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RechAUT - Variability of Groundwater Recharge and its Implication for Sustainable Land Use in Austria

Final report

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Abstract

Water in the vadose zone is an essential part of the global water cycle making up some of the largest freshwater resources on Earth. Climate as well as land use change are known to alter water fluxes in the vadose zone, and thus changes in groundwater recharge rates. Despite the fact that any change of groundwater recharge would have dramatic impacts on the availability of water, and hence, severe economic and ecological consequences, we know little about past and future groundwater recharge rates for Austria. Therefore, the objective of this study was to quantify and predict groundwater recharge rates, their variability and uncertainties and the potential impacts for land use and water management in Austria.

Soil water fluxes at 14 Austrian monitoring sites were influenced by the East-West gradient in altitude and climatic conditions at the local and regional scale. At the dry and warm eastern locations, recharge rates were low (< 250 mm a^{-1}) and seasonality was high since near zero recharge was estimated for the summer months. At the western and central Austrian locations, the fraction of recharge from precipitation and absolute recharge estimates were high (~ 450 - 1320 mm a^{-1}) and temporal variation in recharge and actual evapotranspiration was influenced by snow accumulation and snow melt. For predicting future recharge rates at the local scale, uncertainties were mainly related to the differences in climate projections. Model results for groundwater recharge rates according to the selected climate projections indicated increasing groundwater recharge rates at locations in the East of Austria, whereas predictions were ambivalent at locations in central and western Austria. For these sites, one scenario predicted a decrease in annual recharge rates of up to 20% in the far future (2071-2100) as compared to the past (1991-2020).

For the nationwide analysis, spatial information on soil hydraulic properties were derived by combining soil data from different sources. Two methods based on machine learning approaches were tested to directly and indirectly estimate saturated hydraulic conductivity (K_s). While the resulting soil property maps of the indirect approach were able to largely reproduce the original data variability, the prediction of K_s includes high levels of uncertainties and the predicted vertical distribution of K_s is not plausible. The spatial distribution of K_s in the direct approach resembles available global maps. In the existing global K_s maps as well as in the results of the direct approach the small-scale variability of K_s is reduced.

The integrated modelling framework for the Seewinkel region showed that vineyards are the dominant land use, regardless of the climate scenario if there are no restrictions on groundwater extraction for irrigation. Irrigation water use and regional net benefits of agricultural production continuously decrease with more restrictive policies on groundwater extraction for irrigation, with largest decreases under a dry and smallest decreases under a wet climate scenario, whereby cropland and other (abandoned) land gain in importance. If groundwater extraction for irrigation is restricted, high flexibility in land use is required to efficiently adapt land use and management to the climate scenarios. Further a Bayesian Network was developed for the Seewinkel region that can be used for reasoning and analysis of the design of groundwater policies and for giving information on the influence of irrigation water availability on agricultural productivity and farmers' income. This integrated modelling framework was also applied to Upper Austria for testing efficient agricultural adaptation to three precipitation scenarios with declining precipitation sums and more frequent dry spells as well as to groundwater use scenarios, limiting irrigated agricultural land.

Kurzfassung

Das Wasser in der vadosen Zone ist ein wesentlicher Bestandteil des globalen Wasserkreislaufs und stellt eine der größten Süßwasserressourcen der Erde dar. Klima- und Landnutzungsänderungen wirken sich auf Wasserflüsse in der vadosen Zone und damit auf die Grundwasserneubildungsraten aus. Obwohl Veränderungen der Grundwasserneubildung Auswirkungen auf die Wasserverfügbarkeit und damit wirtschaftliche und ökologische Folgen hätten, wissen wir nur wenig über vergangene und zukünftige Grundwasserneubildungsraten in Österreich. Ziel dieser Studie war es, die Grundwasserneubildungsraten, ihre Variabilität und Unsicherheiten sowie die potenziellen Auswirkungen auf die Landnutzung und Wasserwirtschaft in Österreich zu quantifizieren und vorherzusagen.

Die Größe der Bodenwasserflüsse an 14 österreichischen Messstellen wurden durch einen Ost-West-Gradienten aufgrund klimatischer Bedingungen auf lokaler und regionaler Ebene beeinflusst. An den trockenen und warmen östlichen Standorten waren die Neubildungsraten niedrig (< 250 mm a^{-1}) und die Saisonalität war hoch, da in den Sommermonaten kaum Neubildung stattfand. An den westlichen und zentralen Standorten Österreichs waren Neubildungsraten hoch (∼ 450 - 1320 mm a^{-1}), und die zeitliche Variation der Neubildung und der tatsächlichen Evapotranspiration wurde durch Schneeakkumulation und Schneeschmelze beeinflusst. Bei der Vorhersage zukünftiger Grundwasserneubildungsraten auf lokaler Ebene waren Unsicherheiten auf die Unterschiede in den Klimaprojektionen zurückzuführen. Die Modellergebnisse für die Grundwasserneubildungsraten gemäß den ausgewählten Klimaprojektionen deuten auf steigende Raten an Standorten im Osten Österreichs hin, während die Vorhersagen an Standorten in Zentral- und Westösterreich uneindeutig sind. Für diese Standorte wurde in einem Szenario ein Rückgang der jährlichen Grundwasserneubildungsrate um bis zu 20 % in der fernen Zukunft (2071-2100) im Vergleich zur Vergangenheit (1991-2020) vorhergesagt.

Für die landesweite Analyse wurden räumliche Informationen über die hydraulischen Eigenschaften des Bodens durch die Kombination von Bodendaten aus verschiedenen Quellen abgeleitet. Es wurden zwei auf maschinellem Lernen basierende Methoden zur direkten und indirekten Schätzung der gesättigten hydraulischen Leitfähigkeit (K_s) getestet. Während die resultierenden Bodeneigenschaftskarten des indirekten Ansatzes in der Lage waren, die Variabilität der ursprünglichen Daten weitgehend zu reproduzieren, ist die Vorhersage von K_s mit großen Unsicherheiten behaftet und die vorhergesagte vertikale Verteilung von K_s ist nicht plausibel. Die räumliche Verteilung von K_s im direkten Ansatz ähnelt den verfügbaren globalen Karten. Sowohl in den vorhandenen globalen K_s-Karten als auch in den Ergebnissen des direkten Ansatzes ist die kleinräumige Variabilität von K_s reduziert.

Der integrierte Modellierungsansatz für die Region Seewinkel zeigte, dass Weinbau unabhängig vom Klimaszenario die vorherrschende Flächennutzung ist, wenn es keine Beschränkungen für die Grundwasserentnahme zur Bewässerung gibt. Die Bewässerungswassernutzung und der regionale Nettonutzen der landwirtschaftlichen Produktion nehmen mit restriktiveren Maßnahmen zur Grundwasserentnahme für die Bewässerung kontinuierlich ab, wobei die größten Rückgänge bei einem trockenen und die geringsten bei einem feuchten Klimaszenario zu verzeichnen sind, wobei Ackerland und andere (aufgegebene) Flächen an Bedeutung gewinnen. Wenn die Grundwasserentnahme für die Bewässerung eingeschränkt wird, ist eine hohe Flexibilität bei der Landnutzung erforderlich, um die Landnutzung und -bewirtschaftung effizient an die Klimaszenarien anzupassen. Es wurde ein Bayes'sches

Analyse für die Region Seewinkel entwickelt, die für die Argumentation und Analyse der Gestaltung von Grundwasserrichtlinien und für Informationen über den Einfluss der Verfügbarkeit von Bewässerungswasser auf die landwirtschaftliche Produktivität und das Einkommen der Landwirte verwendet werden kann. Dieser integrierte Modellierungsansatz wurde auch auf Oberösterreich angewandt, um die effiziente Anpassung der Landwirtschaft an drei Niederschlagsszenarien mit abnehmenden Niederschlagssummen und häufigeren Trockenperioden sowie an Grundwassernutzungsszenarien zu testen, die die bewässerte landwirtschaftliche Fläche einschränken.

Introduction

Water resources are the natural foundations of life and essential for agricultural production and drinking water supply. Safeguarding these global water resources, particularly in the context of global change, the United Nations agreed to the Sustainable Development Goal 6 with the aim to have access to safe water, to ensure its availability and to sustainably manage water resources – a goal which is critical to the health of humans and ecosystems. In the last two decades, the main focus in protecting water has been on the sustainable use of surface water and groundwater resources. For example, the European Union has set a time frame for water quality improvements, i.e. achieving a good chemical and ecological status of groundwater and surface water bodies as outlined in the Groundwater Directive and the Water Framework Directive. However, an essential part of the global water cycle has received little attention, but it makes up some of the largest freshwater resources on Earth: water in the vadose zone. Soil water fluxes and particular the amount of groundwater recharge (GWR) and how it changes over space and in time in Austria remains to be investigated. Therefore, this project tackles one of the most challenging problems with water availability: prediction of the variability and associated uncertainties of groundwater recharge and its implication for sustainable water and land use.

Objectives

The aim of this project was to quantify and predict groundwater recharge rates, their variability and uncertainties and the potential impacts for land use and water management in Austria. To address this aim the project

- made use of the existing long-term monitoring infrastructure with soil water monitoring data for up to 20 years at 14 locations in Austria,
- developed and applied new calibration and validation procedures for the estimation of soil hydraulic properties as well as evapotranspiration and groundwater recharge rates and associated uncertainties at the local scales for the past and the future,
- upscaled local information on soil hydraulic properties to the regional scale and simulated groundwater recharge rates using an hydrological model for Austria
- assessed the implications of climate and socio-economic drivers on water availability, land use and crop production using an integrated bio-physical, economic modelling approaches and analysing the model uncertainties.

The project aims were achieved in five different working packages, and the outcomes of the study are: (i) a set of scientifically based mathematical models on different scales for simulation and prediction of water fluxes and soil water balance in Austria, (ii) figures and maps giving information on groundwater recharge rates including their uncertainties for current and future climate conditions, and (iii) integrated land-water management guidelines for specific regions in Austria to provide policy advice on sustainable utilization and management of soil water resources for specific regions in Austria in the context of global change.

Results - Work Package 1

Coordination, integration and dissemination

The aim of workpackage 1 was to coordinate the project, ensure the communication as well as exchange of results between project partners, integrate the outcome of the project individual results, and disseminate results in close cooperation with other WPs.
Annual meetings were held to report the progress of the individual work packages and to create synergies between those. For stakeholder involvement and project dissemination three RechAUT specific workshops and two "Grundwasser-Cluster" workshops were organized (details see chapter *Dissemination*); the final "Grundwasser-Cluster" workshop was held in Vienna and organized by the RechAUT team.
Results of the project were presented at the ÖAW mid- and end-term workshops, at several national and international conferences, and in invited talks. Seven research articles were already published in peer-reviewed journals; three in non-peer reviewed journals. Four more manuscript are currently prepared for publication in peer-reviewed journals. Details are given in the Chapter *Dissemination*.

Results - Work Package 2

Data collection and soil water monitoring

The main aim of this work package was to collect available data on soil hydrological and soil physical data and provide these data as basis for computations in the other work packages. This included a literature research on available, published data and the observations at the 14 stations of the "Hydrographie-Monitoring-Netzwerk" of the unsaturated zone in Austria.
Available soil information for Austria were considered from different sources including the eBOD (a polygon soil texture map based on 31806 samples and 11713 soil profiles of the BfW (Bundesforschungszentrum für Wald)), the BZI (Bundeszustandsinventur with 13352 samples, 5067 profiles) and the BAW-IKT (Bundesamt für Wasserwirtschaft - Institut für Kulturtechnik und Bodenwasserhaushalt) and further used in WP 4 for deriving spatially distributed fields of soil hydraulic properties for Austria-wide hydrological modelling (Zeitfogel et al. 2022, 2023).
For the 14 monitoring stations, the raw data of the water content and matric potentials were quality controlled, sorted and additional information on soil types and meteorological data were collected from literature and Geosphere Austria (Figure 2.1). The data were further used to calibrate soil hydrological models including uncertainty analysis and to assess the local soil water fluxes of the past (Schübl et al. 2023) and the future (Schübl et al., to be submitted) within WP3.

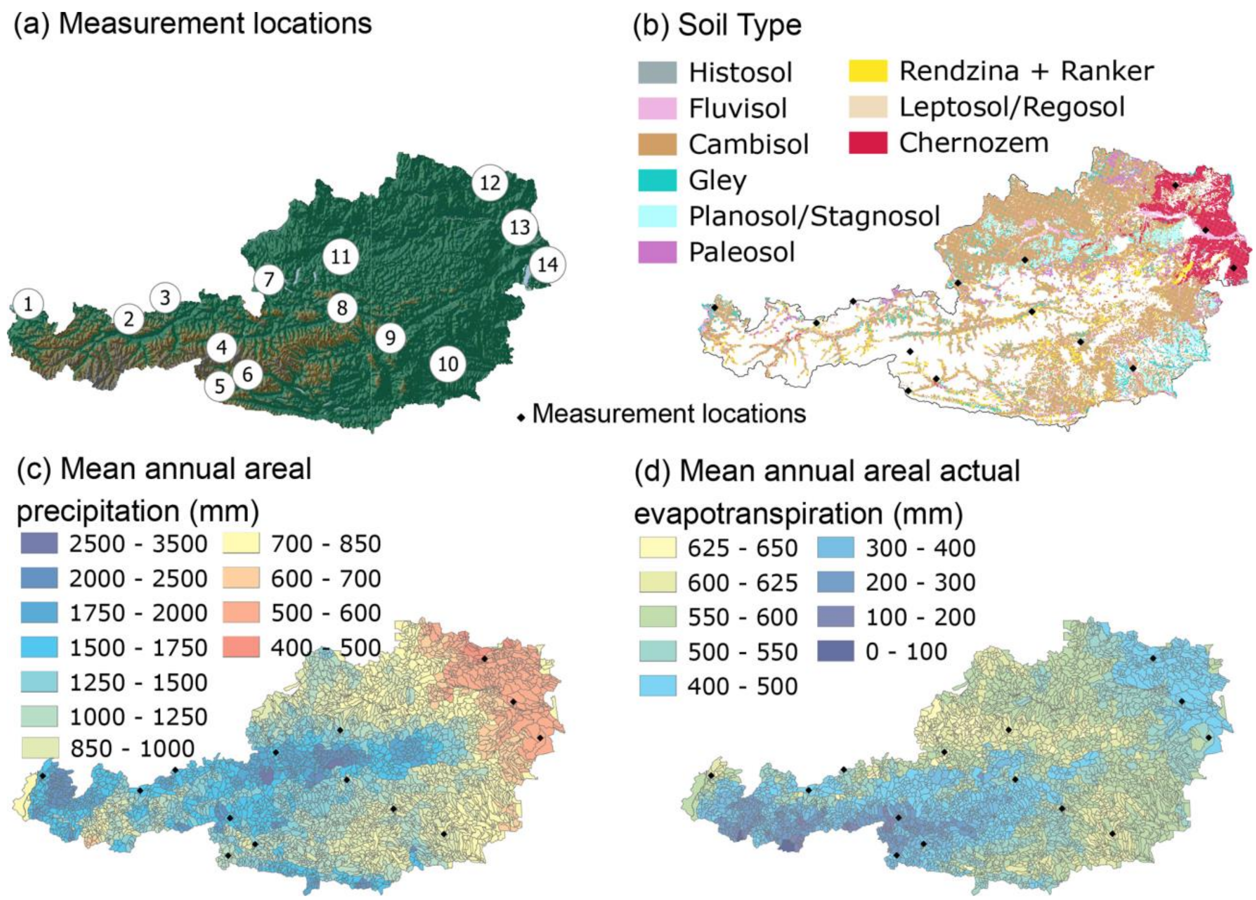

Figure 2.1: Panel (a) outlines the locations of the following 14 monitoring sites in Austria: (1) Lauterach, (2) Leutasch, (3) Achenkirch, (4) Gschlössboden, (5) Sillianberger Alm, (6) Zettersfeld, (7) Elsbethen, (8) Gumpenstein, (9) Aichfeld-Murboden, (10) Kalsdorf, (11) Pettenbach, (12) Schalladorf, (13) Lobau, and (14) Frauenkirchen. Panel (b) provides the soil map data basis: digital oil map of Austria, 1 km raster, Federal Forest Research Center (BFW, 2016). Panel (c) shows the Hydrological Atlas of Austria (HAO) mean areal annual precipitation (Kling et al., 2007b), and panel (d) shows the HAO mean areal annual actual evapotranspiration (Kling et al., 2007a); maps from the HAO where compiled using QGIS (QGIS Development Team, 2022); source: Schübl et al. (2023).

Results - Work Package 3

Groundwater recharge estimation and uncertainty analysis at the plot scale

The main aim of this WP was: i) to provide a rigorous statistical basis for providing guidance on measurements required for soil water flux analysis, ii) to obtain an accurate numerical description, including an integrated Bayesian model calibration framework, of the unsaturated flow in the vadose zone and a reliable estimation of the groundwater recharge fluxes at the 14 monitoring sites, iii) to use this modelling framework to predict future soil water fluxes and their uncertainties considering different climate change scenarios.

i) A Bayesian Perspective on the Information Content of Soil Water Measurements for the Hydrological Characterization of the Vadose Zone

The estimation of groundwater recharge is generally challenging, as direct measurements are hardly possible. Alternatively, transient measurements from soil water monitoring installments can be coupled with Richards-based solvers to inversely estimate soil hydraulic parameters (SHP) and numerically describe vadose zone water fluxes, such as groundwater recharge. In order to reduce model predictive uncertainty, the experimental setup should be designed to maximize the information content of observations. We therefore used a Bayesian approach to evaluate which observation types are most effective in reducing uncertainties in the estimation of SHPs and consequently groundwater recharge for a range of hydrological conditions including different soil textures and climates (Schübl et al., 2022).

We found that the most sensitive parameters for estimating cumulative recharge were the van Genuchten model shape parameters n and α; for estimating peaks in recharge fluxes (in a humid climate), it was the saturated hydraulic conductivity Ks and the saturated water content θ_s. We found that the combination of seepage flow, soil water content, and soil matric potential measurements leads to highly informative designs especially for fine textured soils, while results from coarse soils are generally affected by higher uncertainty. In general, matric potential proved to be a more informative variable than soil water content; it was most effectively combined with seepage measurements for sandy soils and with soil water content observations for fine textures in dry climate. The results of this study can help to prioritize measurement types for soil water monitoring installments for the estimation of SHPs and groundwater recharge for different climates (Figure 3.1).

	Climate					
	Humid			**Dry**		
	Soil texture			**Soil texture**		
	Coarse (Sand) → Fine (Silt)			Coarse (Sand) → Fine (Silt)		
n	**Recommended measurements**			**Recommended measurements**		
1	Q*	Q/MP	Q	**Q***	MP	MP
2	**Q+MP***	**Q+MP**	**MP+SWC**	Q+MP	**Q+MP**	**MP+SWC**
	Effect of 3rd observation type			Effect of 3rd observation type		
3	+/-	+	+	+/-	+/-	--
	*higher temporal resolution recommended (> daily)					

Figure 3.1: Guideline for the most efficient choice of soil water measurements for constraining model uncertainties, depending on soil type and climate (Q: lysimeter outflow; SWC: soil water content in two depths, MP: matric potential in two depths). Here, n = 1 shows the prioritization for one single observation type. The recommended combination of two observation types (n = 2) was more effective in all cases except for sand in dry conditions. The addition of the third observation type was either beneficial (+), had a minor effect (+/-), or - in the case of Silt loam and Silt in the dry scenario - had a negative effect (–); source: Schübl et al. (2022).

ii) Estimating vadose zone water fluxes from soil water monitoring data: a comprehensive field study in Austria

We applied a Bayesian probabilistic framework in combination with a physically-based soil water model to make use of long-term measurements of volumetric soil water content at 14 sites in Austria in order to estimate local soil water balances, derive groundwater recharge rates, and simultaneously evaluate the associated uncertainties. We further investigated factors which influenced groundwater recharge rates and uncertainties to provide a comprehensive analysis of the unsaturated zone at the monitoring sites.

The estimation of Soil Hydraulic Parameters (SHPs) resulted in good fits to the measured soil water content and acceptable fits to local lysimeter seepage measurements. The estimated long-term averages in recharge ranged from 44 mm a^{-1} in the dry East to 1578 mm a^{-1} in the West (Table 3.1). Recharge rates were plausible when compared to literature values where available, as were estimated long-term actual evapotranspiration rates when compared to the values of the Hydrological Atlas of Austria (HAO) (Kling et al., 2007). The parameter estimation based on soil water content measurements was partly subject to considerable uncertainties; they were high in the residual water content (θ_r) and soil hydraulic conductivity (K_s) parameters, and moderate to low for shape parameters of the soil water retention curves α and n as well as the saturated water content parameters (θ_s) where the uncertainty range was usually smaller than 0.5 times the value of the median estimate. Uncertainty ranges of θ_r were between 0.002 - 0.2 cm^3 cm^{-3} (the latter corresponding to the entire prior range); uncertainty ranges of K_s ranged from 2 cm day^{-1} to 3813 cm day^{-1}, in one case 26 times the value of the median estimate. Higher uncertainties in shape parameters and the saturated hydraulic conductivity parameter were linked with coarser soil textures and resulted in higher uncertainties in recharge peak predictions. The absolute uncertainty in recharge sums derived from SHP uncertainty ranged between 5-47 mm a^{-1}; the relative uncertainty (IQR/median) was 1% at sites with high absolute rates in a wet climate, and 39% with low absolute potential recharge rates in a dry climate.

Table 3.1: Local long-term average water balances at 14 sites, showing precipitation (P), potential evapotranspiration (ETp), and the simulated potential groundwater recharge (GWR) and actual evapotranspiration (ETa) with the 95% credible interval from propagated parameter uncertainty. Source: Schübl et al. (2023).

	Period ($mm\,a^{-1}$)	P ($mm\,a^{-1}$)	ET_p ($mm\,a^{-1}$)	GWR ($mm\,a^{-1}$)	ET_a (%)	GWR/P
Lauterach	1996–2018	1578	700	907^{+4}_{-4}	672^{+3}_{-4}	57^{+1}_{-0} %
Leutasch	2008–2018	1235	622	665^{+9}_{-7}	521^{+7}_{-10}	54^{+2}_{-1} %
Achenkirch	2017–2018	1533	673	1022^{+14}_{-16}	480^{+14}_{-14}	67^{+1}_{-1} %
Gschlössboden	2012–2018	1493	552	1319^{+7}_{-9}	170^{+2}_{-6}	88^{+0}_{-1} %
Sillianberger Alm	1997–2018	1023	707	578^{+13}_{-12}	439^{+10}_{-13}	57^{+1}_{-1} %
Zettersfeld	2012–2018	1353	634	926^{+15}_{-10}	399^{+10}_{-15}	68^{+1}_{-1}\%·
Elsbethen	1996–2018	1468	665	853^{+10}_{-6}	614^{+6}_{-10}	58^{+1}_{-0} %
Gumpenstein	1996–2018	1100	661	641^{+8}_{-11}	448^{+11}_{-8}	58^{+1}_{-1} %
Aichfeld-Murboden	1996–2018	813	728	244^{+3}_{-2}	557^{+2}_{-3}	30^{+0}_{-0} %
Kalsdorf	1996–2018	852	801	229^{+23}_{-24}	623^{+19}_{-31}	27^{+3}_{-3} %
Pettenbach	1996–2018	1031	789	459^{+18}_{-19}	558^{+20}_{-20}	45^{+2}_{-2} %
Schalladorf	1996–2018	484	893	45^{+7}_{-7}	431^{+6}_{-7}	9^{+1}_{-1} %
Lobau	1996–2018	570	913	44^{+8}_{-9}	520^{+9}_{-8}	8^{+1}_{-2} %
Frauenkirchen	2005–2018	601	882	92^{+15}_{-9}	526^{+10}_{-16}	15^{+2}_{-1} %

Estimated potential groundwater recharge rates at the Austrian soil water monitoring sites were influenced by the East-West gradient in altitude and climatic conditions: the dry continental climate at the eastern locations was associated with low fractions of potential groundwater recharge from precipitation and high seasonality in potential recharge rates. In contrast, the wet and snow influenced climate at western and central Austrian sites came with high potential recharge rates and lower temporal variability in recharge than in the East, but with a higher seasonality in actual evapotranspiration. Sandy soil textures were associated with higher potential recharge rates and lower actual evapotranspiration. However, precipitation and potential evapotranspiration were more influential variables than soil properties on estimated potential recharge rates and their temporal variability (Figure 3.2).

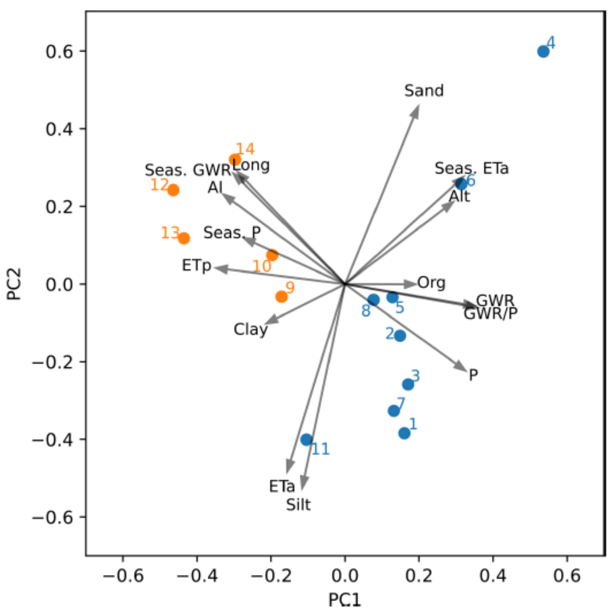

Figure 3.2: Principle component analysis biplot for which the included variables at the 14 sites are as follows: potential annual groundwater recharge (GWR); annual precipitation (P); annual potential evapotranspiration (ETp); annual actual evapotranspiration (ETa); the fraction of groundwater from precipitation (GWR=P); seasonalities (Seas.) in GWR, P, and ETa; longitude (Long); altitude (Alt); and sand, silt, clay, and organic matter (Org) percentages. Clusters of monitoring sites with similar characteristics are shown in orange (sites in Eastern Austria) and blue (sites in Western Austria). Source: Schübl et al. (2023).

iii) Effects of climate change on local groundwater recharge rates in Austria

Changes in the soil water regime caused by atmospheric warming affect recharge through the vadose zone in mountainous as well as semi-arid regions at all altitudes (Eitzinger et al., 2013). The alpine areas are especially impacted by climate change with stronger warming compared to the global average (Gobiet et al., 2014). A decline in groundwater resources in the mountainous regions of Austria would be alarming since they constitute an important source for the recharge of alluvial aquifers in the lowlands and are used for water supply of urban areas (Bauer and Plan, 2022; Plan et al., 2009). As a detailed study on the effect of climate change on groundwater recharge in Austria is still missing, we investigated how local groundwater recharge rates will evolve under the influence of climate change for a wide range of hydrological conditions, using RCP 4.5 and 8.5 emission scenarios. This helped to identify factors influencing trends in hydrologically relevant variables and annual and seasonal trends in groundwater recharge.

The past comparison of cumulative sums of precipitation and calculated reference evapotranspiration ET_0 from ÖKS15 grid cells with the corresponding INCA grid data (2012 - 2022) at the sites gave ambivalent results for precipitation and showed that ET_0 was overestimated by all projections at lower elevations. Past comparison of the four climate projections with observations from the closest SPARTACUS station data (1981 - 2020) showed that projections collectively underestimated the past increase in precipitation and temperature at several sites. Overall, MOHC4.5 and IPSL8.5 projections were closer to trends in past measurements than the two ICHEC projections. IPSL8.5 predicted a strong increase in summer precipitation (Figure 3.3), especially at lower elevations, combined with unchanging or slightly decreasing ET_0 rates. In contrast, MOHC4.5 predicted a pronounced decrease of summer precipitation, an increase in atmospheric evaporative demand and longer droughts, especially in the West and at high altitudes. Both ICHEC scenarios were between these two extremes. Consequently, potential groundwater recharge rates in the IPSL8.5 scenario increased, most notably in the East, whereas they decreased in the MOHC4.5 scenario. Both ICHEC scenarios showed comparatively little and at most sites insignificant changes in groundwater recharge over the entire projection period (1981 - 2100). The median of all future recharge predictions (2021 - 2100) for the respective sites in this study was close to the modeled past average (1981 - 2020). An exception in the present study are the sites in the very East (Schalladorf, Lobau, Frauenkirchen) where future recharge rates are increasing at the median of all projections. This trend would signify relief for the water scarcity in the East of Austria.

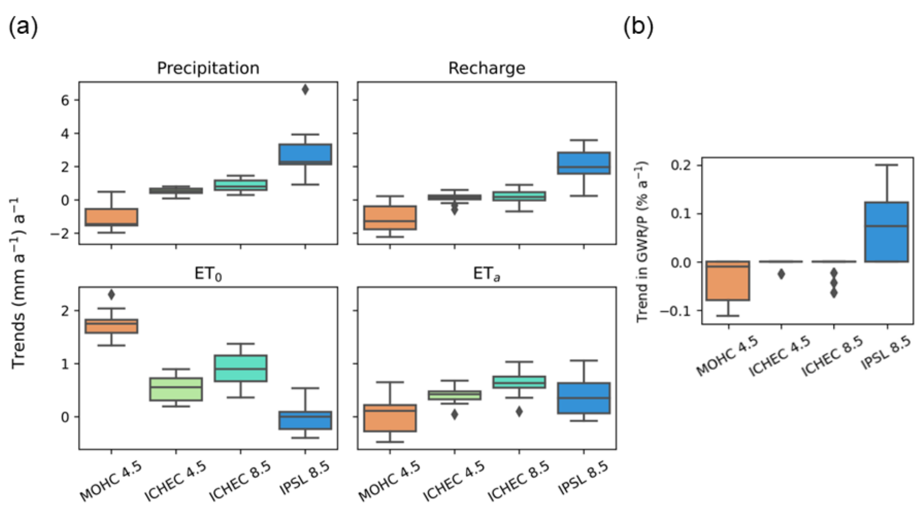

Figure 3.3: (a) Trends in precipitation, reference evapotranspiration (ET_0), modelled groundwater recharge, actual evapotranspiration, and (b) fraction of recharge from precipitation at 14 locations for the 4 climate projections. The trends in annual rates were calculated using the Mann-Kendall test for the time series of annual sums of the entire 1981-2100 simulation period as change in (mm a^{-1}) a^{-1}. Insignificant trends are shown as zero.

From the results across all projections, increasing recharge rates are to be expected during the winter months for western and central Austrian sites, followed by decreasing recharge peaks in spring (Figure 3.4). These developments were related to increased amounts of winter precipitation with a smaller fraction of snowfall. The amount and seasonal duration of groundwater recharge was reduced in the MOHC4.5 projection, however, not due to the changes in the snow regime, but due to decreasing summer precipitation resulting in longer drought periods with close to zero recharge during summer and autumn. These drought periods were predicted to last increasingly longer within the calendar year and led to a decrease by more than 20% in far future rates (2071 - 2100) compared to the past at the western and mountainous sites. This trend according to MOHC4.5 would be an alarming development, since water resources from these areas also supply dry regions in the lowlands of Austria.

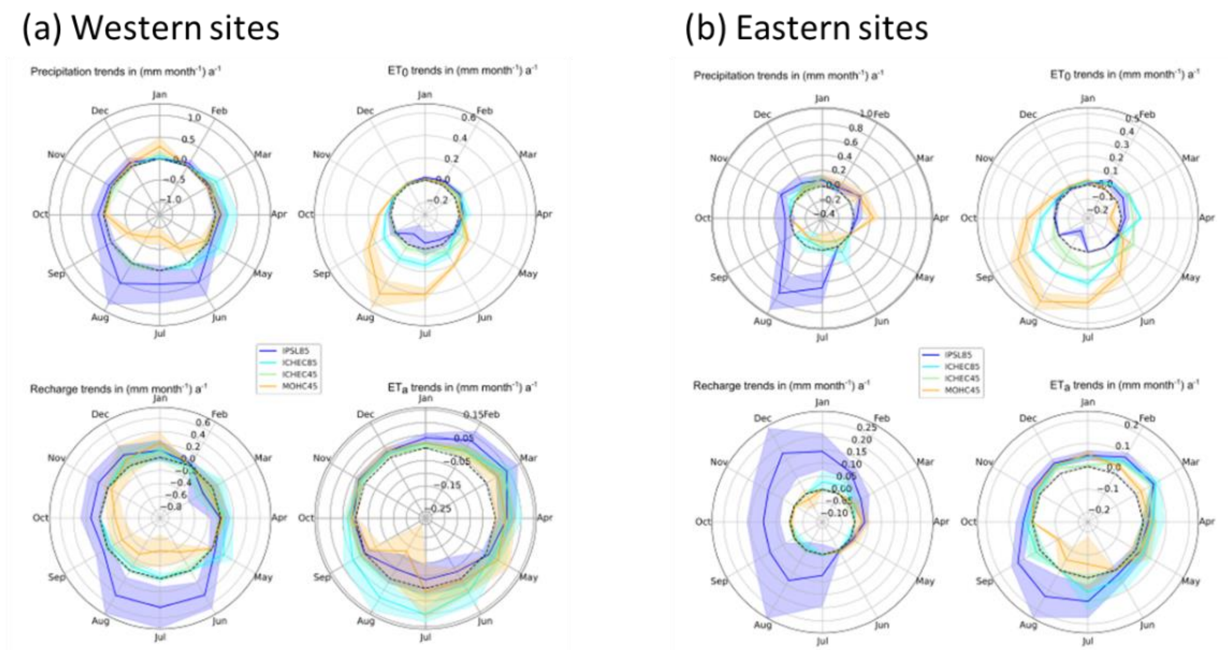

Figure 3.4: Monthly trends in precipitation, reference evapotranspiration (ET0), modelled recharge, and actual evapotranspiration rates for the (a) western sites (Lauterach, Leutasch, Achenkirch, Gschlössboden, Sillianberger Alm, Zettersfeld, Gumpenstein, Elsbethen, Aichfeld, and Pettenbach) and (b) eastern sites (Kalsdorf, Schalladorf, Lobau, and Frauenkrichen); circular plots with trends in mm month^{-1} a^{-1} on the radial and months on the polar axis. The zero line is black and dashed; inside the zero-line, negative monthly trends are shown, outside are positive trends. Solid lines show the mean and the shaded areas the standard deviation for each climate scenario for the sites.

The combined uncertainty in recharge prediction from climate scenarios and SHP uncertainty was in general high. Most of the variance in simulated future recharge predictions originated from different climate scenarios which explained > 88% of the variance in mean annual rates at the sites. The proportion of variance explained by climate scenarios was smallest at the dry, eastern sites. With dry conditions, prediction uncertainties were therefore more affected by soil hydraulic parameter uncertainties. Since the differences between climate projections were great compared to uncertainties of the soil hydrological model, it would be beneficial to use ensembles covering the entire range of expected possibilities in the future. Climate projections should be updated to the next generation of climate models. Additionally, the effects of climate change on local potential groundwater recharge rates – estimated for grass-covered sites in this study – may interact with changes in land use. Future developments in land use should therefore be considered in context with results from this study to further improve the assessment of future groundwater recharge in Austria.

Results - Work Package 4

<u>*Groundwater recharge estimation and uncertainty analysis at the regional scale*</u>

The main objectives of WP 4 were i) to provide spatial distributed fields of relevant soil hydraulic properties needed for the Austrian wide model, including their uncertainties, ii) to establish an Austrian wide hydrological model, and iii) to estimate spatially distributed GWR fields, including uncertainties for current conditions as well as for scenarios of future climate conditions.

i) Spatially distributed fields of soil hydraulic properties for Austria-wide hydrological modelling

Saturated hydraulic conductivity (K_{sat}) and other soil (hydraulic) properties are fundamental for modelling hydrological processes, such as the quantification of future groundwater recharge rates. Yet, for many areas in Austria soil information is lacking. A survey and summary of "available" soil information had been an initial step of the project. An overview is given in Fig. 4.1.

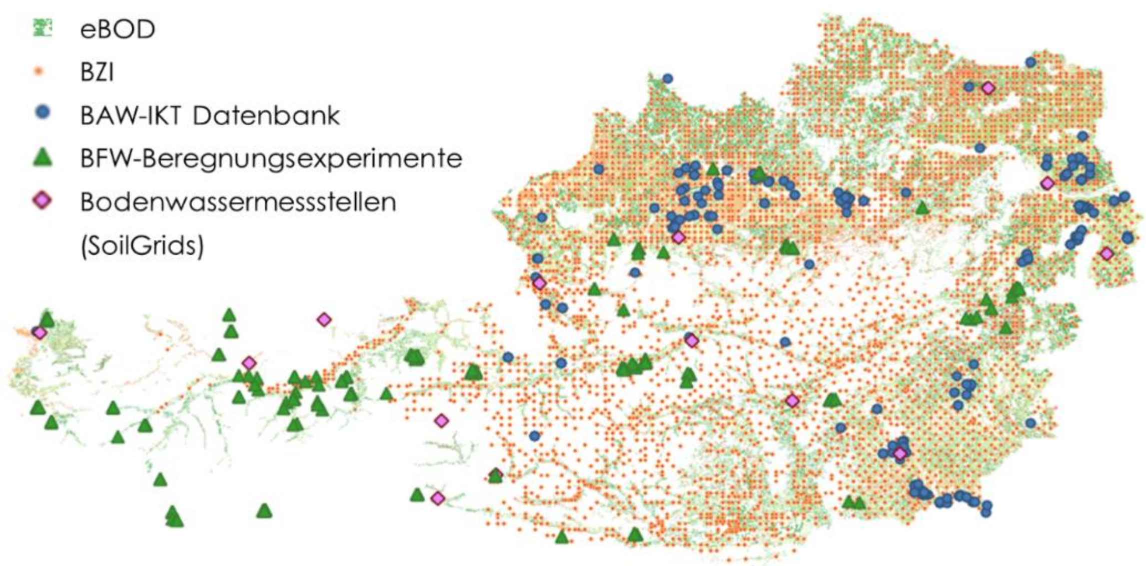

Fig. 4.1: Available Soil information for Austria. Data include: eBOD – a polygon soil texture map based on 31806 samples and 11713 soil profiles of the BfW (Bundesforschungszentrum für Wald); BZI (Bundeszustandsinventur) – 13352 samples, 5067 profiles; BAW-IKT (Bundesamt für Wasserwirtschaft - Institut für Kulturtechnik und Bodenwasserhaushalt): 250 profiles and 604 samples with texture and K_{sat} information; BWF – infiltration experiments (407 at 203 sites) and 14 governmental monitoring sites (see WP 3).

Available global and regional digital soil mapping products differ in scale and degree of data aggregation, as well as in spatial coverage. K_{sat} and soil properties in general are characterized by a high spatial variability at all scales. Currently, there is no single data product available which covers the whole study area and still displays the variability of local soil observations. Fig. 4.2. gives an overview about the variability of soil texture and K_{sat} measurements and illustrates a variability of orders of magnitude even for soils from "homogeneous" polygons.

Thus, one challenge is to combine soil data from different sources and resolutions and simultaneously to preserve the characteristically high spatial variability of soil properties. Two approaches have been tested and compared to produce spatially distributed K_{sat} maps for Austria: In the indirect approach two machine learning (ML) models (XGBoost and FNN, Feed foreward Neuronal Networks) were trained with available local soil data sources and environmental raster datasets to predict the soil parameters sand, silt, clay and humus for the area of Austria. K_{sat} was then determined by applying existing pedotransfer-functions (PTFs) on the previously regionalized soil parameters. In the second direct approach, ML models were directly trained with available soil hydraulic datasets to predict K_{sat}.

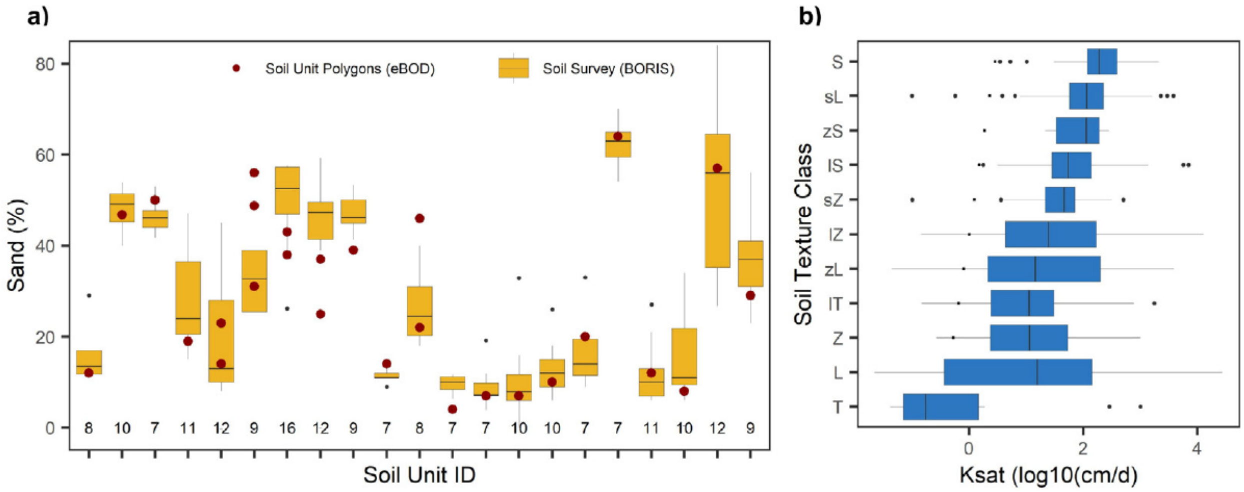

Fig. 4.2: Analysis of data variability: (a) Comparison of the measured sand fractions of soil profiles (boxplot) – provided by BORIS and located within soil units of the digital soil map eBOD – with the sand fractions (dot) of the eBOD profile assigned to the respective soil unit. All values are taken from the top horizon. The digits right above the x-axis describe the number of soil profiles located within each soil unit. In some cases – represented by two dots per Soil Unit ID – two eBOD profiles are assigned to the same soil unit. (b) Variability of lab-measured $Ksat$ of the soil hydraulic database provided by BAW. The $Ksat$ values in log10 (cm/d) are categorized by soil texture class according to the Austrian soil classification triangle (S/s = sand/sandy, L/l = loam/loamy, Z/z = Silt/silty, T = Clay).

While the resulting soil property maps of the indirect approach are able to largely reproduce the original data variability, the prediction of K_{sat} includes high levels of uncertainties. In both approaches XGBoost outperforms FNN. The derived soil maps help to reduce current gaps in soil data availability for Austria, but also highlight the need for additional K_{sat} field data acquisition. Resulting K_{sat}-maps and related uncertainties for the indirect approach are illustrated in Fig. 4.3. Further details on methods and detailed results can be taken from Zeitfogel et al. (2022, 2023).

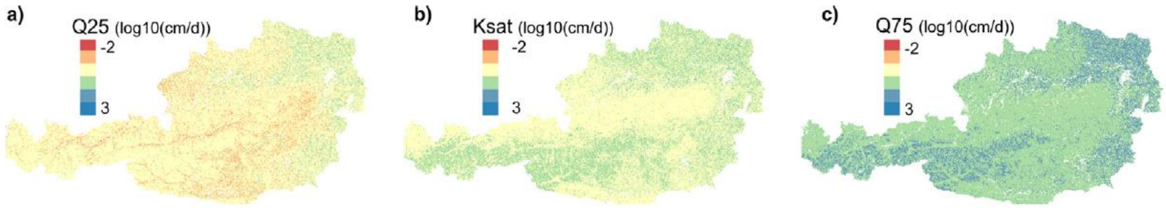

Fig. 4.3: Results of the Indirect approach - EU-PTF derived (a) 25% quantile of $Ksat$, (b) mean $Ksat$, and (c) 75% quantile of $Ksat$ for the top horizon. The land cover classes built-up, sealed surfaces, snow, and ice and water were excluded from the spatial predictions

ii) Establish an Austrian-wide hydrological model for GWR and model calibration

Initially, it was planned to apply the Noah-MP coupled regional climate and land surface model. However, after an analysis of required run-times especially for the final climate scenario analysis, we decided to set-up the HyWa -internally developed COSERO-model (Kling et al., 2015). Fig. 4.4. shows schematically the different hydrological storages and runoff generation/infiltration processes considered in the model. It is also indicated how and where the results from part i) will be used to parameterize storage size and threshold values from K_{sat} and texture maps. Further details on model structure and required data, including meteorological data are given e.g. Schulz et al. (2016). A spatial resolution of 1*1km² and a monthly temporal resolution is considered.

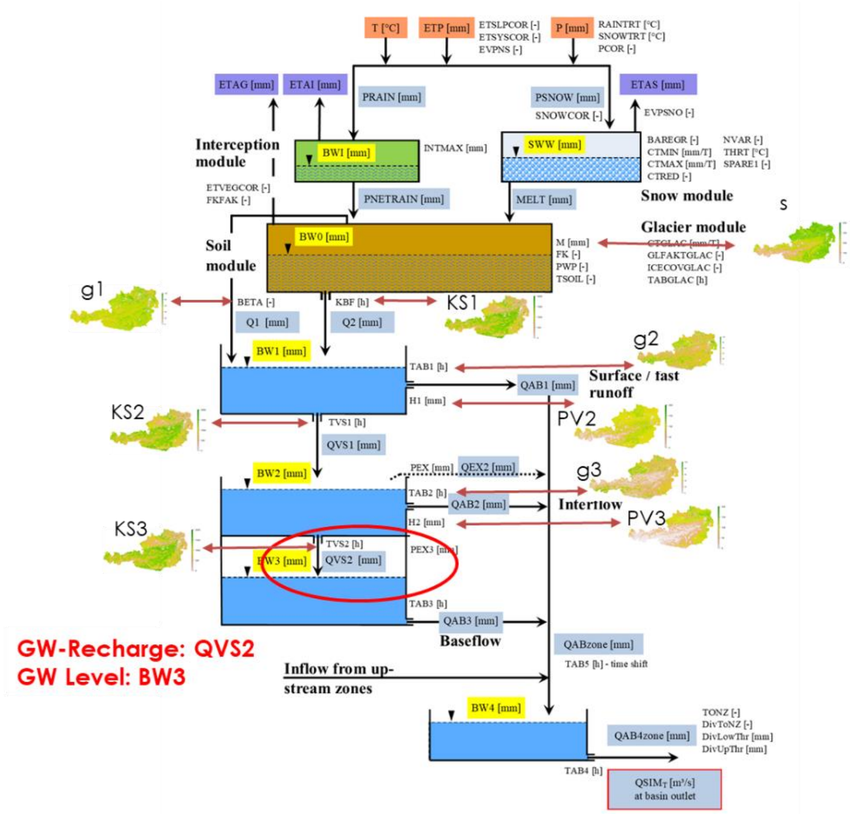

Fig. 4.4: The distributed hydrological model COSERO (Kling et al., 2015). Illustrated are storages and fluxes considered and how soil information from i) will enter the parameterization of the model.

In order to manage the data flow, the model domain of Austria was separated into 3 different, hydrologically independent regions as illustrated in figure 4.5. For model calibration meteorological and runoff data from 1994-2017 were considered with a spin off period of 4 years to obtain adequate internal states/storages of the model. 35 basins were excluded from calibration due to strong human induced impacts on the runoff dynamics (hydropower, diversion etc.). 21 parameters were considered in the calibration process using a mixed (70% NSE, 30% log NSE) objective function. The model was validated for the time period 1981-1993.

iii) Estimation of spatially distributed GWR fields, including uncertainties for current conditions as well as for scenarios of future climate conditions

Figure 4.6 (left) presents the ground water recharge rates for the reference period of 1981-2010 as estimated by the calibrated COSERO model. They compare well to data presented by Martinsen et al. (2022) using satellite data and machine learning techniques.

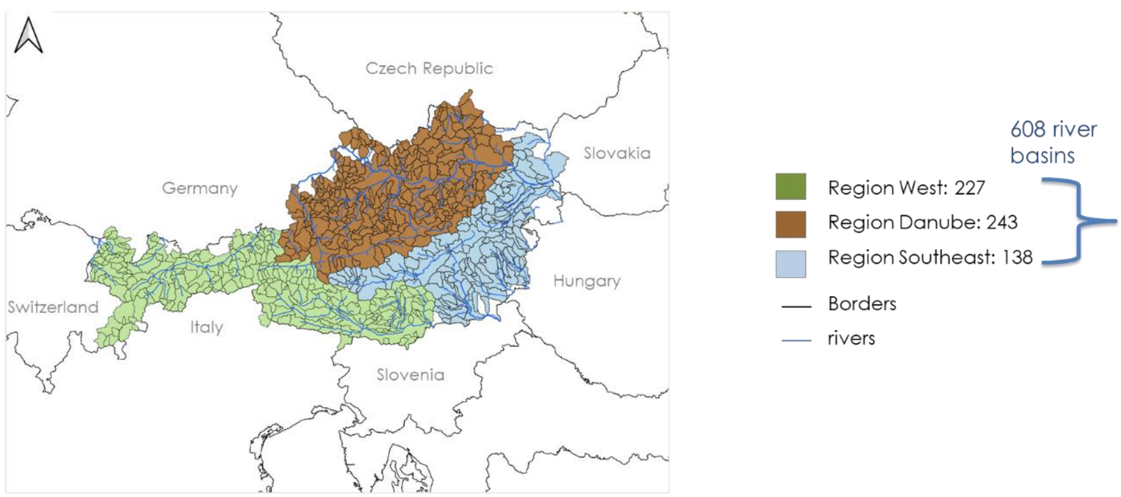

Fig. 4.5: The spatial model setup in different regions to make simulations and scenario analysis manageable.

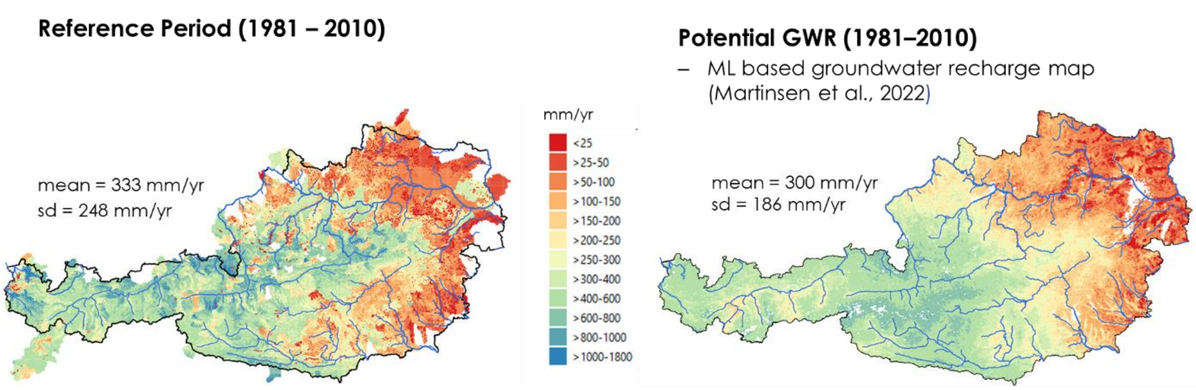

Fig. 4.6: (left) GW-recharge map for the reference period 1981-2010 using the calibrated COSERO model; (right) Potential groundwater recharge map using a machine learning approach as presented by Martinsen et al. 2022.

A more detailed comparison of COSERO results with locally derived GWR-estimates from WP3 show some significant differences that are illustrated in Fig. 4.7. Some possible reasons are different time periods that have been used compared to the COSERO estimates (4-22 years vs. 40years), impacts of glaciers, but also limitations in the ET_a estimation of COSERO.

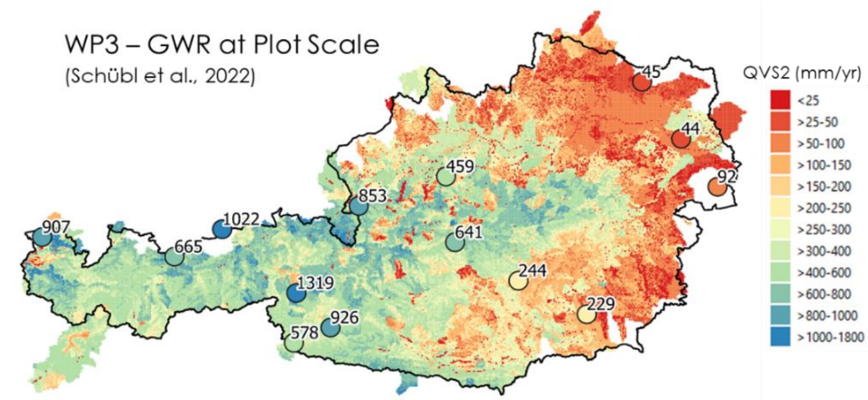

Fig. 4.7: GW-recharge map for the reference period 1981-2010 using the calibrated COSERO model compared to local estimates of GWR from WP3 (Schübl et al. 2022).

Based on the data and the calibrated COSERO model from i) and ii), we will use the ÖKS15 regional climate scenarios (2021-2050) as boundary conditions in order to derive future changes and general uncertainties of GWR at the Austrian level. From these data, sensitive regions with low GWR or high variabilities of future GWR might be extracted and communicated to relevant stakeholders. This part of objective iii) had to be postponed due to a 1 year maternity leave of project employee DI Zeitfogel who will continue her work and PhD starting in August. Results from scenario analysis will be published as soon as possible.

Results - Work Package 5

Implications of climate and socio-economic drivers on water availability, land use and crop production

WP5 aimed at modelling interactions between climatic, agronomic, hydrological, and socioeconomic processes and conditions by considering agricultural and water policy objectives as well as climate change scenarios for Austria and selected regions. In particular, we aimed at (i) investigating climate change scenario impacts on agricultural production, agricultural land use, and regional water balances in Austria, (ii) identifying efficient land use and management to adapt to climate change, and (iii) assessing trade-offs between land and water policy objectives.

Methods

An integrated modelling framework has been developed and applied for Austria and selected regions. A schematic overview of the integrated modelling framework is given in Figure 5.1. It consists of a statistical climate model for Austria (Strauss et al., 2013), the crop rotation model CropRota (Schönhart et al., 2011), the bio-physical process model EPIC (Williams, 1995), and the bottom-up economic land and water use optimization model BiomAT (Feusthuber et al., 2017; Mitter and Schmid, 2021; Stürmer et al., 2013).

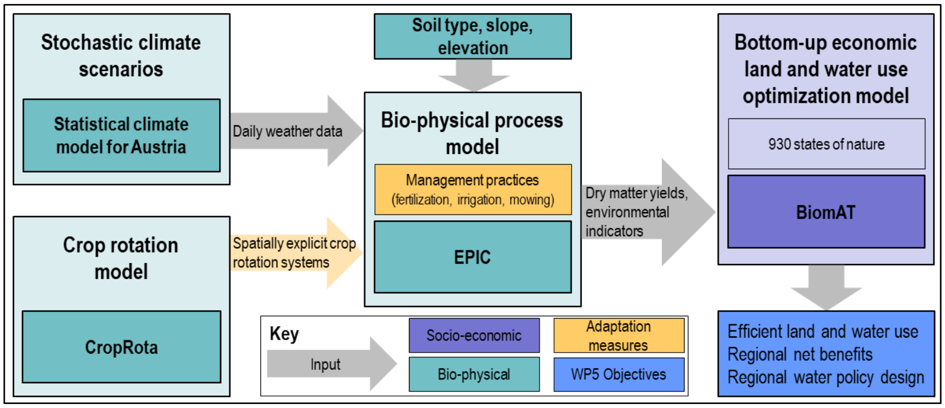

Figure 5.1. Schematic overview of the integrated modelling framework.

In addition, a Bayesian Network has been used to explore the causal relationships between agricultural land, groundwater and nature management and how they may change under climate change in the semi-arid Austrian Seewinkel region. A Bayesian Network is a probabilistic graphical model that allows to combine information and data from different sources (i.e. qualitative, e.g. expert knowledge; quantitative, e.g. modelling results, observational data) with varying spatial and temporal resolution (Koller and Friedman, 2009).

Key results

i) Integrated land and water use modelling

We have modelled regional groundwater extraction volumes, land and irrigation water use, land management, and net benefits of agricultural production change under stochastic climate scenarios and imposed restrictions on groundwater extraction for irrigation in the Seewinkel region. The region is located in Eastern Austria. It is characterized by Pannonian climate, and the agricultural sectors is the main user of groundwater. Climate change induced droughts may impede the renewal of the groundwater body, with impacts on agricultural production.

The key results for the Seewinkel region can be summarized as follows:

- Without restrictions on groundwater extraction for irrigation, the entire Seewinkel region is irrigated and vineyards are the dominant land use, regardless of the climate scenario.
- Irrigation water use and regional net benefits of agricultural production continuously decrease with more restrictive policies on groundwater extraction for irrigation, with largest decreases under a dry and smallest decreases under a wet climate scenario, whereby cropland and other (abandoned) land gain in importance.
- If groundwater extraction for irrigation is restricted, high flexibility in land use is required to efficiently adapt land use and management to the climate scenarios.

Figure 5.2 shows the spatial heterogeneity of average annual irrigation water use in the Seewinkel region for three stochastic climate scenarios and three selected λ levels. λ represents restrictions on groundwater extraction for irrigation by a policy. More detailed results are presented in Mitter and Schmid (2021).

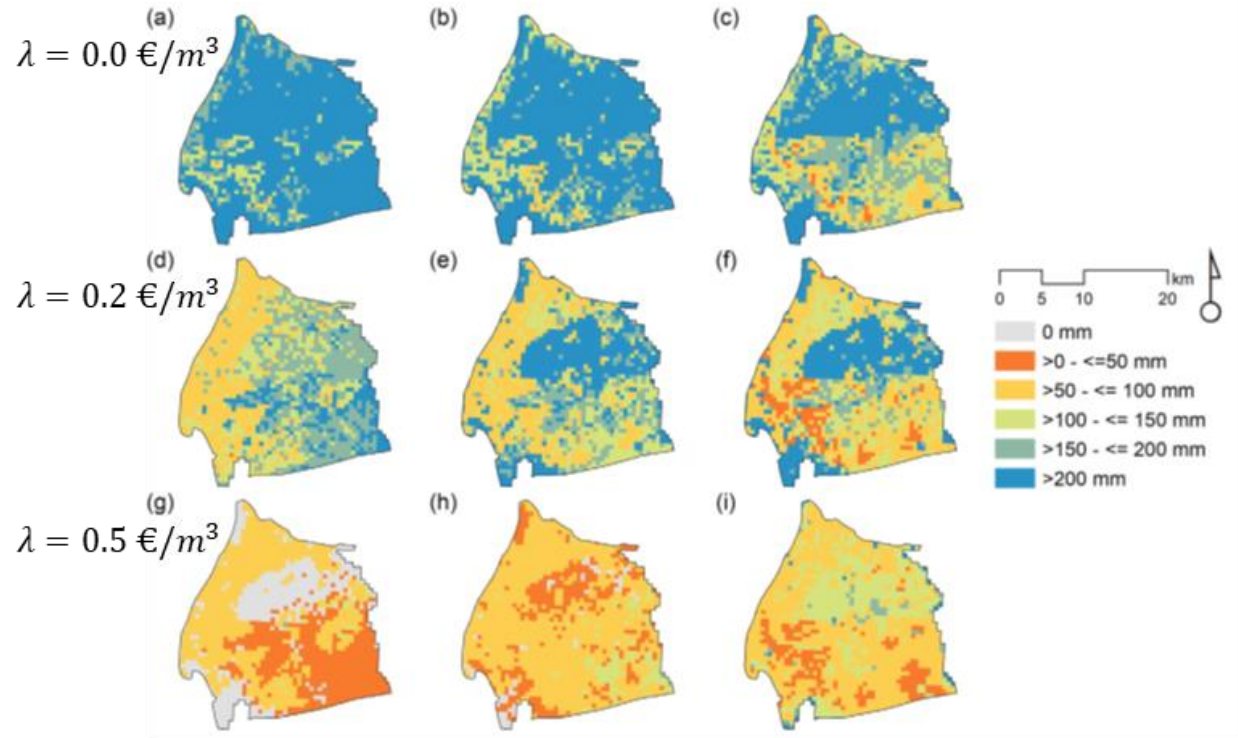

Figure 5.2. Average annual irrigation water use in the Seewinkel region (in mm) by three λ levels, i.e., 0.0 €/m³, 0.2 €/m³ and 0.5 €/m³ and three climate scenarios (dry, first column; similar compared to the past, second column; wet, third column). Note: The marginal value of groundwater extraction for irrigation ranges from 0 to 0.7 €/m³ in the analysis. The model results were averaged over the 30 realizations for each climate scenario.

Building on the findings outlined above, we have assessed the impacts of three stochastic climate scenarios on trade-offs and co-benefits between the regional net benefits from agricultural production and three environmental goals by computing stochastic Pareto frontiers. In particular, we have minimized groundwater extraction (GWEX) for agricultural irrigation, have minimized nitrate leaching in the percolate (NO3), and have maximized topsoil organic carbon stocks (SOC), while allowing a percentage change reduction of regional net benefits from agricultural production.

Figure 5.3 shows, exemplarily, stochastic Pareto frontiers between regional net benefits from agricultural production and GWEX and the co-benefits for NO3 under a climate scenario resembling past conditions. Three net benefit reduction levels, i.e., -1%, -10%, -20%, are presented. At a 1% (10%, 20%) reduction level of net benefits from agricultural production, GWEX can be reduced on average by 19% (68%, 94%) and NO3 decreases by 2% (3.9%, 4%), on average, compared to the reference situation. Co-benefits to SOC are overall small. SOC increases on average by 0.007% (0.02%, 0.11%) at NB reduction levels of 1% (10%, 20%) if GWEX is minimized. More detailed results are shown in Karner et al. (2021).

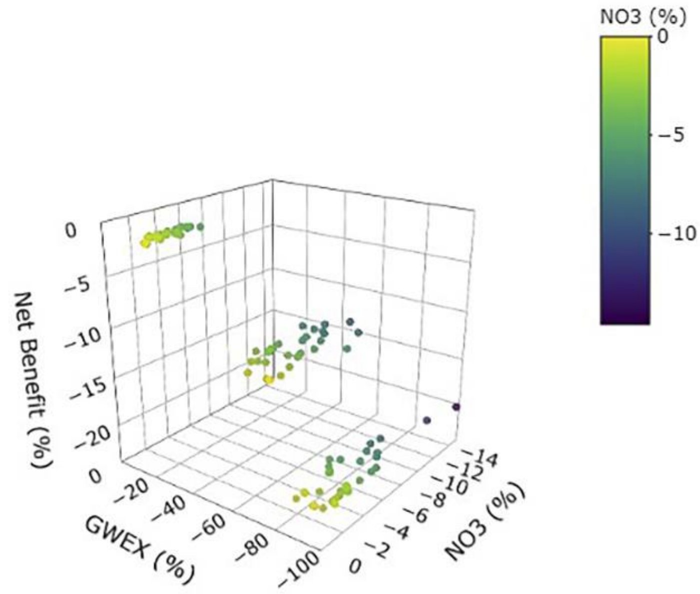

Figure 5.3. Visualization of the stochastic Pareto frontier between net benefits from agricultural production and groundwater extraction for irrigation (GWEX) and the co-indicator nitrate leaching (NO3) (also shown by colour for ease of visualization) under SIMILAR climate conditions. The results of three net benefit reduction levels are shown, i.e. 1%, 10% and 20%.

ii) Bayesian Network of land and water use relationships

The developed Bayesian Network considers both agricultural and environmental concerns, i.e., the preservation of highly endangered saltine lakes. First, a graphical structure, i.e. a directed acyclic graph, was developed (Figure 5.4). Therefore, most relevant variables to be presented and their causal relationships (the connections between variable) were selected and defined. This was an iterative process, informed by known bio-physical processes and causal relationships as well as expert knowledge of regional stakeholders and interests (Kropf et al., 2021b, 2021a). The result of this step is a Bayesian Network consisting of 20 variables. Second, the variable discretization of the Bayesian Network resulted in a finite number of mutually exclusive variable states. Third, the conditional probability tables were defined for all connected variables, considering every potential combination of variable states. The final network can then be used for reasoning and analysis. Results show, for instance, that the design of groundwater policies significantly influences irrigation water availability, agricultural productivity, and farmers' income. For instance, a more restrictive policy, focusing on environmental protection, decreases the probability of sufficient irrigation water availability for agricultural production if land use remains unchanged. However, the extent to which groundwater management influences agricultural productivity and the ecological state of saltine lakes depends on future climate conditions. For instance, the probability of obtaining a good ecological state of the saltine lakes decreases with decreasing precipitation sums regardless of agricultural land use and policy makers' interests.

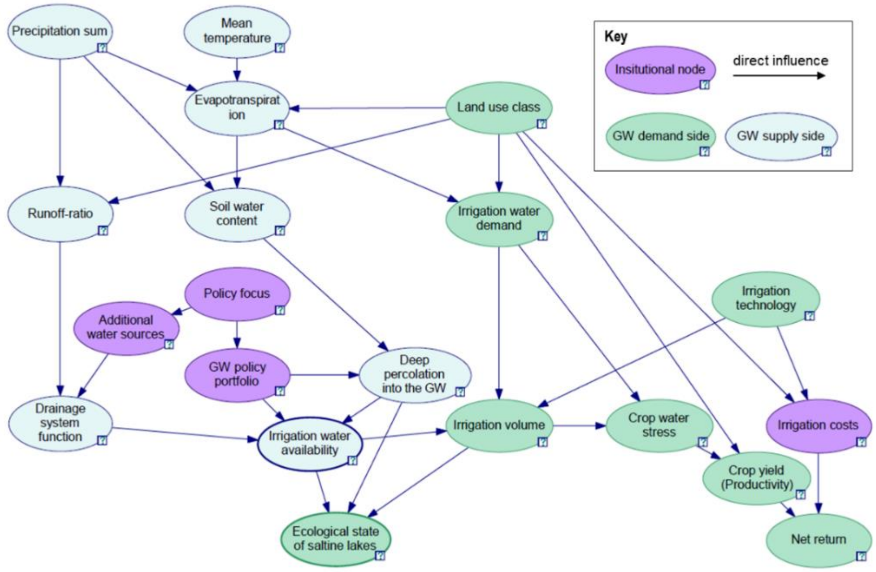

Figure 5.4: The Bayesian Network for the Seewinkel region: representation of the graphical structure, i.e. a directed acyclic graph.

iii) Scenarios of agricultural adaptation and irrigation water demand in Upper Austria

Agricultural adaptation including irrigation is expected to gain in importance in the upcoming decades, even in regions where production conditions are comparably favourable, for example, due to fertile soils with large water holding capacities. Currently, crop management adaption to changing and declining precipitation sums, such as the installation of irrigation systems, is often assessed for a few crops (e.g. field vegetable production) in Upper Austria. Although the irrigation area has more than doubled between 2010 and 2020 (to 3,296 ha) in Upper Austria, the share of irrigation area is less than 2.7% of the total irrigated area in Austria (i.e. 122,347 ha; Statistik Austria, 2022). Hence, we have modelled efficient agricultural adaptation to three precipitation scenarios (Strauss et al., 2013) with declining precipitation sums and more frequent dry spells in Upper Austria. The effects of precipitation scenarios and crop management adaptation are illustrated by potential agricultural irrigation water demand as well as agricultural production and net returns.

The results for Upper Austria show that efficient agricultural adaptation differs between the precipitation scenarios and regions. In the reference precipitation scenario (SDRY1), about 890 ha cropland are irrigated of a total of 288,00 ha cropland in Upper Austria, referring to an irrigation water demand of 1.2 mil. m³. The irrigation water demand is highest in the Machland region, i.e., 76% of the total irrigation water demand in Upper Austria are used in the Machland region. The model results show that irrigation of grain maize (including seed maize production) and cereals is considered as efficient in the Machland region. Efficient agricultural adaptation to precipitation scenarios with a moderate (SDRY2) and severe (SDRY3) increase in dry spells leads to an increase in irrigated cropland and irrigation water demand. In SDRY2, irrigation water demand is highest for the regions Machland and Eastern Mühlviertel. In both regions, the model results show a similar irrigation water demand of about 4.1 mil. m³ and an irrigated cropland area of about 3,200 ha. However, the share of irrigated cropland on total regional cropland is higher in the Machland (53.2%) than in the Eastern Mühlviertel (7.8%). In SDRY3, the total irrigated cropland and irrigation water demand further increase to about 13,700 ha and 22,6 mil. m³. The model results also show that efficient agricultural adaptation to the precipitation scenarios leads to changes in crop rotations, tillage practices, and cover crop cultivation.

Without restrictions of the total irrigated cropland, the modelled total agricultural production and net returns in SDRY2 and SDRY3 are similar to SDRY1 at the Upper Austria level. However, there are substantial regional differences. While some regions even show an increase compared to the reference precipitation scenario SDRY1, considerable decreases in agricultural production and net returns are modelled in the intensively irrigated regions. Building on recent studies that show the impact of climate change on usable (groundwater) resources for drinking water supply, agricultural production, and industry (e.g. Lindinger et al., 2021), we have further assessed the impact of groundwater management scenarios with limitations of total irrigated cropland to a maximum of 7,000 ha and 3,500 ha in Upper Austria. *Figure 5* shows spatially the area of irrigated cropland for all modelled precipitation and groundwater management scenarios. In the reference precipitation scenario (SDRY1), the groundwater management scenarios have little effect on cropland irrigation, agricultural production and net returns. In SDRY2 (SDRY3), the groundwater management scenarios lead to a decrease in the irrigation water demand between 12,6% (50,6%) and 50,9% (71,3%) compared to SDRY2 (SDRY3) without a limitation of irrigated cropland. The model results for these scenarios also show that total agricultural production and net returns decrease when the irrigated cropland is restricted. On average, decreases are in a low single-digits percentage range. However, the restriction of irrigated cropland can lead to production declines of >10% in some regions. More detailed results are presented in Falkner et al. (*in print*).

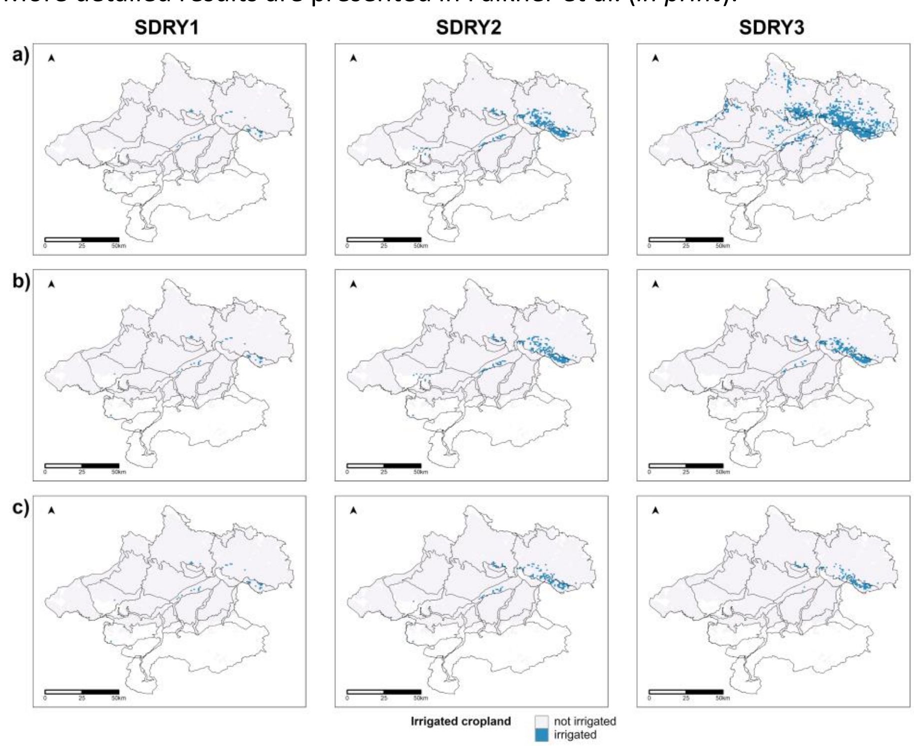

Figure 5.5: Irrigated cropland in Upper Austria for the reference precipitation scenario SDRY1 (resembling historically observed climate conditions), SDRY2 (moderately increase in dry spells), and SDRY3 (severe increase in dry spells) and the groundwater management scenarios where irrigated cropland is a) no limited, b) limited to max. 7,000 ha, and c) limited to max. 3,500 ha. Note: no cropland in white areas.

Dissemination

Publications

Publications in peer-reviewed international journals:

Falkner, K., Mitter, H., and Schmid, E., (in print) Modellierung der Auswirkungen von Niederschlags- und Grundwasserbewirtschaftungsszenarien auf den landwirtschaftlichen Bewässerungsbedarf und die Produktion in Oberösterreich [Modelling the impacts of precipitation and groundwater management scenarios on agricultural irrigation demand and production in Upper Austria]. Austrian Journal of Agricultural Economics and Rural Studies.

Karner, K., Schmid, E., Schneider, U.A., and Mitter, H. (2021) Computing stochastic Pareto frontiers between economic and environmental goals in a semi-arid agricultural production region. Ecological Economics 185, 107044. https://doi.org/10.1016/j.ecolecon.2021.107044

Mitter, H., and Schmid, E. (2021) Informing groundwater policies in semi-arid agricultural production regions under stochastic climate scenario impacts. Ecological Economics 180, 106908. https://doi.org/10.1016/j.ecolecon.2020.106908

Schübl, M.A., Brunetti, G., Fuchs, G., and Stumpp, C. (2023) Estimating vadose zone water fluxes from soil water monitoring data: a comprehensive field study in Austria. Hydrology and Earth System Sciences 27, 1431-1455, https://doi.org/10.5194/hess-27-1431-2023

Schübl, M., Stumpp, C., and Brunetti, G. (2022) A Bayesian perspective on the information content of soil water measurements for the hydrological characterization of the vadose zone. Journal of Hydrology 613, 128429, https://doi.org/10.1016/j.jhydrol.2022.128429

Tudose, N.C., Cheval, S., Ungurean, C., Broekman, A., Sanchez-Plaza, A., Cremades, R., Mitter, H., Kropf, B., Davidescu, S.O., Dinca, L., Cacovean, H., Marin, M., Miksa, K., and Pereira, P. (2022). Climate services for sustainable resource management: The water—energy—land nexus in the Tărlung river basin (Romania). Land Use Policy 119, 106221. https://doi.org/10.1016/j.landusepol.2022.106221

Zeitfogel, H., Feigl, M., and Schulz, K. (2023) Soil information on a regional scale: Two machine learning based approaches for predicting saturated hydraulic conductivity. Geoderma 433, 116418, https://doi.org/10.1016/j.geoderma.2023.116418

Publications in preparation (to be submitted to peer-reviewed international journals):

Schübl, M., Brunetti, G., and Stumpp, C. (to be submitted) Effects of climate change on local groundwater recharge rates in Austria. Water Resources Research.

Schulz, K., Feigl, M., and Zeitfogel, H. (in preparation). The effect of data aggregation on regression behaviour. Geoderma.

Wallner, M., Schübl., M, Brunetti, G., and Stumpp, C. (in preparation) Evaluation of pedotransferfunctions for estimating soil hydraulic properties and groundwater recharge. Vadose Zone Journal.

Zeitfogel, H., Feigl, M., Herrnegger, M., and Schulz, K. (in preparaion) Austrian wide groundwater recharge under climate change conditions. Hydrol. Earth Syst. Sci.

Publications in national periodicals and publication series:

Birk, S., Bahn, M., Schiller, A., and Stumpp, C. (2020) Das Themencluster „Grundwasser“ im ÖAW-Programm „Earth System Sciences – Wasser in Gebirgsräumen“. Wasserland Steiermark 1/2020: 16-19, https://www.wasserwirtschaft.steiermark.at/cms/dokumente/10046052_1356921/d0b5ede9/Wasserland-STMK_Zeitung_A4_01-20_Web.pdf

Brunetti, G., Schübl, M., Santner, K., and Stumpp, C. (2022) Sensitivitätsanalyse zu Infiltrationsprozessen in Böden. Österreichische Wasser- und Abfallwirtschaft 74, 179-186, https://doi.org/10.1007/s00506-022-00839-8

Zeitfogel, H., Feigl, M., and Schulz, K. (2022) Österreichweite Regionalisierung bodenhydraulischer Eigenschaften. Österreichische Wasser- und Abfallwirtschaft, 74, 166–178, https://doi.org/10.1007/s00506-022-00842-z

Presentation at international and national conferences

Falkner, K., Mitter, H., Schmid, E., 2022. Modelling crop management adaptation to scenarios of declining precipitation sums in Upper Austria. Joint Conference of the Slovenian Association of Agricultural Economists DAES and the Austrian Association of Agricultural Economists ÖGA - Societal changes and their implications on agri-food systems and rural areas 2022, Ljubljana, Slovenia, 22.09.2022 - 23.09.2022. In: Tomšič, M; Novak, A; Travnikar, T; Juvančič, L (Eds.), Societal Changes and Their Implications on Agri-Food Systems and Rural Areas; ISBN: 978-961-94943-1-8

Falkner, K., Kropf, B., Schmid, E., Mitter, H., 2021. A Bayesian Network for analysing the relationships between agricultural land and groundwater management under climate change in the Seewinkel region. [Poster]. Landscape 2021 - Diversity for Sustainable and Resilient Agriculture, Berlin, Germany, 20.09.2021 - 22.09.2021. In: Ewert, F; Feindt, P (Eds.), Diversity for Sustainable and Resilient Agriculture, p. 163

Falkner, K., Kropf, B., Schmid, E., Mitter, H., 2021. A Bayesian Network to support agricultural land and groundwater management under climate change in the Seewinkel region. 31. Jahrestagung der Österreichischen Gesellschaft für Agrarökonomie ÖGA 2021 - Strategien für den Agrar- und Ernährungssektor und den ländlichen Raum in Zeiten multipler Krisen, Vienna, Austria, 16.09.2021 - 17.09.2021. In: ÖGA (Eds), Strategien für den Agrar- und Ernährungssektor und den ländlichen Raum in Zeiten multipler Krisen (Strategies for the agricultural and food sector and rural areas in times of multiple crises), p. 55-56

Karner, K., Mitter, H., Schneider, U., Schmid. E., 2021. Does it matter which Agro-Ecological Objectives are optimized first? - insights from a multi-objective optimization experiment. XVI EAAE Congress, Prague, Czech Republic, 20.07.2021 - 23.07.2021. In: Raising the Impact of Agricultural Economics: Multidisciplinarity, Stakeholder Engagement and Novel Approaches, 12 pages.

Karner, K., Schmid, E., Mitter, H., 2021. Optimizing land and water use for multiple environmental policy objectives under climate change – a case study from Austria. International Online Joint Conference of the international degrowth research networks, the International Society for Ecological Economics and the European Society for Ecological Economics. Online conference hosted by the University of Manchester, 05.07.2021 - 08.07.2021. In: ISEE, ESEE, International degrowth research network (Eds.), Book of Abstracts, p. 195-196

Karner, K., Schmid, E., Mitter, H., 2021. Optimizing land and water-based ecosystem services under climate change – a regional case study application in Austria. 3rd ESP Europe Conference, Tartu, Estonia and online, 07.06.2021 - 10.06.2021. In: ESP, Ecosystem Services Science, Policy and Practice in the face of Global Changes, book of abstracts.

Karner, K., Mitter, H., Schmid E., 2021. Analyzing competing land use policy objectives under climate change – a regional case study from Austria. EGU General Assembly 2021, online, 19.04.2021 - 30.04.2021, EGU21-8155.Schübl, M., Stumpp, C., and Brunetti, G. (2021). Estimating soil hydraulic parameters from lysimeter data: a Bayesian perspective. 19. Gumpensteiner Lysimetertagung 2021, online, 13-14 Apr 2021, 149 - 152. ISBN: 978-3-902849-83-0

Schübl, M., Stumpp, C., and Brunetti, G. (2021). On the identifiability of soil hydraulic parameters in lysimeter experiments: a Bayesian perspective. EGU General Assembly 2021, online, 19–30 Apr 2021, EGU21-11111. https://doi.org/10.5194/egusphere-egu21-11111

Schübl, M., Stumpp, C., and Brunetti, G. (2022). Uncertainty assessment and dataworth evaluation for estimating soil hydraulic parameters and recharge fluxes from lysimeter data. EGU General Assembly 2022, Vienna, Austria, 23–27 May 2022, EGU22-3782. https://doi.org/10.5194/egusphere-egu22-3782

Schübl, M., Stumpp, C., and Brunetti, G. (2022). A Bayesian Perspective on the Information Content of Soil Water Measurements for the Hydrological Characterization of the Vadose Zone. XXIV International Conference Computational Methods in Water Resources, Gdansk, Poland, 19-23 June 2022, 118.

Stumpp, C., Schübl, M., and Brunetti, G. (2022). Groundwater recharge estimation and uncertainty analysis for various soils in Austria. EGU General Assembly 2023, Vienna, Austria, 24–28 April 2023, EGU23-8548. https://meetingorganizer.copernicus.org/EGU23/EGU23-8548.html

Stumpp, C., Brunetti, G., Canet-Marti, A., Liebhard, G., Nolz, R., Schübl, M., and Strohmeier, S. (2022) Sustainable soil management and climate - A soil physics perspective. International Soil Law and Governance Conference, 20.10.2022, Vienna, Austria.

Stumpp, C., Schübl, M., Wallner, M., and Brunetti, G. (2022) Quantification of soil hydraulic properties and groundwater recharge rates at soil wa-ter monitoring sites across Austria. 4. Workshop zur alpinen

Hydrologie 2022 - Hydrologische Prozesse im Hochgebirge im Wandel der Zeit, Obergurgl, Austria, 23.03.-25.03.2022.

Zeitfogel, H; Feigl, M; Schulz, K. (2021): Variability across scales - exploring methods for predicting soil properties from multiple sources, EGU General Assembly 2021, online, 19–30 Apr 2021, EGU21-4142.

Invited Talks

Stumpp, C. (2022) Quantification of Soil Water Fluxes - Challenges and Opportunities. BayCEER Kolloquium, 23.06.2022, Bayreuth, GERMANY

Stumpp, C. (2022) Quantification of water fluxes in the unsaturated zone. FH-DGGV Online Seminar Series – What's new in Hydro?, 28.04.2022, virtuell/online

Zeitfogel, H., and Schulz, K. (2023) Regionalisierung von bodenhydrologischen Eigenschaften für Österreich, WINALP21, Österreichische Bodenkundliche Gesellschaft, 28.09.2023.

Stakeholder workshops

Stakeholderworkshop Wasserressourcen im Klimawandel: Konsequenzen für Wasser-, Energie- und Landwirtschaft, Graz, 7.02.2020.

Stakeholderworkshop Wasserressourcen im Klimawandel: Konsequenzen für Wasser-, Energie- und Landwirtschaft, Vienna, 27.09.2022.

Three WP5 related stakeholder meetings were held in Upper Austria during the course of the project. They were organized in collaboration with the Amt der Oö. Landesregierung in September 2021, December 2021 and March 2022. Representatives of the agriculture and water sectors as well as meteorologists participated in the workshop. The major aims of the workshops were to get a common understanding of the regional situation and challenges, to select climate and develop groundwater management scenarios, to share data sources, and to face validate outputs of the integrated modeling framework.

Habilitation, Doctoral and Master theses

Falkner, K., (2022): Integrated modelling of crop pest abundance and regulation policies under climate change: The case of the Western Corn Rootworm in Austria.; Doctoral dissertation; Institute of Sustainable Economic Development - Universität für Bodenkultur Wien

Mitter, H., (2022): Towards integrated research in agricultural adaptation to climate and socio-economic change. Universität für Bodenkultur Wien; Habilitation in Environmental Economics and Environmental Sociology

Karner, K., (2021): A mixed-method approach to support sustainable regional management of agricultural land and water resources under climate change. Doctoral dissertation; Institute of Sustainable Economic Development - Universität für Bodenkultur Wien

Salzmann, J. (2022): Estimation of groundwater recharge at selected sites in Austria: comparing conceptual and physically-based models. Master's thesis, University of Graz. (In collaboration with ESS groundwater cluster project Integrative Groundwater Assessment)

Santner, K. (2021): Evaluation of soil-specific infiltration capacity in dependence on soil moisture and precipitation intensity. Master thesis - Institut für Bodenphysik und landeskulturelle Wasserwirtschaft, BOKU-Universität für Bodenkultur Wien

Wallner, M. (2021): Evaluation of pedotransferfunctions for estimating soil hydraulic properties and groundwater recharge. Master Thesis - Institut für Bodenphysik und landeskulturelle Wasserwirtschaft, BOKU-Universität für Bodenkultur Wien

Projects and other activities related to / emerging from RechAUT

- InfCapAT – Abschätzung der österreichweiten Infiltrationskapazitäten. Funded by the ministry (BMLRT) and based on results from the RechAUT project, the infiltration capacity was estimated on the regional for Austria, and the dependence on moisture content and rainfall intensities on the local scale for the different monitoring sites from the RechAUT project.

- COST Action: WATSON (WATer isotopeS in the critical zONe) is an EU funded network of researchers and stakeholders which centers its interest on the Critical Zone, the dynamic skin of the Earth that extends from vegetation canopy to groundwater. WATSON collects, integrates, and synthesizes current interdisciplinary scientific knowledge on the partitioning and mixing of water in the critical zone and on groundwater recharge taking advantage of the unique tracing capability of stable water isotope. Christine Stumpp is a working group co-leader on groundwater recharge rates. The RechAUT project results will be relevant for gathering European wide data on groundwater recharge rates.

Career Development of Project Related Team Members

Katharina Falkner has worked on the RechAUT project and has completed her doctoral studies in 2022. She is now working at BOKU and at the Austrian Institute of Economic Research (WIFO) in the research groups Climate, Environmental and Resource Economics.

Katrin Karner has completed her doctoral studies in 2021 and is currently working as a post-doc researcher at BOKU.

Hermine Mitter was part of the project team and has completed her habilitation in 2022. She was awarded the venia docendi in Environmental Economics and Environmental Sociology. Currently, she is working as a senior scientist at BOKU.

Katharina Santner finished her Master Thesis at BOKU in 2021. She moved to Portugal.

Marleen Schübl will finish her PhD thesis (defense) in September 2023. Since January 2023, she is project team member at VERBUND Energy4Business GmbH.

Marion Wallner finished her Master Thesis at BOKU in 2021. She works at Kompetenzzentrum Boden in the team of „Anwendungen, Themenkarten & Wissenstransfer".

Hanna Zeifogel will get back from maternity leave in August 2023 and finish her PhD thesis.

Moritz Feigl already holds a PhD, has supported the project in the field of "Machine Learning" and has successfully implemented a spin-off in the field of AI (baseflow.ai GmbH) with his colleague Christoph Klinger.

Claire Benner already holds a PhD, supported the project AI applications, remote sensing data, and Python programming; she joined "Doctors Without Borders" in disaster early warning/global remote sensing in May 2023.

References

Bauer, C. and Plan, L. (2022) Karst Landscapes in Austria. World Geomorphological Landscapes, pages 87–104.

BFW: Österreichische Bodenkartierung (2016) https://bodenkarte.at/ (last access: 25 March 2023).

Eitzinger, J., Trnka, M., Semeradova, D., Thaler, S., Svobodova, E., Hlavinka, P., Siska, B., Takac, J., Malatinska, L., Novakova, M., et al. (2013) Regional climate change impacts on agricultural crop production in Central and Eastern Europe–hotspots, regional differences and common trends. The Journal of Agricultural Science, 151(6), 787–812.

Feusthuber, E., Mitter, H., Schönhart, M., Schmid, E. (2017) Integrated modelling of cost-effective policies to regulate Western Corn Rootworm under climate change in Austria. Agric. Syst. 157, 93–106. https://doi.org/10.1016/j.agsy.2017.07.011.

Gobiet, A., Kotlarski, S., Beniston, M., Heinrich, G., Rajczak, J., and Stoffel, M. (2014) 21st century climate change in the European Alps-A review. Science of the Total Environment 493, 1138–1151.

Kling, H., Nachtnebel, H. P., and Fürst, J. (2007a) Hydrological Atlas of Austria – Mean annual areal actual evapotranspiration (3.3), Lebensministerium (BMLFUW), Vienna.

Kling, H., Nachtnebel, H. P., and Fürst, J. (2007b) Hydrological Atlas of Austria – Mean annual areal precipitation (2.3), Lebensministerium (BMLFUW), Vienna.

Kling, H., Stanzel, P., Fuchs, M. and Nachtnebel, H.P. (2015) Performance of the COSERO precipitation-runoff model under non-stationary conditions in basins with different climates. Hydrology Sciences Journal 60, 1374-1393, doi: 10.1080/02626667.2014.959956.

Koller, D., Friedman, N., (2009) Probabilistic graphical models: principles and techniques. Cambridge: MIT Press.

Kropf, B., Mitter, H., Schmid, E. (2021a) Wahrgenommene Zielkonflikte und Synergien von sektorenübergreifenden Maßnahmen zur Förderung nachhaltiger Ressourcennutzung in der Region Seewinkel. Austrian J. Agric. Econ. Rural Stud. 30, 75–82. https://doi.org/10.15203/OEGA_30.10.

Kropf, B., Schmid, E., Mitter, H. (2021b) Multi-step cognitive mapping of perceived nexus relationships in the Seewinkel region in Austria. Environ. Sci. Policy 124, 604–615. https://doi.org/10.1016/j.envsci.2021.08.004

Lindinger, H., Grath, J., Brielmann, H., Schönbauer, A., Gattringer, I., Formanek, C., Broer, M., Rosmann, T., Holler, C., Szerencsits, M., Neunteufel, R., Sinemus, N., Grunert, M., Germann, V. (2021) Wasserschatz Österreichs: Grundlagen für nachhaltige Nutzungen des Grundwassers (Projektbericht). BMLRT, Wien, Österreich.

Martinsen, G., et al. (2022) Developing a pan-European high-resolution groundwater recharge map-Combining satellite data and national survey data using machine learning. Science of the Total Environment 822, doi: 10.1016/j.scitotenv.2022.153464.

Plan, L., Decker, K., Faber, R., Wagreich, M., and Grasemann, B. (2009) Karst morphology and groundwater vulnerability of high alpine karst plateaus. Environmental Geology, 58(2):285–297.

Schönhart, M., Schmid, E., Schneider, U.A. (2011) CropRota – A crop rotation model to support integrated land use assessments. Eur. J. Agron. 34, 263–277. https://doi.org/10.1016/j.eja.2011.02.004.

Schübl, M., Stumpp, C. and Brunetti, G. (2022) A Bayesian perspective on the information content of soil water measurements for the hydrological characterization of the vadose zone. J. Hydrol. 613, doi: 10.1016/j.jhydrol.2022.128429.

Schübl, M.A., Brunetti, G., Fuchs, G., and Stumpp, C. (2023) Estimating vadose zone water fluxes from soil water monitoring data: a comprehensive field study in Austria. Hydrology and Earth System Sciences 27, 1431-1455, https://doi.org/10.5194/hess-27-1431-2023

Schübl, M., Brunetti, G., and Stumpp, C. (to be submitted) Effects of climate change on local groundwater recharge rates in Austria. Water Resources Research.

Schulz, K., Herrnegger, M., Wesemann, J. and Klotz, D. (2016). Kalibrierung COSERO – Mur für PROVIS. VERBUND A.G., Endbericht.

Statistik Austria (2022) Agrarstrukturerhebung 2020. Statistik Austria.

Strauss, F., Moltchanova, E., Schmid, E. (2013) Spatially Explicit Modeling of Long-Term Drought Impacts on Crop Production in Austria. Am. J. Clim. Change 02, 1–11. https://doi.org/10.4236/ajcc.2013.23A001.

Stürmer, B., Schmidt, J., Schmid, E., Sinabell, F. (2013) Implications of agricultural bioenergy crop production in a land constrained economy – The example of Austria. Land Use Policy 30, 570–581. https://doi.org/10.1016/j.landusepol.2012.04.020.

Williams, J.R. (1995) The EPIC Model, in: Computer Models of Watershed Hydrology, Water Resources Publications. Singh V.P., pp. 909–1000.

Zeitfogel, H., Feigl, M., Schulz, K. (2022) Österreichweite Regionalisierung bodenhydraulischer Eigenschaften. Österreichische Wasser- und Abfallwirtschaft, 74, 166–178, doi: 10.1007/ s00506-022-00842-z.

Zeitfogel, H., Feigl, M., Schulz, K. (2023) Soil information on a regional scale: Two machine learning based approaches for predicting saturated hydraulic conductivity. Geoderma, 433, doi: 10.1016/j.geoderma.2023.116418.