, 13D, 13F). High probabilities indicate changes or trends; probabilities above 0.85 denote high significance ($\alpha = 0.15$, commonly applied in geosciences). For the MK test, Kendall's Tau (Figures 13A, 13C, 13E) indicates trend direction, with positive values representing increases and negative values decreases.

Significant changes and trends in P are currently evident only in limited areas, mainly at higher altitudes in the Alps and Dinaric Alps. In contrast, significant changes and trends in ET are more widespread, although no high significance is reached in the southwest, the Adriatic region, and the southeast. Spatial patterns of ET further indicate that the influence of vegetation, groundwater depth, and topography varies regionally (e.g., Sava River basin in Figure 12D). Because variability in P and ET is superimposed in a complex manner at larger catchment scales, no significant change in the overall Q regime is detected at that level. However, at smaller spatial scales within river systems, significant local changes occur. Overall, ET has changed significantly across approximately half of Slovenia in recent decades. At the river-basin and district aggregation level shown in Figure 1, only changes in spatiotemporal ET patterns in the Drava and Sava basins reach significance at the $\alpha = 0.15$ level.

The simulation results (grid data) shown in Figures 3 to 11 can be downloaded for free (see Frantar and Herrmann 2026).

# 5 Evaluation of the runoff simulation

For Slovenia, the 76 catchments were identified as suitable for evaluating the simulated Q (Figure 14). The evaluation was conducted for two 30-year periods, 1981–2010 and 1991–2020. For almost all gauges, good to very good agreement between observed and simulated values is evident, as most points are located close to the 1:1 line or at least within a maximum deviation of 30%. Individual deviations are difficult to explain in detail. Overall, they reflect a combination of uncertainties related to the evaluation methodology and the inherent uncertainties of the mGROWA model setup.

For the period 1981–2010, the NSE and PBIAS values are 0.86 and +10.5%, respectively, indicating very good overall model performance, but also a slight underestimation of Q. In the period 1991–2020, the NSE and PBIAS values are 0.74 and +15.4%, respectively, which can still be considered a good overall model performance. The underestimation is somewhat more pronounced in this period.

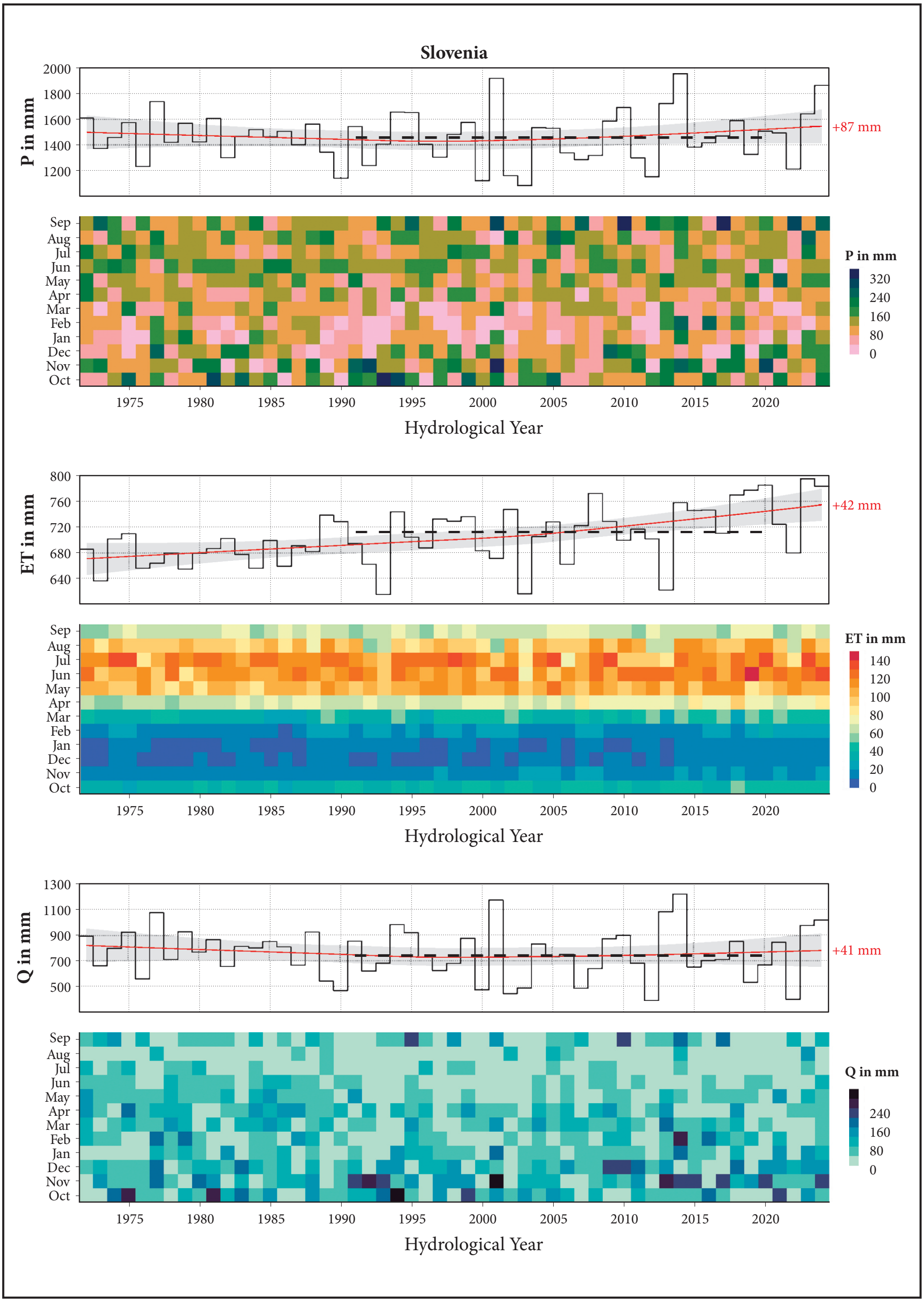


Figure 6: Time series of annual and monthly precipitation (P, top), evapotranspiration (ET, middle) and runoff (Q, bottom) in Slovenia from 1972 to 2024. LOESS-42 trend lines in red, 30-year average 1991–2020 dashed in black, 95%-confidence limits as grey band.

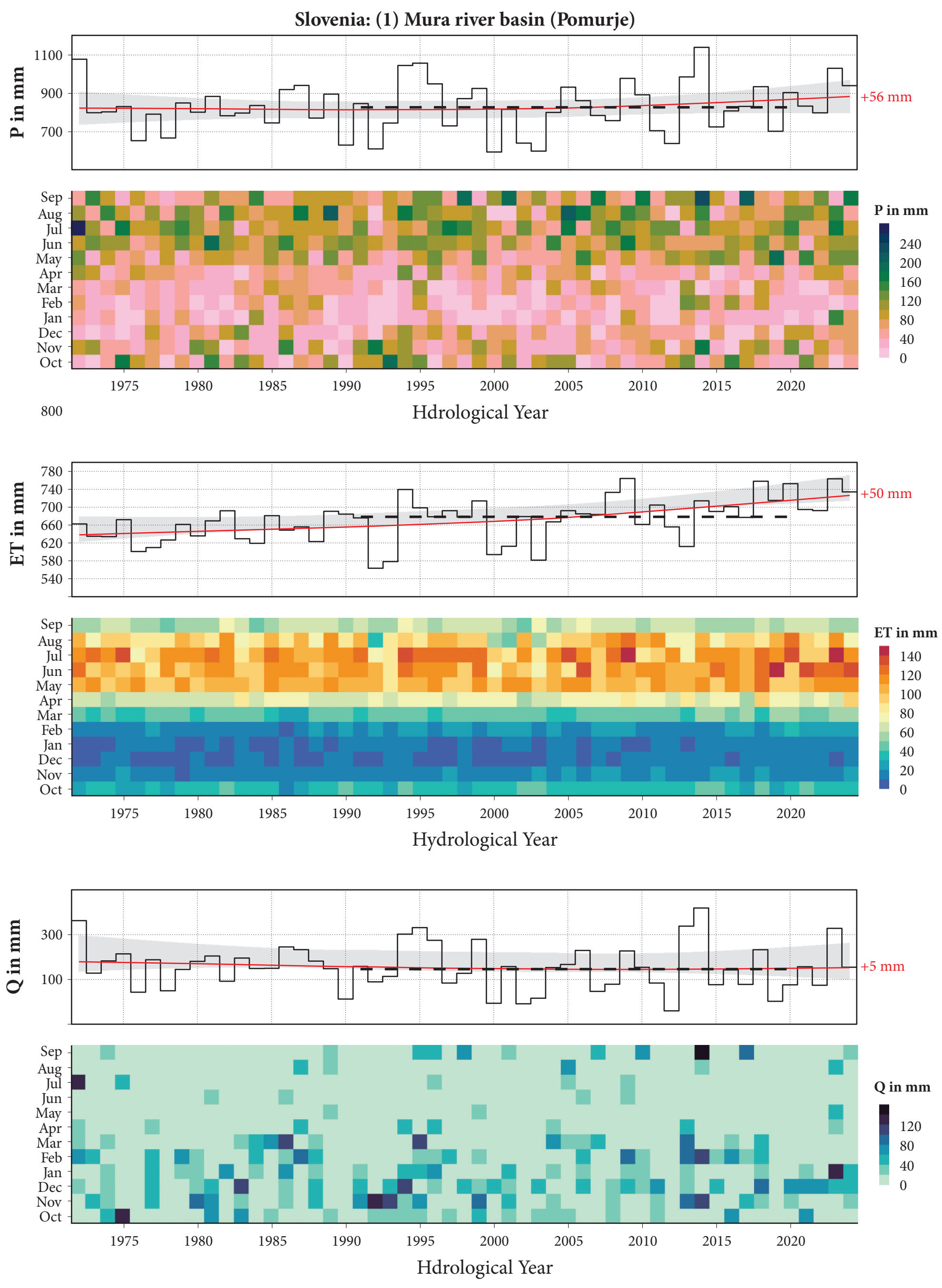


Figure 7: Time series of annual and monthly precipitation (P, top), evapotranspiration (ET, middle) and runoff (Q, bottom) in (1) Mura river basin (Pomurje) from 1972 to 2024. LOESS-42 trend lines in red, 30-year average 1991–2020 dashed in black, 95%-confidence limits as grey band.

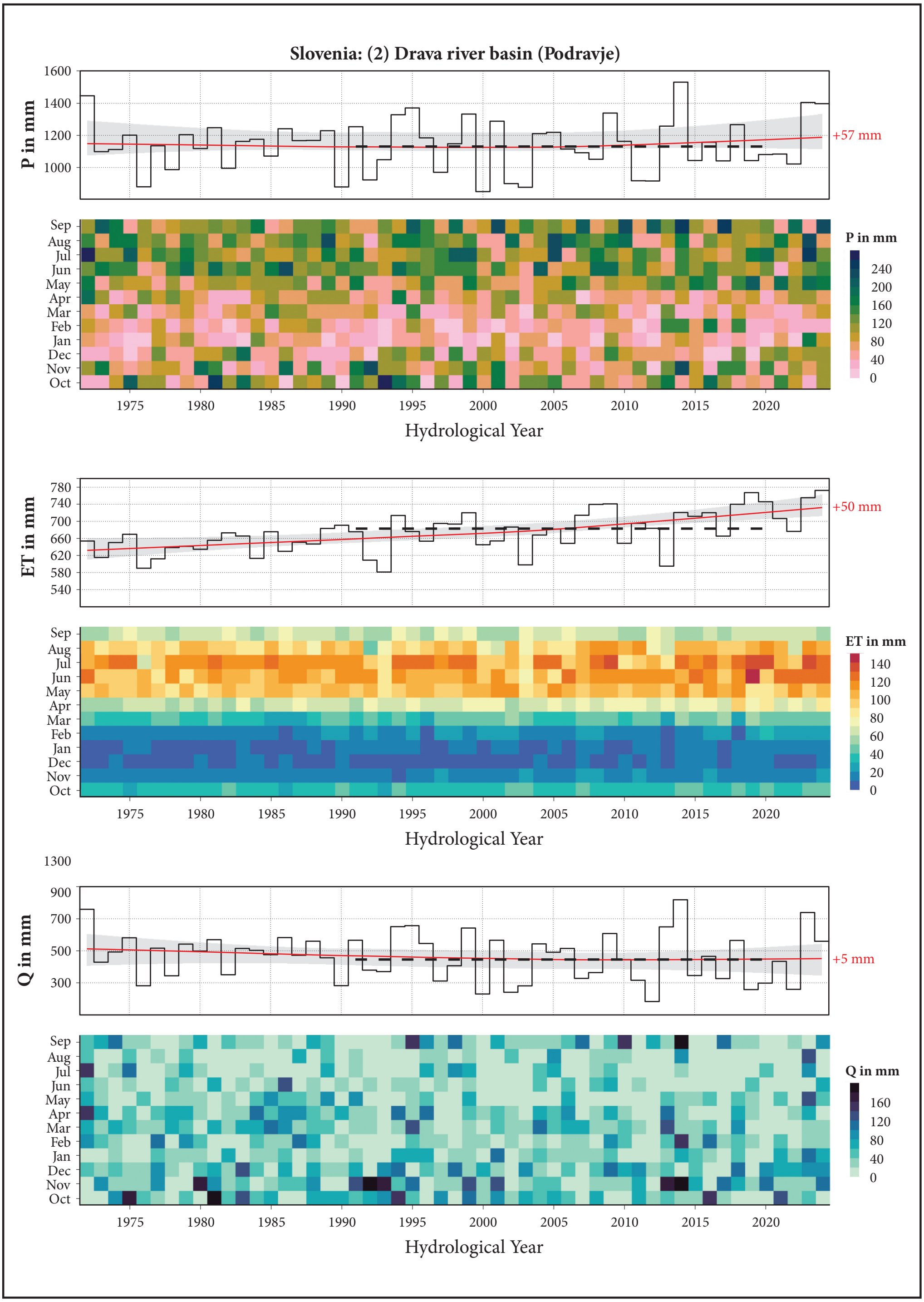


Figure 8: Time series of annual and monthly precipitation (P, top), evapotranspiration (ET, middle) and runoff (Q, bottom) in (2) Drava river basin (Podravje) from 1972 to 2024. LOESS-42 trend lines in red, 30-year average 1991–2020 dashed in black, 95%-confidence limits as grey band.

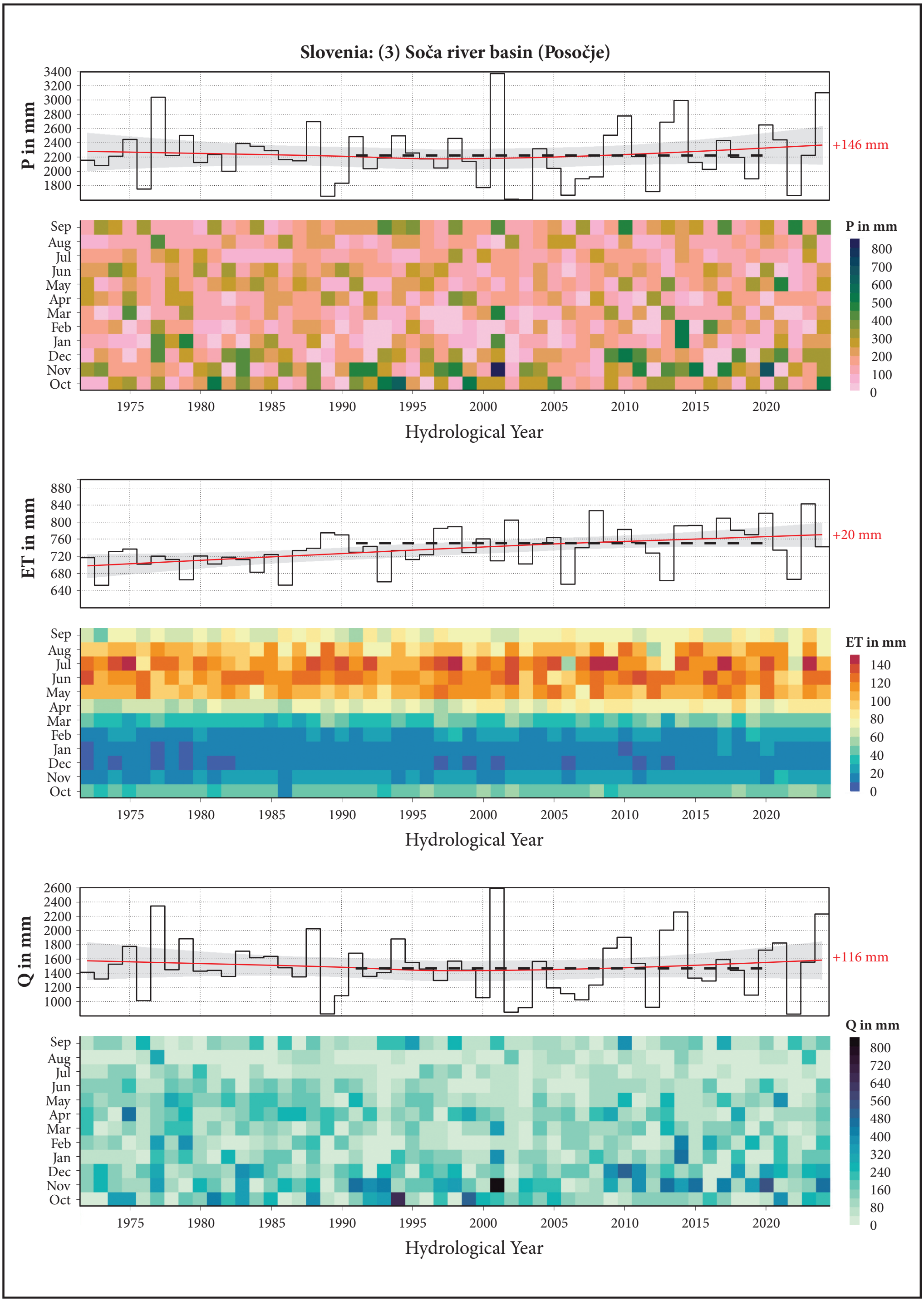


Figure 9: Time series of annual and monthly precipitation (P, top), evapotranspiration (ET, middle) and runoff (Q, bottom) in (3) Soča river basin (Posočje) from 1972 to 2024. LOESS-42 trend lines in red, 30-year average 1991–2020 dashed in black, 95%-confidence limits as grey band.

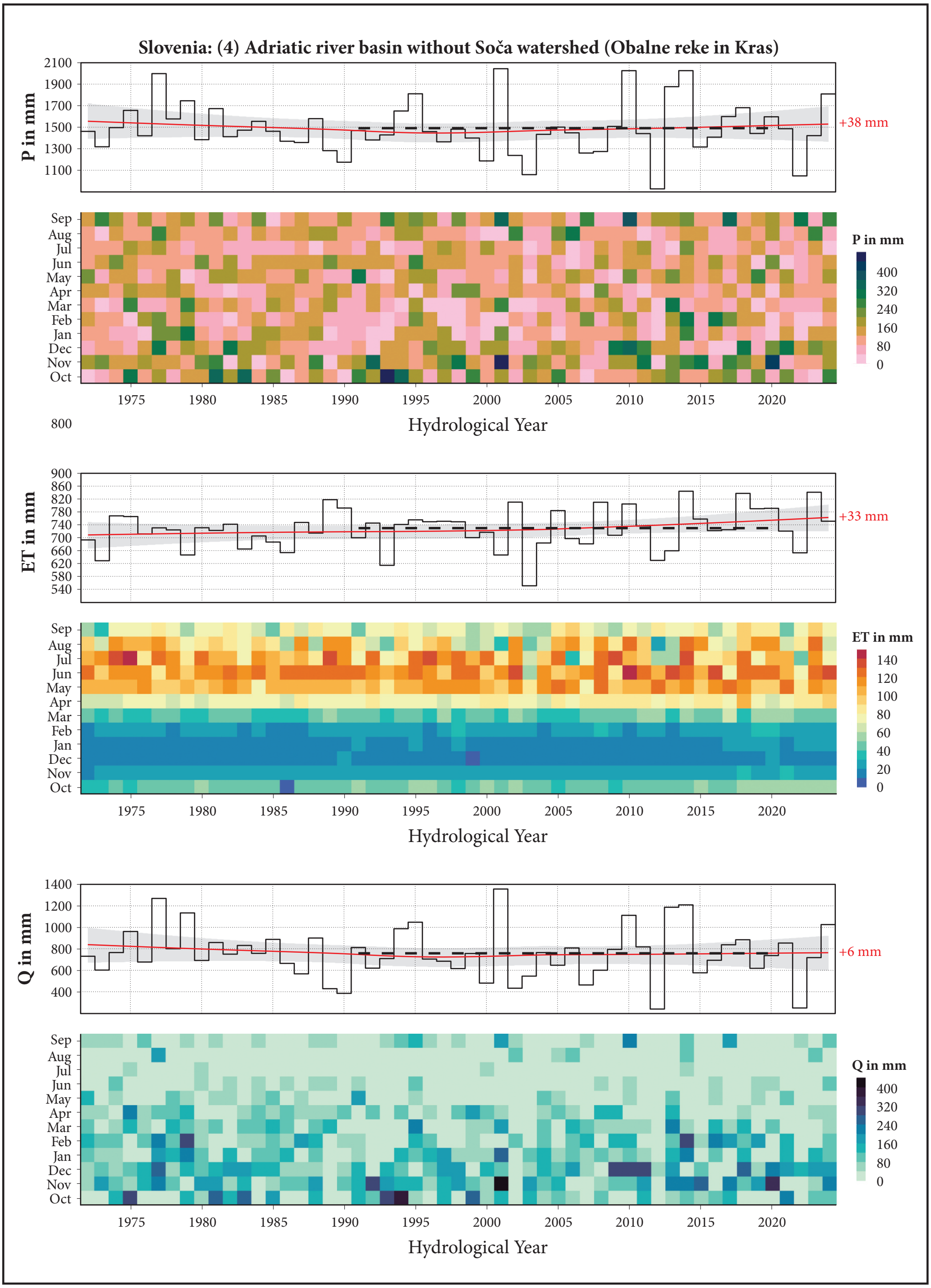


Figure 10: Time series of annual and monthly precipitation (P, top), evapotranspiration (ET, middle) and runoff (Q, bottom) in (4) Adriatic river basin without Soča watershed (Obalne reke in Kras) from 1972 to 2024. LOESS-42 trend lines in red, 30-year average 1991–2020 dashed in black, 95%-confidence limits as grey band.

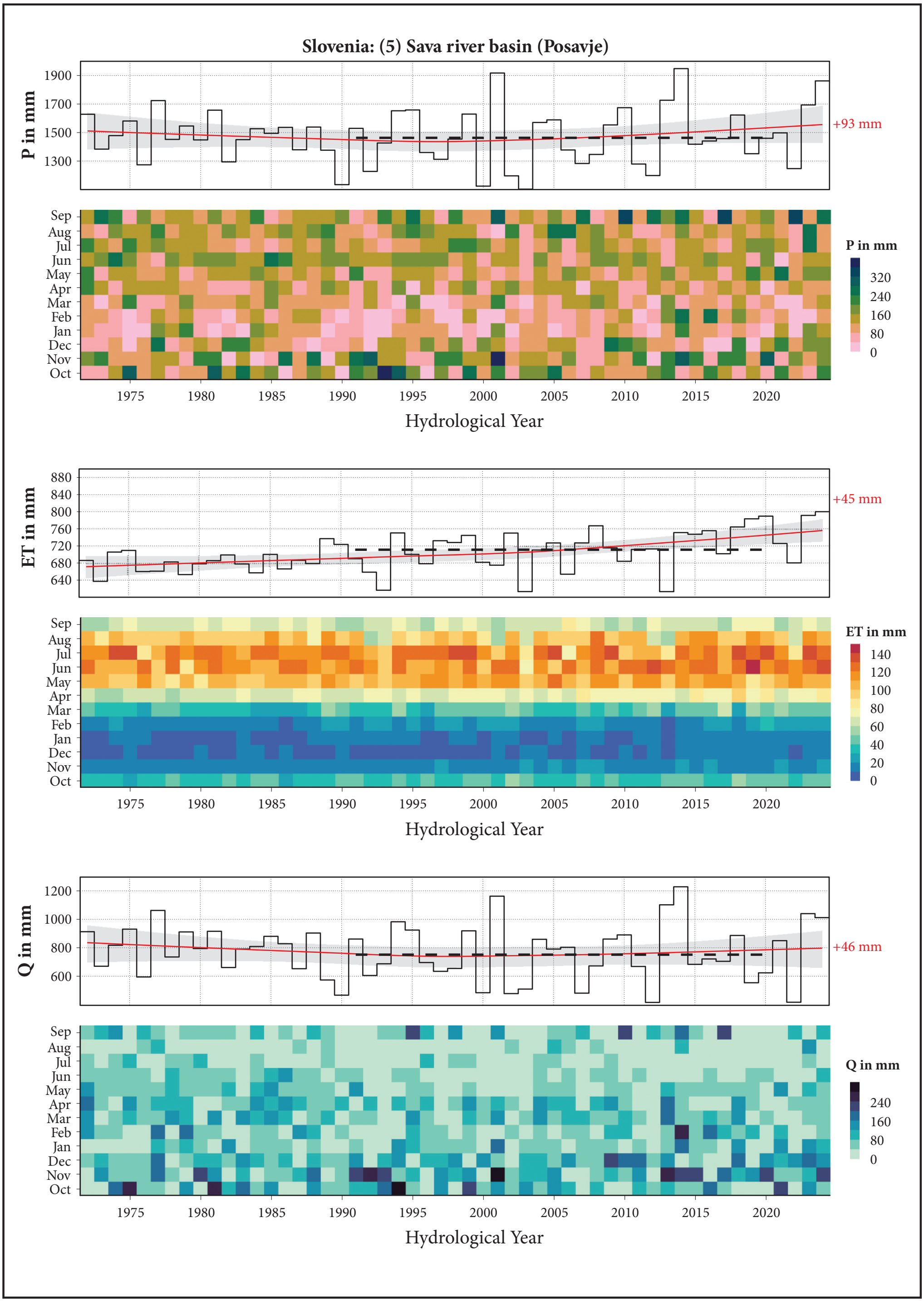
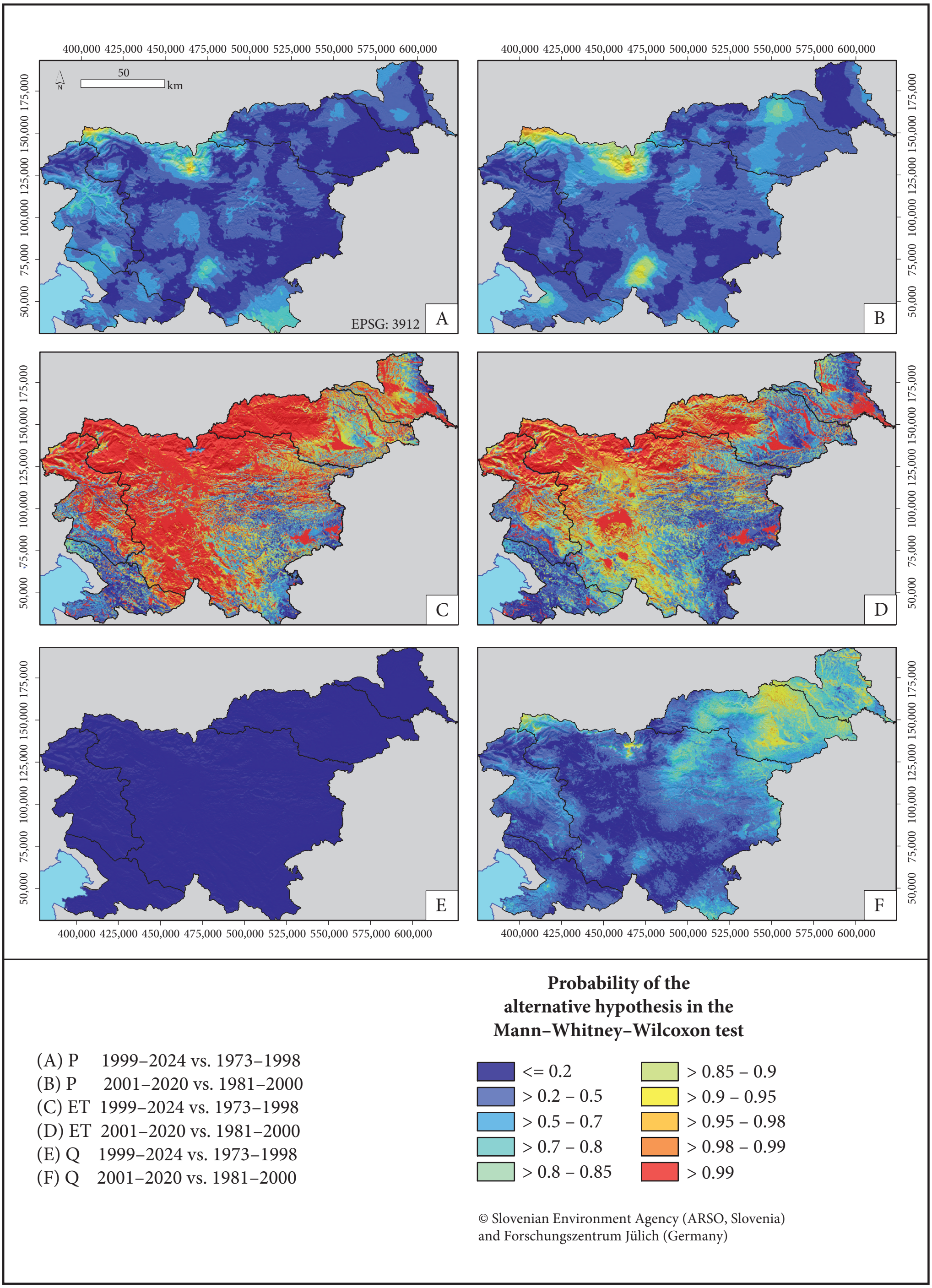


Figure 11: Time series of annual and monthly precipitation (P, top), evapotranspiration (ET, middle) and runoff (Q, bottom) in (5) Sava river basin (Posavje) from 1972 to 2024. LOESS-42 trend lines in red, 30-year average 1991–2020 dashed in black, 95%-confidence limits as grey band.



© Slovenian Environment Agency (ARSO, Slovenia)
and Forschungszentrum Jülich (Germany)

Figure 12: Grid-based probability of the alternative hypothesis in the Mann–Whitney–Wilcoxon test for the two sets of time spans and modelled long-term precipitation (P), evapotranspiration (ET) and runoff (Q). The geographic coordinate system of the map of Slovenia is *MGI 1901 / Slovene National Grid (EPSG: 3912)*, axis labels show metres.

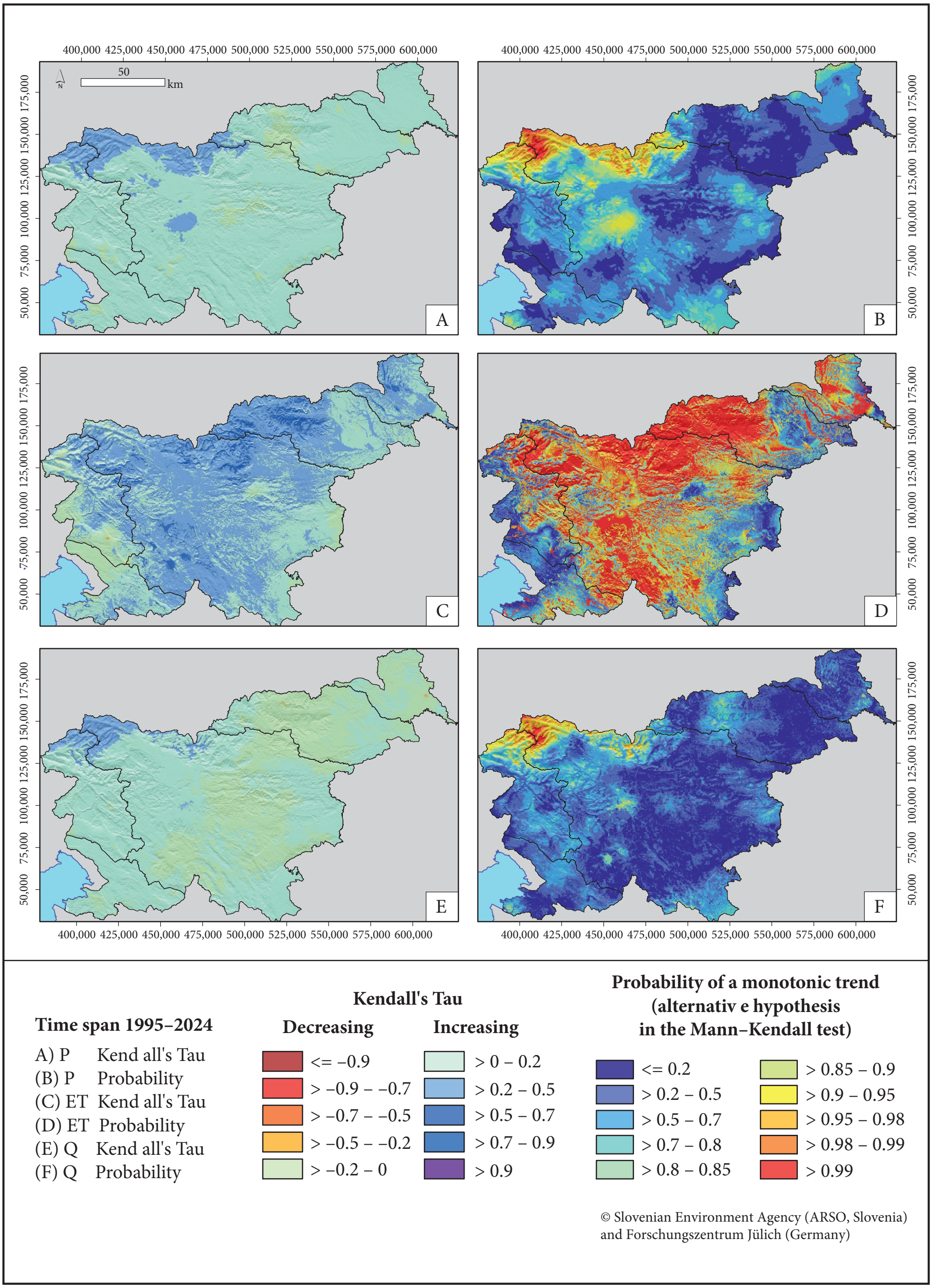


Figure 13: Grid-based probability of a monotonic trend (alternative hypothesis in the Mann–Kendall test) and Kendall's Tau for the time span 1995-2024 and modelled long-term precipitation (P), evapotranspiration (ET) and runoff (Q). The geographic coordinate system of the map of Slovenia is *MGI 1901 / Slovene National Grid (EPSG: 3912)*, axis labels show metres.

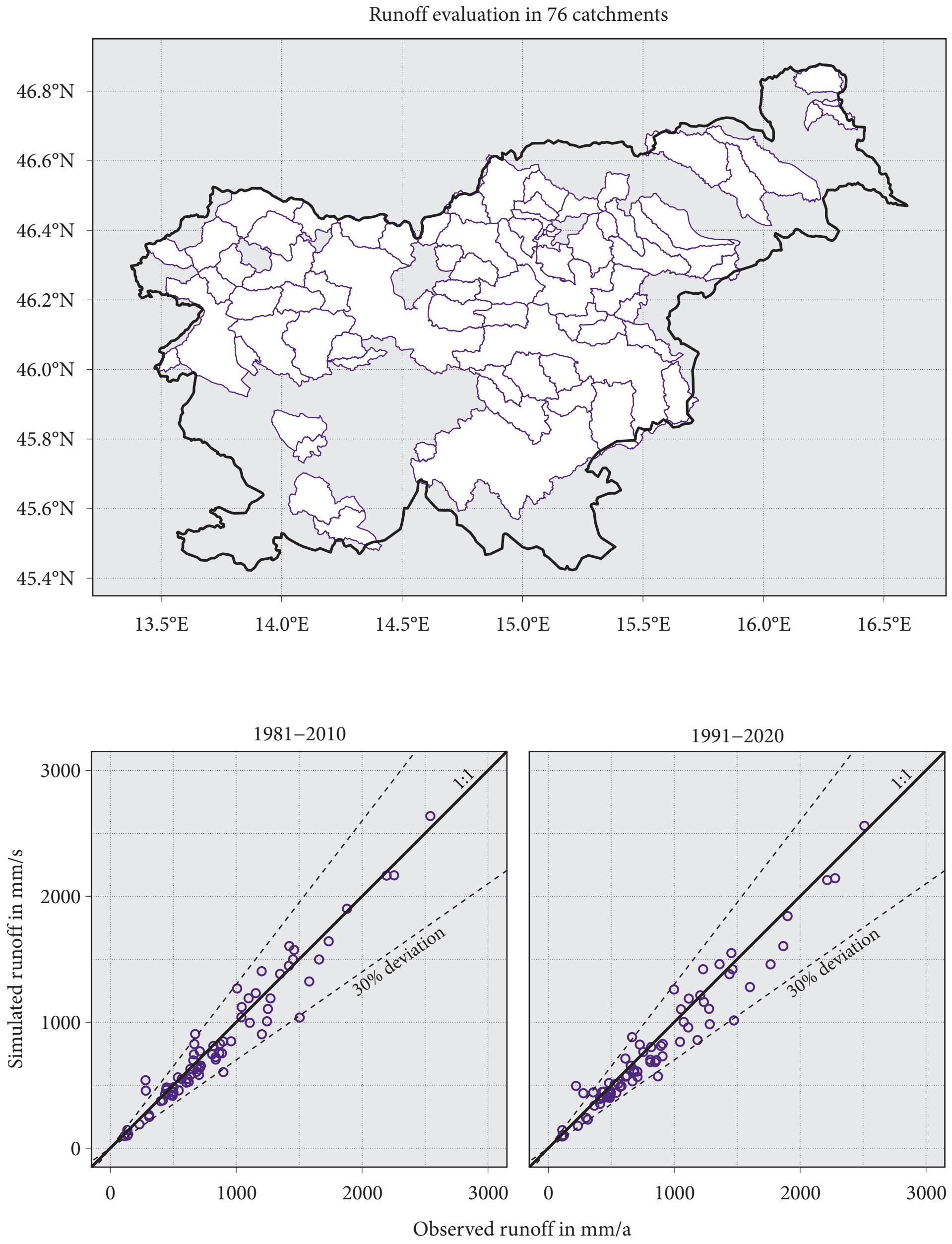


Figure 14: Simulated versus observed Q in Slovenia in 76 reference catchments and the two periods 1981–2010 and 1991–2020.

# 6 Discussion and implementation

The mGROWA simulation presented in this study is based on a temporally constant spatial distribution of parameters that represent the influence of land use, terrain, vegetation, and soil properties on evapotranspiration and runoff formation. Consequently, the effects of climate variability and change between 1972 and 2024 on the present land-surface state in Slovenia are examined. For example, land use changes and other human interventions were not reconstructed, and their potential impacts on the water balance were therefore not assessed. However, the mGROWA model would be technically capable of performing such analyses if suitable input data were available.

In the evaluation chapter, a slight underestimation of Q was identified. One important reason for this tendency is the use of uncorrected distributions of P. Point measurements of P and spatial interpolation are subject to bias. However, it is very difficult to determine the exact influence on the overall simulation bias. Moreover, correcting individual variables may obscure underlying uncertainties. This is illustrated by the fact that the magnitude of bias differs between the two evaluation periods, despite their 20-year overlap. A bias correction of P would not eliminate this discrepancy because it would have a consistent effect on the entire simulated period. Presumably, there is another relevant influence on the overall bias due to the methodology behind the calculation of ET. The parameters used in the simulation were set constant over time. The upward trend in ET levels (Figure 6), particularly since about 2005, supports this interpretation. From a modelling perspective we can conclude that this phenomenon must be further observed and further scientific efforts must be made to improve the parameterisation of the model.

The results chapter demonstrates pronounced spatial and temporal variability, as well as trends and changes in P, ET, and Q across Slovenia. The emerging picture is complex and reflects the superposition of regional climate variability with site-specific characteristics. Similar ranges of positive and negative, as well as significant and insignificant, changes in discharge have been reported for Slovenian rivers by Oblak et al. (2021). Based on observed changes, Stojilković and Brečko Grubar (2024) proposed a modern typology of discharge regimes in Slovenia. ETo represents a key driver of variability and change and forms the basis for ET calculation in mGROWA. Spatially variable ETo trends related to global warming were reported for Slovenia by Maček et al. (2018) and are also reflected in our reconstructed ET patterns. Comparable climate-related impacts on discharge regimes have been reported for Croatia (Čanjevac and Orešić 2018). In Austria, the COSERO model, which is conceptually similar to mGROWA, has recently been established (Zeitfogel et al. 2025), although detailed trend analyses based on this model are not yet available.

All of these studies highlight the need for continuous observation and evaluation of trends and changes. Importantly, the objective of this study was not to prove climate-change impacts on Slovenia's water balance, but to provide a data basis that supports water-resources management in identifying relevant long- and mid-term changes. Such changes do not necessarily require statistically significant trends in individual climate variables. Nevertheless, analysis of the LOESS-42 trend line and its 95% confidence limits provides a robust framework for assessing recent climatic variability and trends. The overlap of the 95%-confidence limits and the 30-year mean can be interpreted as an early indication of emerging change in one of the components under investigation.

With the implementation of mGROWA as a national water balance model, Slovenian water-resources management and other stakeholders will benefit from state-of-the-art, model-based assessments. The simulation will be continued at the Slovenian Environment Agency (ARSO), providing a long-term data basis for research and operational applications that extend beyond the scope of this study. The comprehensive data basis is already being used for various purposes, for example for reporting by the Slovenian government under the EU Water Framework Directive, for identifying regions with water stress, supporting policy decisions and allocation of water rights, for regional and local water-resources assessments, defining boundary conditions for groundwater models, assessing ecosystem services (Bogataj and Frantar 2025), and analysing drought severity. Finally, the mGROWA-based annual hydro-climatological trend indicator is intended to serve as essential contribution to a national Slovenian Water Resources and Drought Monitor.

# 7 Conclusion

The results of the mGROWA simulation for the period 1972–2024 provide a comprehensive data basis that contributes to an improved understanding of the spatio-temporal variability of water balance components in Slovenia under ongoing climate change. Statistical analyses demonstrate a significant increase in evapotranspiration over large parts of the country. However, due to above-average precipitation in recent years, this increase has not yet translated into a country-wide decline in mean runoff. The proposed hydroclimatological trend indicator has proven to be a useful tool and represents a promising future element for monitoring changes in water balance components in Slovenia.

From a scientific perspective, the existing simulation results also enable analyses of the influence of meteorological drought on the severity of hydrological drought. Shifts and changes in this relationship are expected in the future. Moreover, the current mGROWA setup can serve as a basis for comprehensive climate-impact studies, for example by linking outputs from Regional Climate Models (RCMs) or Shared Socioeconomic Pathways (SSPs) to mGROWA. This will allow the assessment of projected future water balance components and facilitate systematic comparisons with the current state of knowledge.

Finally, further improvements in the underlying data basis and in the mGROWA methodology itself are expected to reduce remaining uncertainties. Nevertheless, with regard to retrospective analyses, such improvements are not expected to lead to fundamentally different conclusions about the impact of climate change on the national-scale water balance in Slovenia.

ACKNOWLEDGEMENT: We would like to thank Jože Uhan, Mojca Dolinar, Joško Knez and Frank Wendland for organising the funding for the implementation of the mGROWA model in Slovenia as part of the established research collaboration between the Slovenian Environment Agency (ARSO) and Forschungszentrum Jülich (Germany).

RESEARCH DATA: For information on the availability of research data related to the study, please visit the article webpage: https://doi.org/10.3986/AGS.14632.

# 8 References

Allen, R. G., Pereira, L. S., Raes, D., Smith, M. 1998: Crop evapotranspiration – Guidelines for computing crop water requirements. FAO Irrigation and drainage paper 56. FAO – Food and Agriculture Organization of the United Nations.

Andjelov, M., Mikulič, Z., Tetzlaff, B., Uhan, J., Wendland, F. 2016: Groundwater recharge in Slovenia: Results of a bilateral German-Slovenian Research project. Forschungszentrum Jülich GmbH.

Bevacqua, E., Rakovec, O., Schumacher, D. L., Kumar, R., Thober, S., Samaniego, L., Seneviratne, S. I., Zscheischler, J. 2024: Direct and lagged climate change effects intensified the 2022 European drought. Nature *Geoscience* 17-11. https://doi.org/10.1038/s41561-024-01559-2

Bogataj, N., Frantar, P. 2025: Groundwater recharge as a basis for the assessment of ecosystem services on common land: The case of the Primorska region in Slovenia. *Acta geographica Slovenica* 65-3. https://doi.org/10.3986/AGS.14319

Čanjevac, I., Orešić, D. 2018: Changes in discharge regimes of rivers in Croatia. *Acta geographica Slovenica* 58-2. https://doi.org/10.3986/AGS.2004

Disse, M. 1995: Modellierung der Verdunstung und der Grundwasserneubildung in ebenen Einzugsgebieten. Fakultät für Bauingenieur- und Vermessungswesen der Universität Fridericiana zu Karlsruhe (TH).

Dolinar, M. 2009: Prostorska interpolacija mesečnih padavin (metodologija). *Internal report*. Ministrstvo za okolje in prostor, Agencija Republike Slovenije za okolje.

Ehlers, L., Herrmann, F., Blaschek, M., Duttmann, R., Wendland, F. 2016: Sensitivity of mGROWA-simulated groundwater recharge to changes in soil and land use parameters in a Mediterranean environment and conclusions in view of ensemble-based climate impact simulations. *Science of The Total Environment* 543, Part B. https://doi.org/10.1016/j.scitotenv.2015.04.122

Engel, N., Müller, U., Schäfer, W. 2012: BOWAB – Ein Mehrschicht-Bodenwasserhaushaltsmodell. In: Klimawandel und Bodenwasserhaushalt. *GeoBerichte* 20. Landesamt für Bergbau, Energie und Geologie. https://doi.org/10.48476/geober_20_2012

Ertl, G., Herrmann, F., Elbracht, J. 2022: Bestimmung der Grundwasserneubildungshöhen für Festgesteinsgebiete in Niedersachsen. Grundwasser 27. https://doi.org/10.1007/s00767-021-00503-0

Ertl, G., Herrmann, F., Schlinsog, T., Elbracht, J. 2018: Auswirkungen von Klimaänderungen auf die Grundwasserneubildung in Niedersachsen. *Wasser und Abfall* 20-9. https://doi.org/10.1007/s35152-018-0097-1

European Commission 2015: Guidance document on the application of water balances for supporting the implementation of the WFD – Final – Version 6.1 – 18/05/2015. *Technical report*. Publications Office. https://doi.org/10.2779/352735

Festgesteinsgebiete in Niedersachsen. *Grundwasser* 27. https://doi.org/10.1007/s00767-021-00503-0

Frantar, P. 2007: Geographical overview of water balance of Slovenia 1971–2000 by main river basins. *Acta geographica Slovenica* 47-1. https://doi.org/10.3986/AGS47102

Frantar, P. 2008 (ed.): Vodna bilanca Slovenije 1971–2000. Water balance of Slovenia 1971–2000. Ministrstvo za okolje in prostor, Agencija Republike Slovenije za okolje.

Frantar, P., Herrmann, F. 2026: National-scale water balance in Slovenia (1972–2024): Long-term trends and variability in water balance components. *Dataset*. Jülich DATA. https://doi.org/10.26165/JUELICH-DATA/UKYJHY

Gupta, H. V., Sorooshian, S., Yapo, O. P. 1999: Status of automatic calibration for hydrologic models: Comparison with multilevel expert calibration. *Journal of Hydraulic Engineering* 4-2. https://doi.org/10.1061/(ASCE)1084-0699(1999)4:2(135)

Helsel, D. R., Hirsch, R. M. 1992: Statistical methods in water resources. Elsevier.

Herrmann, F., Chen, S., Heidt, L., Elbracht, J., Engel, N., Kunkel, R., Müller, U. et al. 2013: Zeitlich und räumlich hochaufgelöste flächendifferenzierte Simulation des Landschaftswasserhaushalts in Niedersachsen mit dem Model mGROWA. *Hydrologie und Wasserbewirtschaftung* 57-5. https://doi.org/10.5675/HyWa_2013,5_2

Herrmann, F., Hübsch, L., Elbracht, J., Engel, N., Keller, L., Kunkel, R., Müller, U. et al. 2017: Mögliche Auswirkungen von Klimaänderungen auf die Grundwasserneubildung in Niedersachsen. *Hydrologie und Wasserbewirtschaftung* 61-4. https://doi.org/10.5675/HyWa_2017,4_3

Herrmann, F., Keller, L., Kunkel, R., Vereecken, H., Wendland, F. 2015: Determination of spatially differentiated water balance components including groundwater recharge on the Federal State level – A case study using the mGROWA model in North Rhine-Westphalia (Germany). *Journal of Hydrology: Regional Studies* 4, Part B. https://doi.org/10.1016/j.ejrh.2015.06.018

Herrmann, F., Keuler, K., Wolters, T., Bergmann, S., Eisele, M., Wendland, F. 2021: Mit der Modellkette RCP-GCM-RCM-mGROWA projizierte Grundwasserneubildung als Datenbasis für zukünftiges Grundwassermanagement in Nordrhein-Westfalen. *Grundwasser* 26. https://doi.org/10.1007/s00767-020-00471-x

Hiederer, R. 2013: Mapping soil properties for Europe – spatial representation of soil database attributes. *Technical report*. Publications Office of the European Union. https://doi.org/10.2788/94128

Huntington, T. G. 2006: Evidence for intensification of the global water cycle: Review and synthesis. *Journal of Hydrology* 319-1,4. https://doi.org/10.1016/j.jhydrol.2005.07.003

Intergovernmental Panel on Climate Change (IPCC) 2023: Summary for policymakers. Climate change 2021 – the physical science basis: Working Group I contribution to the sixth assessment report of the Intergovernmental Panel on Climate Change. Cambridge University Press. https://doi.org/10.1017/9781009157896.001

Kendall, M. G. 1938: A new measure of rank correlation. *Biometrika* 30-1,2. https://doi.org/10.1093/biomet/30.1-2.81

Kolbezen, M., Pristov, J. 1998: Površinski vodotoki in vodna bilanca Slovenije. Surface watercourses and water balance of Slovenia. Ministrstvo za okolje in prostor, Hidrometeorološki zavod Republike Slovenije. http://hmljn.arso.gov.si/vode/publikacije%20in%20poro%C4%8Dila/bilanca6190_2_BESEDILO.pdf

Maček, U., Bezak, N., Šraj, M. 2018: Reference evapotranspiration changes in Slovenia, Europe. *Agricultural and Forest Meteorology* 260–261. https://doi.org/10.1016/j.agrformet.2018.06.014

Mann, H. B. 1945: Nonparametric tests against trend. *Econometrica* 13-3. https://doi.org/10.2307/1907187

Mann, H. B., Whitney, D. R. 1947: On a test of whether one of two random variables is stochastically larger than the other. *The Annals of Mathematical Statistics* 18-1. https://doi.org/10.1214/aoms/1177730491

Matheron, G. 1963: Principles of geostatistics. *Economic Geology* 58-8. https://doi.org/10.2113/gsecongeo.58.8.1246

Mauget, S. A. 2003: Multidecadal regime shifts in U.S. streamflow, precipitation, and temperature at the end of the twentieth century. *Journal of Climate* 16-23. https://doi.org/10.1175/1520-0442(2003)016<3905:Mrsius>2.0.Co;2

McNamara, I., Flörke, M., Uschan, T., Baez-Villanueva, O. M., Herrmann, F. 2024: Estimates of irrigation requirements throughout Germany under varying climatic conditions. *Agricultural Water Management* 291. https://doi.org/10.1016/j.agwat.2023.108641

Milly, P. C., Betancourt, J., Falkenmark, M., Hirsch, R. M., Kundzewicz, Z. W., Lettenmaier, D. P., Stouffer, R. J. 2008: Stationarity is dead: Whither water management? *Science* 319-5863. https://doi.org/10.1126/science.1151915

Moriasi, D. N., Arnold, J. G., Liew, M. W. V., Bingner, R. L., Harmel, R. D., Veith, T. L. 2007: Model evaluation guidelines for systematic quantification of accuracy in watershed simulations. *Transactions of the ASABE* 50-3. https://doi.org/10.13031/2013.23153

Nash, J. E., Sutcliffe, J. V. 1970: River flow forecasting through conceptual models: Part I – A discussion of principles. *Journal of Hydrology* 10-3. https://doi.org/10.1016/0022-1694(70)90255-6

Oblak, J., Kobold, M., Šraj, M. 2021: The influence of climate change on discharge fluctuations in Slovenian rivers. *Acta geographica Slovenica* 61-2. https://doi.org/10.3986/AGS.9942

Pfeifer, S., Bülow, K., Gobiet, A., Hänsler, A., Mudelsee, M., Otto, J., Rechid, D. et al. 2015: Robustness of ensemble climate projections analyzed with climate signal maps: Seasonal and extreme precipitation for Germany. *Atmosphere* 6-5. https://doi.org/10.3390/atmos6050677

Scherrer, S. C., de Valk, C., Begert, M., Gubler, S., Kotlarski, S., Croci-Maspoli, M. 2024: Estimating trends and the current climate mean in a changing climate. *Climate Services* 33. https://doi.org/10.1016/j.cliser.2023.100428

Schulla, J. 1997: Hydrologische Modellierung von Flussgebieten zur Abschätzung der Folgen von Klimaänderungen. *Ph.D. thesis*. Züricher Geographische Schriften. Verlag Geographisches Institut ETH Zürich. https://doi.org/10.3929/ethz-a-001763261

Stojilković, B., Brečko Grubar, V. 2024: Discharge regimes of Slovenian rivers: 1991–2020. *Acta geographica Slovenica* 64-3. https://doi.org/10.3986/AGS.13654

Strandhagen, E., Marcus, W. A., Meacham, J. E. 2006: Views of the rivers: Representing streamflow of the Greater Yellowstone ecosystem. *Cartographic Perspectives* 55. https://doi.org/10.14714/CP55.328

Tetzlaff, B., Andjelov, M., Kuhr, P., Uhan, J., Wendland, F. 2015: Model-based assessment of groundwater recharge in Slovenia. *Environmental Earth Sciences* 74-7. https://doi.org/10.1007/s12665-015-4639-5

Tetzlaff, B., Kuhr, P., Vereecken, H., Wendland, F. 2009: Aerial photograph-based delineation of artificially drained areas as a basis for water balance and phosphorus modelling in large river basins. *Physics and Chemistry of the Earth, Parts A/B/C* 34-8,9. https://doi.org/10.1016/j.pce.2009.02.002

van Genuchten, M. T. 1980: A closed-form equation for predicting the hydraulic conductivity of unsaturated soils. *Soil Science Society of America Journal* 44-5. https://doi.org/10.2136/sssaj1980.03615995004400050002x

Wilcoxon, F. 1945: Individual comparisons by ranking methods. *Biometrics Bulletin* 1-6. https://doi.org/10.2307/3001968

Xiong, J., Xu, L., Chandanpurkar, H. A., Famiglietti, J. S., Zhang, C., Ghiggi, G., Guo, S. et al. 2023: ET-WB: water-balance-based estimations of terrestrial evaporation over global land and major global basins. *Earth System Science Data* 15-10. https://doi.org/10.5194/essd-15-4571-2023

Zeitfogel, H., Herrnegger, M., Schulz, K. 2025: Regional-scale assessment of groundwater recharge and the water balance for Austria. *Journal of Hydrology: Regional Studies* 59. https://doi.org/10.1016/j.ejrh.2025.102297