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Predictions of groundwater storages and levels based on the results of climate models and scenarios

(Predikce vývoje hladin a zásob podzemní vody na základě výsledků klimatických modelů a scénářů)

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***Abstract**:* During the PERUN project, comprehensive groundwater flow models were developed for selected areas of the Czech Republic that are significant for groundwater management (the South Bohemian Basin, the Cretaceous formations of the right-bank tributaries of the Elbe, the Vysoké Mýto and Ústí synclines, the Tertiary formations of the Carpathian foredeep, and the Cretaceous formations of the lower Kamenice and Křinice rivers). In the initial stages, the flow models were calibrated, and a retrospective analysis of the period 1981–2020 was performed. The final two years of the project involved the implementation of predictive simulations. Groundwater recharge in the predictive simulations was specified based on the results of the BILAN hydrological model (VUV TGM v.v.i.), calculated for the outputs of the ALADIN-CLIMATE/CZ climate model and the SSP2-4.5 scenario for the year 2030. The ALADIN-CLIMATE/CZ model predicted an increase in precipitation of up to 8.5%, but the increase in groundwater recharge reached as much as 27%. The increase in groundwater recharge predicts an increase in groundwater reserves, levels, and baseflow, which is inconsistent with observations. In 2025, the reasons for the increase in groundwater recharge (beyond the increase in precipitation totals) were identified and presented by VUV TGM v.v.i. Based on the comments, the calculation of the hydrological balance using the BILAN model was modified, and the new results were submitted. Groundwater recharge in the projection periods determined based on the results of the ALADIN-CLIMATE/CZ model remains higher than in the current period for most HGRs, even after adjusting the calculation. Groundwater recharge was determined not only for the ALADIN-CLIMATE/CZ model but also for six other climate models and five climate change scenarios. The variability of the results from climate models and climate scenarios was evaluated using steady-flow models, which simulated 104 model variants corresponding to specific combinations of climate models, scenarios, and periods. Given the predicted rise in groundwater levels and reserves, the final phase of the project will involve important discussions among the developers of climate models, hydrological models, and groundwater flow models.

***Keywords**:* Groundwater flow Modeling – Climate Scenarios – Groundwater Recharge

***Abstrakt**:* V průběhu řešení projektu PERUN byly pro vybrané vodohospodářsky významné oblasti ČR realizovány komplexní modely proudění podzemní vody (jihočeské pánve, křída pravostranných přítoků Labe, vysokomýtská a Ústecká synklinála, terciér karpatské předhlubně a křída dolní Kamenice a Křinice). V úvodních etapách byly modely proudění kalibrované a bylo realizované zpětné hodnocení období 1981–2020. V posledních dvou letech projektu následovala realizace predikčních simulací. Dotace podzemní vody byly v predikčních simulacích zadané na základě výsledků hydrologického modelu BILAN (VUV TGM v.v.i.), vypočtené pro výstupy klimatického modelu ALADIN-

CLIMATE/CZ a scénář SSP2-4.5 a období 2030. Model ALADIN-CLIMATE/CZ predikoval zvýšení srážek až o 8,5 %, nárůst dotace podzemní vody však dosahoval až 27 %. Nárůst dotace podzemní vody predikuje zvýšení zásob a hladin podzemní vody a základního odtoku, což je v rozporu s pozorováním. V roce 2025 byly identifikovány důvody nárůstu dotace podzemní vody (nad rámec zvýšení srážkových úhrnů) a prezentovány VUV TGM v.v.i.. Na základě připomínek došlo ke změně výpočtu hydrologické bilance modelem BILAN a předání nových výsledků. Dotace podzemní vody v predikčních obdobích stanovených na základě výsledků modelu ALADIN-CLIMATE/CZ vychází i po úpravě výpočtu pro většinu HGR vyšší než pro současné období. Dotace podzemní vody byly kromě modelu ALADIN-CLIMATE/CZ stanoveny pro dalších 6 klimatických modelů a 5 scénářů vývoje klimatu. Variabilita výsledků klimatických modelů a klimatických scénářů byla zhodnocena modely ustáleného proudění, kterými bylo simulováno 104 modelových variant odpovídajících specifickým kombinacím klimatických modelů, scénářů a období. Vzhledem k predikovanému nárůstu hladin a zásob podzemní vody bude poslední etapě projektu důležitá diskuse mezi zpracovateli klimatických modelů, hydrologických modelů a modelů proudění podzemní vody.

***Klíčová slova**:* Dotace podzemní vody – klimatické scénáře – modelování proudění podzemní vody

Introduction

In the PERUN project, groundwater issues related to the impacts of drought and climate change are assessed in five regions of water management significance (the South Bohemian Basin, the Cretaceous formations of the right-bank tributaries of the Elbe, the Vysoké Mýto and Ústí synclines, the Tertiary formations of the Carpathian foredeep, and the Cretaceous formations of the lower Kamenice and Křinice rivers). Comprehensive groundwater flow models were developed for the selected areas. In the initial stages of the project, simulations of steady-state groundwater flow (calibration of the steady-state model – typical flow conditions) were performed, and simulations of transient flow (retrospective analysis of the period 1981–2023) were carried out.

Within the groundwater flow model, climate change is accounted for in the form of changes in the magnitude and temporal distribution of groundwater recharge (infiltration into groundwater). Changes in infiltration lead to changes in groundwater levels and in the volume of groundwater flowing through the hydrogeological structure to natural and artificial drainage points (river network, springs, and pumping wells). The magnitude and variability of groundwater recharge are calculated in VUV TGM v.v.i. using the BILAN hydrological model (Horáček et al. 2009; Pavlík and Vizina 2022) based on data from individual climate models and scenarios (Institute of Global Change Research, Czech Academy of Sciences, v. v. i.). In 2024, predictive simulations of transient groundwater flow for the year 2030 were conducted, using input data from the *ALADIN-CLIMATE/CZ* (Caian et al. 2015) climate model and the SSP2-4.5 emissions scenario (O'Neill et al. 2016).

The ALADIN-CLIMATE/CZ model predicted an increase in the hydrological model's input precipitation of 1% to 8.5% (depending on the period and scenario); however, the increase in groundwater recharge reached 12% to 27%. A significant increase in groundwater recharge predicts an increase in groundwater reserves and levels and an increase in baseflow, which contradicts observations from the past two decades.

In 2025, possible reasons for the significant increase in groundwater recharge (beyond the increase in precipitation totals) were identified and presented to representatives of VUV TGM v.v.i. Based on the comments presented, the calculation of the hydrological balance using the BILAN model was revised, and new results on groundwater recharge trends were submitted for the historical period 1990–2020 and the projection periods 2030, 2050, 2070, and 2085 (for selected HGRs).

Groundwater recharge trends were determined not only using the ALADIN-CLIMATE/CZ model but also for six additional climate models and five climate change scenarios. The variability of the results from the climate models and climate scenarios was assessed in 2025 using steady-flow models, which

were used to simulate 104 model variants corresponding to specific combinations of climate models, scenarios, and time periods.

Data

To assess trends in groundwater reserves, data were provided for 55 hydrogeological regions (HGRs), with 26 result variants for each HGR, encompassing various combinations of climate models, climate scenarios, and time periods (Tab. 1). The BILAN model was also used to calculate a time period representing the current state (2005). During the Perun project, the ALADIN-CLIMATE/CZ model was developed (and refined for the territory of the Czech Republic) by the co-investigators.

Table 1. The forecast period of the hydrological model.

2005	2030	2050	2070	2085
1.1991–12.2020	1.2015–12.2044	1.2035–12.2064	1.2025–12.2084	1.2070–2.2099

Precipitation (calculated using climate models developed by the Institute for Global Change Research, Czech Academy of Sciences) serves as the input variable for the BILAN hydrological balance model; based on specified model parameters, this precipitation is distributed among the individual components of the hydrological balance. The calculated RC value (from the BILAN model), which characterizes the rate of monthly recharge to the groundwater reservoir, is used as input data for the groundwater flow models. The resulting groundwater recharge values are the output of the two preceding models (climatic and hydrological).

Fig. 1 illustrates the change in the proportion of monthly groundwater recharge (RC) during the forecast periods compared to the 2005 period. During the forecast periods, there is a shift in the distribution of total annual recharge across the individual months of the year. While a decrease in groundwater recharge is predicted during the growing season, outside the growing season, compared to the 2005 period, recharge shifts to February and, in particular, December. While groundwater recharge is already minimal in the summer months, and its further decline does not significantly affect the development of groundwater reserves, a several-percent increase in precipitation during the winter months results in a significant replenishment of groundwater reserves.

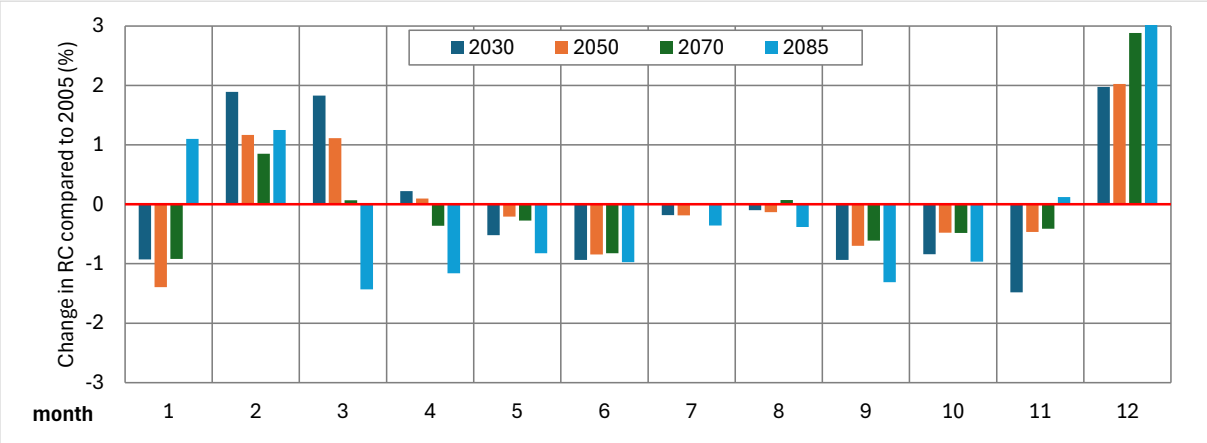


Fig. 1. Change in the proportion of monthly groundwater recharges compared to 2005, all data submitted to HGR, results based on ALADIN245.

In 2025, the possible reasons for the significant increase in groundwater recharge (beyond the increase in precipitation totals) were presented to representatives of VUV TGM v.v.i. Based on the comments presented, the calculation of the hydrological balance using the BILAN model was revised, and new results regarding groundwater recharge trends were submitted for the historical period 1990–2020 and the forecast periods 2030, 2050, 2070, and 2085 (for selected HGRs). A new dataset on groundwater

recharge trends, calculated for 6 climate models and 5 emission scenarios, was used to predict trends in groundwater levels and reserves

Results of predictive simulations

Groundwater storage projections are calculated for 7 climate models (CMCC-ESM2, EC-Earth3, GFDL-ESM4, MPI-ESM1-2-HR, MRI-ESM2-0, TAIESM1, ALADIN CLIMATE/CZ), 4 scenarios (SSP1-2.6, SSP2-4.5, SSP3-7.0, SSP5-8.5), and 4 projection periods (2030, 2050, 2070, 2085). The impact of the predicted groundwater recharge by individual models and scenarios on the development of groundwater levels (and reserves) is evaluated using steady-state flow model calculations. For each area, 104 model variants were calculated, corresponding to all combinations of climate model results, scenarios, and prediction periods. One reference calculation is performed for infiltration values determined for the 2005 period. In each model, infiltration is specified as a multiple of the predicted infiltration relative to the average infiltration determined for the 2005 period.

The statistical information summarized numerically is documented in Tab. 2. In the HGRs located in the Vysoké Mýto and Ústí synclines (4231, 4232, 4270), the mean value of the change in infiltration from all models and scenarios is higher than the current infiltration. In the HGRs of the South Bohemian basins, the mean value is slightly lower (2140, 2151, 2152); for the HGRs in the Carpathian foredeep, the mean value of the change in infiltration is close to the average infiltration, but the individual models exhibit the greatest variation in values.

Table 2. Infiltration statistics calculated for individual models and scenarios.

Ratio: scenario/Infiltration 2005								
4231	**4232**	**4270**	**2140**	**2151**	**2152**	**2241**	**2242**	**HGR**
0.94	1.02	1.00	0.83	0.88	0.84	0.75	0.86	**quartile 25 %**
1.14	1.23	1.17	1.02	1.15	1.06	1.13	1.21	**quartile 75 %**
0.81	0.85	0.85	0.50	0.49	0.45	0.35	0.38	**minimum**
1.42	1.62	1.49	1.36	1.63	1.47	1.99	1.74	**maximum**
1.05	**1.14**	**1.10**	**0.93**	**1.02**	**0.95**	**0.98**	**1.03**	**average**

The results of a series of stationary model runs are presented in the form of box plots, which document the differences between predicted water levels and the current average water level for each period. The wells shown, which exhibit typical water level trends for the HGR, were selected during earlier phases of the project. The statistics for each box (period) represent the results from 26 model runs (combinations of climate models and scenarios). The blue points in the graphs represent results when groundwater recharge is specified based on the ALADIN-CLIMATE/CZ model and the SSP2-4.5 scenario; the red points highlight the differences in water levels calculated using the ALADIN-CLIMATE/CZ model and the SSP5-8.5 scenario.

The South Bohemian basins constitute a significant hydrogeological structure from which approximately 300 l/s of groundwater is abstracted, supplying water to up to 130,000 population equivalents. For the year 2030, the median water level for all calculated variants is above the current level (Fig. 2) for HGR 2160, 2151, and 2152; for HGR 2140, the water levels are at a similar level. For the more distant periods (2070 and 2085), there is a more significant variation in the resulting levels. With the exception of the 2030 period and the SSP2-4.5 scenario, the levels calculated based on input data from the ALADIN-CLIMATE/CZ model are above the current level. They represent maximum values, particularly for the 2070 period.

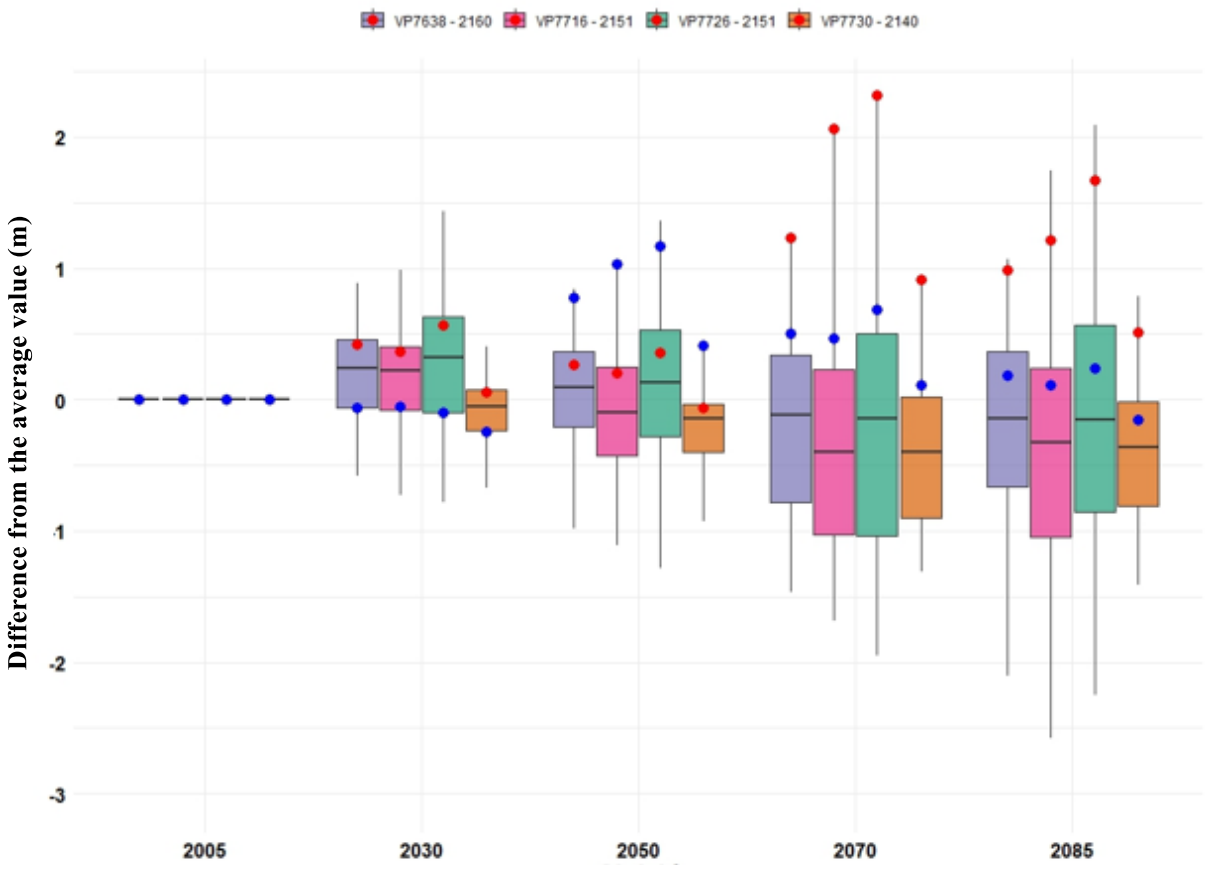


Fig. 2. Changes in water levels during forecast periods – HGR in the South Bohemian Basins.

Fig. 3 shows a box plot for selected wells illustrating the evolution of water levels calculated for individual scenarios and time periods, as well as for various climate models. Predicted groundwater levels based on groundwater recharge determined by the ALADIN-CLIMATE/CZ model have a median (and mean – the cross in the box plot) above the current level in all HGRs and predict an increase in groundwater levels. Most of the results predicting a decline in groundwater levels are based on recharge calculated using the cmcc-esm2 model.

For other simulated areas, the comparison of results for individual models is similar: the ALADIN model yields the wettest results, while the cmcc-esm2 model yields the driest.

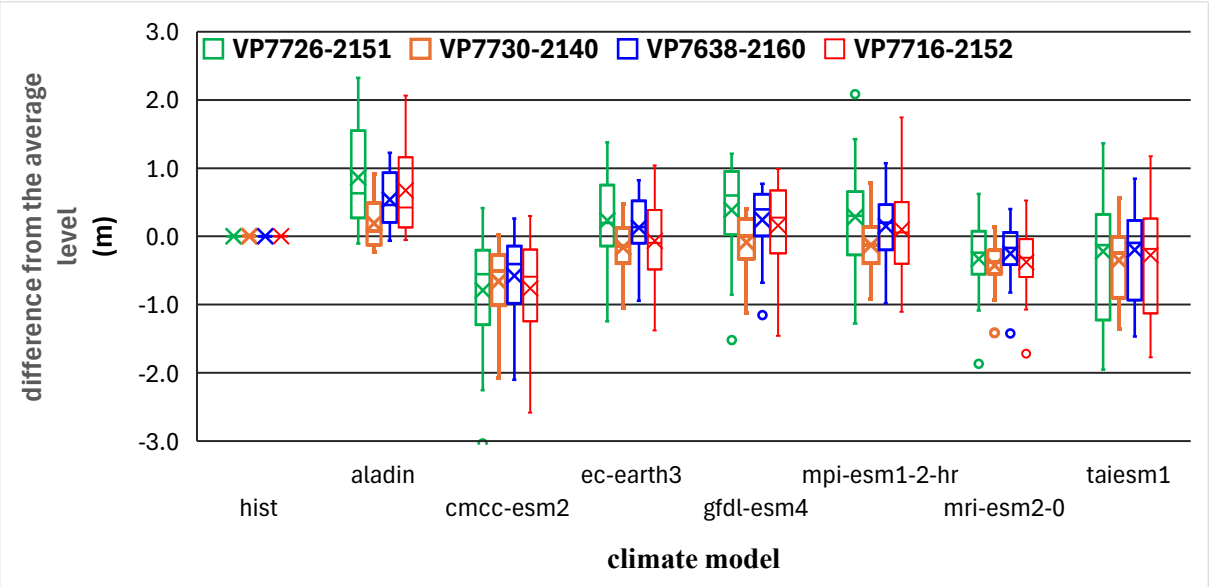


Fig. 3. Changes in water levels during the forecast periods, individual climate models – HGR in the South Bohemian basins.

Fig. 4 illustrates the difference between the water levels in selected wells in the HGR in the Carpathian foredeep and the average groundwater level (shown in the 2005 column of the graph). The Aladin model predicts a rise in groundwater levels in all periods when using both scenarios. In the 2070 and 2085 periods, there is a more significant difference in the results calculated for the individual models. In borehole VB0267, representing HGR 2242, there is a slight rise in water levels in all periods (the mean value of all results). In HGR 2241, the mean value is below the average water level.

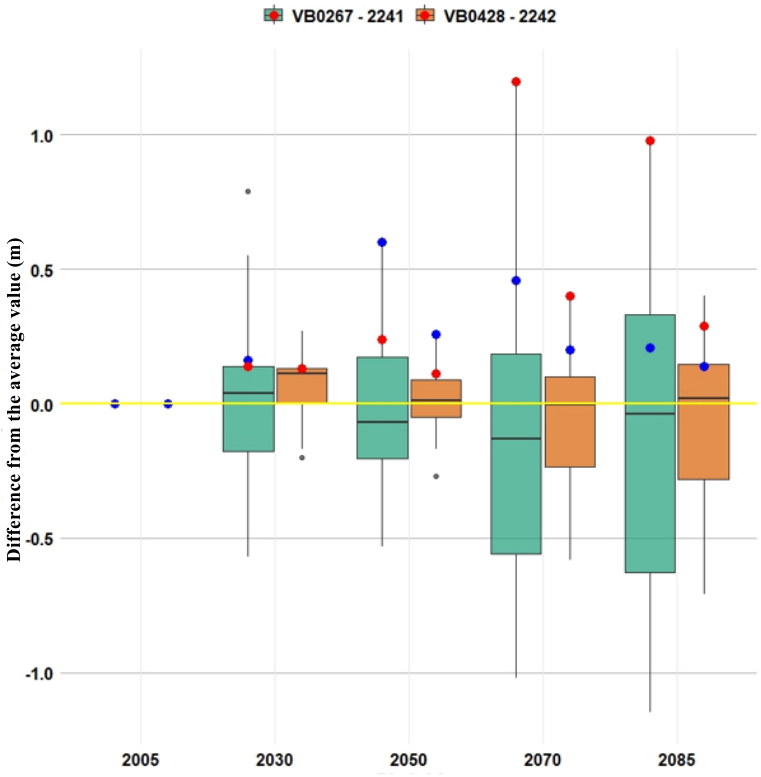


Fig. 4. Changes in water levels during forecast periods – HGR in the Carpathian foredeep.

Fig. 5 illustrates the difference in water levels at selected wells in the HGR area of the right-bank tributaries of the Elbe. The Aladin model predicts an increase in groundwater levels in all periods and

areas under both scenarios. In the 2070 and 2085 periods, there is a more significant difference in the results calculated for the individual models. For all periods, more than half of the calculated levels (by individual models and scenarios) in the evaluated wells are above the current average level (with the exception of two wells in the 2070 period).

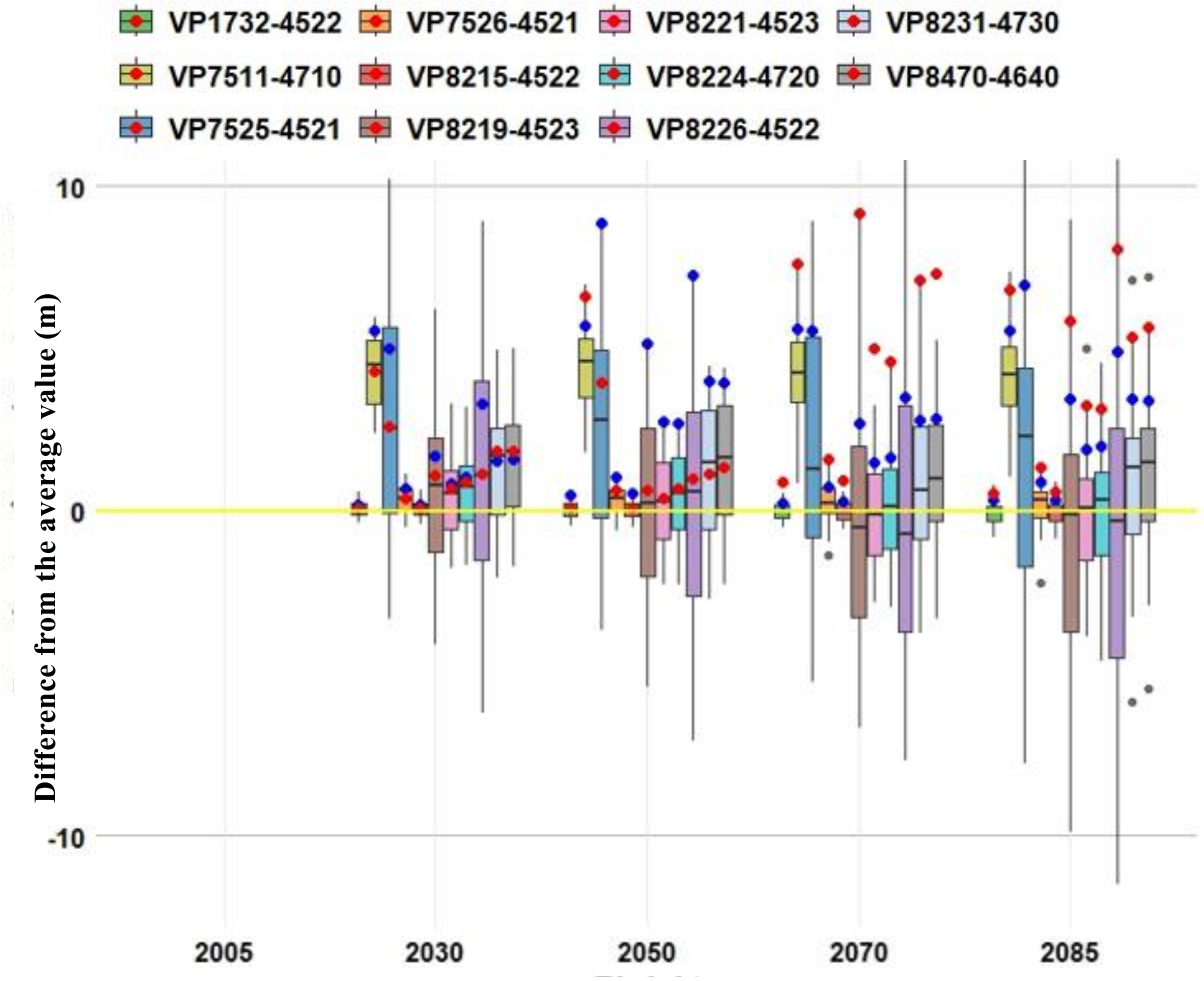


Fig. 5. Changes in water levels during forecast periods – HGR in Elbe river region.

Fig. 6 shows the difference between the water levels in selected wells in the HGR within the Vysoké Mýto and Ústí synclines and the average groundwater level (shown in the 2005 column of the graph). The Aladin model predicts a rise in groundwater levels in all periods under both scenarios. In the periods 2070 and 2085, there is a more significant difference in the results calculated for the individual models.

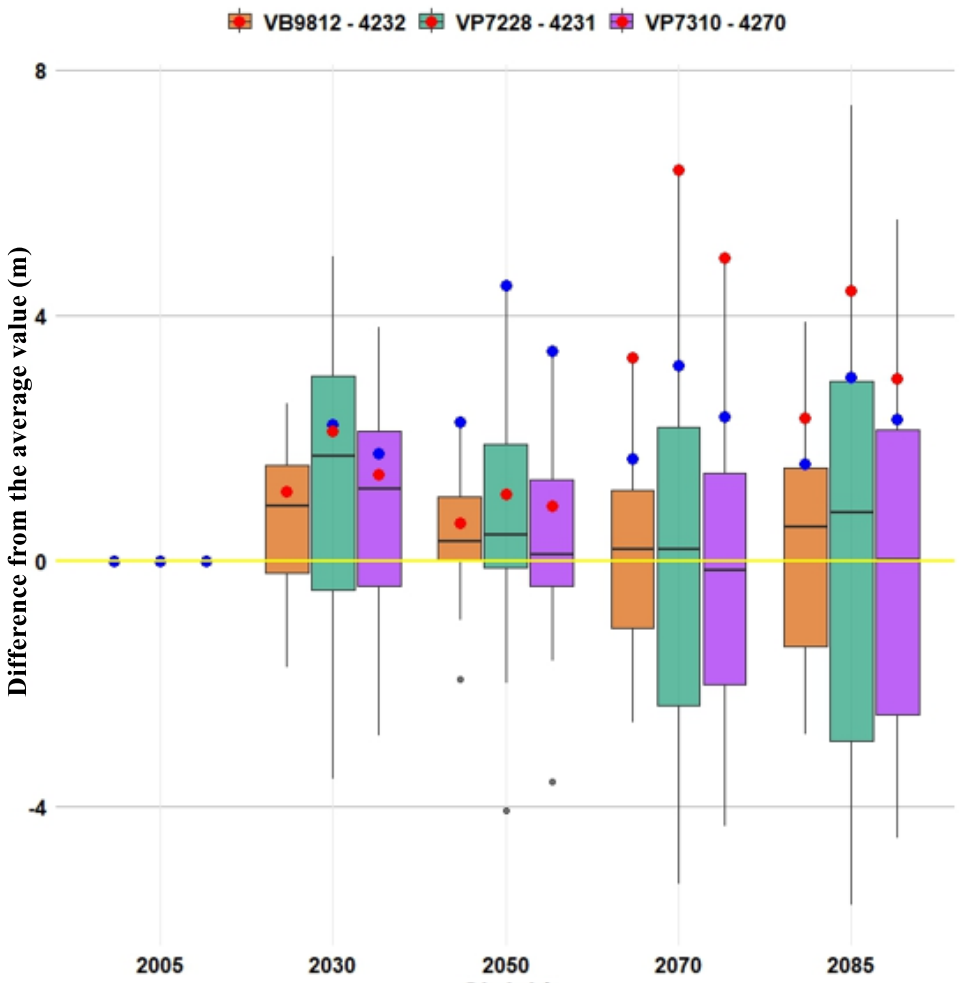


Fig. 6. Changes in water levels during forecast periods – HGR in Vysoké Mýto and Ústí synclines.

Box plots document the predicted changes in water levels in individual wells. The Tab. 3 shows the percentage of all wells in the evaluated areas where an increase in groundwater levels is predicted. The calculation includes results from all models and scenarios. For example, in the South Bohemian basins, 112 wells are compared; for each well, the results of 26 variants of model calculations are compared, which differ according to the climate model and scenario. A total of 2 912 comparisons are performed in the JP, and for the year 2030, for example, a rise in groundwater levels is predicted in 1 543 cases (53%). For two model regions, a decline in groundwater levels is predicted based on a comparison of all model variants; for two others, a rise is predicted, with a significant increase in the area of the right-bank tributaries of the Elbe.

Table 3. Number of wells where an increase in groundwater level is predicted.

	Period/percentage of rising levels				**Average for all periods and calculations**
Area	2030	2050	2070	2085	%
The Vysoké Mýto and Ústí Syncline	71	53	46	48	55
Right-bank tributaries of the Elbe	80	72	67	69	72
The Tertiary of the Carpathian Foredeep	79	36	38	42	49
South Bohemian Basins	53	44	34	37	42

Discussion

Predictive simulations of transient groundwater flow for the year 2030 were carried out, using input data from the ALADIN-CLIMATE/CZ climate model and the SSP2-4.5 emissions scenario. In most HGRs, the prediction indicated an increase in groundwater recharge. With a predicted unit increase in precipitation, there was a several-percent increase in groundwater recharge and a predicted rise in groundwater levels (and reserves), which contradicts observations.

For most HGRs, the projected increase in groundwater recharge during the forecast periods is inconsistent with observed trends in groundwater levels and reserves. Measured data from recent decades show:

- A temperature increase of 2–3 °C over 60 years (1961–2020),
- A decrease in surface runoff in the river network, or a decrease in baseflow,
- A decline in groundwater levels (e.g., for wells in the JP, according to the Mann-Kendall test, a statistically significant trend in water level changes was detected in 64 out of 110 wells; 51 showed a downward trend).
- Decline in groundwater levels below the specified minimum levels for permitted groundwater abstractions (e.g., in HGR 2151), decline in minimum flows below the specified minimum flows (e.g., HGR 4522).

The input data for the predictive simulations are compared with data from the period 1960 to 2022 (or with shorter periods within that timeframe). It cannot be ruled out that the trends in hydrological and hydrogeological variables were also influenced by climate change during this period. The question is why the trends in groundwater recharge (and precipitation) determined by a large portion of the forecast models (particularly the Aladin model) differ from the observed trends in the past period.

It was unclear whether the predicted increase in groundwater recharge was based primarily on data calculated by climate models (Institute of Global Change Research, Czech Academy of Sciences, v. v. i.) or on the results of the hydrological model (implemented at VUV v.v.i.). In 2025, the hydrological model calculation was updated, and new input data on groundwater recharge trends were provided. Despite the change in the hydrological model calculation, an increase in groundwater recharge is still projected (particularly for variants calculated using the ALADIN-CLIMATE/CZ model). In 2025, simulated predictions of groundwater level and storage trends were calculated for a set of climate models and emission scenarios.

Simulations of steady-state groundwater flow confirmed the prediction of increased groundwater recharge when using data from the ALADIN-CLIMATE/CZ climate model (for all scenarios). The most significant increase in groundwater levels is predicted by the ALADIN-CLIMATE/CZ model; among the climate scenarios, the highest levels are projected in simulations based on SSP5-8.5 and SSP1-2.6. The most significant decline is projected in virtually all evaluated HGRs when using results from the cmcc-esm2 model. When using the SSP3-7.0 scenario, most models predict the largest declines in levels. When using the SSP5-8.5 scenario, the model results show the greatest variation. Similarly, the variation in predicted groundwater levels increases with periods further in the future.

Conclusion

The predictive models developed within the PERUN project generally indicate an increase in groundwater recharge, groundwater storage, and groundwater levels in the future. However, these results are somewhat inconsistent with observed trends and therefore require further expert verification and interpretation.

Trends in groundwater levels, potential pumping volumes in major recharge areas, and runoff from the assessed areas suggest a trend consistent with a combination of climate models and scenarios predicting a long-term decline in groundwater recharge (or their use in calculating recharge).

An important part of the work in 2026 is selecting an appropriate format for presenting the model results – particularly for water utilities that operate major catchment areas and supply water to hundreds of thousands of residents.

One of the key strengths of the PERUN project is the close interdisciplinary collaboration among the participating institutions, which enables continuous evaluation and refinement of results throughout the entire modelling chain. Climate scenarios developed by the Global Change Research Institute (CzechGlobe) are based on meteorological data and projections provided by the Czech Hydrometeorological Institute (CHMI). These outputs are subsequently used by the T. G. Masaryk Water Research Institute to drive hydrological models, while the resulting hydrological projections serve as inputs for groundwater prediction models developed by PROGEO Ltd. The project has demonstrated that even when outputs from a particular modelling step appear reasonable and consistent with the selected climate scenario, their propagation through subsequent models may reveal inconsistencies or unrealistic responses. For example, a projected increase in temperature may produce plausible climate model outputs, but when applied within hydrological models it may lead to implausible changes in streamflow, which can be further amplified in groundwater projections. Such findings provide valuable feedback to the entire modelling chain and often require revisiting earlier modelling stages. Through this iterative process, assumptions and model parameters are continuously refined, resulting in climate, hydrological, and groundwater projections that are more robust and better aligned with observed trends from recent decades.

Acknowledgments

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