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An assessment of water management measures for climate change adaptation of agriculture in Seewinkel

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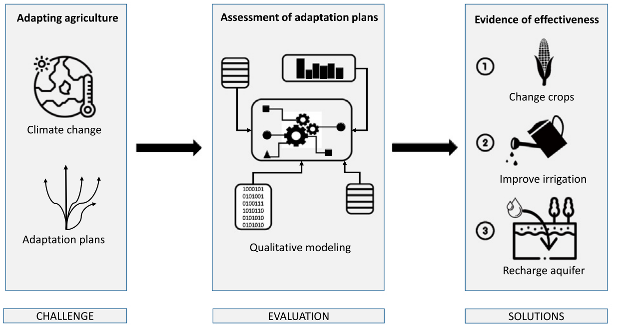
HIGHLIGHTS

- Changes to the demand side are the most effective to preserve the aquifer.
- Irrigation water demand can be reduced by up to 40 %.
- Artificial recharge of the aquifer is the less beneficial measure.
- The aquifer level could be increased by up to 0.43 m above the historical average.
- Some stakeholders hold incorrect perceptions regarding the efficacy of adaptation measures.

GRAPHICAL ABSTRACT



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ABSTRACT

To develop appropriate climate change adaptation plans, evidence of the effectiveness of adaptation measures is required. At a regional scale, however, this information is usually lacking. The region of Seewinkel in Austria was taken as a case study because of its extensive agricultural industry and its unique ecosystem of saline lakes. The goal of the study was to provide stakeholders with evidence to support their climate change adaptation process. Adaptation measures discussed by local stakeholders were analyzed to determine their efficacy. A system dynamics (SD) based model was developed to serve as a tool for the water policy analysis and to be used in place of advanced hydrological models. The model was calibrated using observational data and forced with bias-adjusted EURO-CORDEX climate data for three representative concentration pathways (RCPs) (2010–2100). Three parameters in the model were changed to simulate adaptation measures. The results showed that combined measures, increasing irrigation efficiency and changing crops could reduce water demand by an average of 40 %, 23 % and 23 %, respectively, for all RCPs. The local aquifer's level could be increased above the historical average by an average of 0.43 m by combined measures, 0.20 m by increasing irrigation efficiency, 0.20 m by changing crops and 0.06 m by artificially recharging the aquifer.

Abbreviations: BAU, business-as-usual scenario; COMB, an adaptation scenario in which CROP and IRRI are implemented at the same time; CROP, an adaptation scenario with a shift to less water-demanding crops; CWatM, Community Water Model; EU, European Union; IPCC, Intergovernmental Panel on Climate Change; IRRI, an adaptation scenario with a shift to more efficient irrigation methods; IWD, irrigation water demand; nRMSE, normalized root mean square error; NSE, Nash-Sutcliffe efficiency; RECH, an adaptation scenario in which the aquifer is artificially recharged; RCP, representative concentration pathway; SD, system dynamics.

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1. Introduction

The agricultural sector is the biggest freshwater consumer as it accounts for 70 % of water withdrawals globally (FAO, 2018; IPCC, 2019). Irrigated areas represent 20 % of cropland and generate nearly 40 % of the global food production (Mcdermid et al., 2021; Scanlon et al., 2012). Since the 1960s, irrigation water volume has doubled worldwide (IPCC, 2019). On a global scale, groundwater has declined because of the intensification of groundwater-fed irrigation since the beginning of the 21st century (IPCC, 2022). In dry regions, agricultural groundwater extraction has caused groundwater depletion and influenced the water cycle at local and regional scales (Dalin et al., 2017; Gleeson et al., 2012; IPCC, 2021; Scanlon et al., 2012). As a result, in semi-arid regions, water scarcity is now one of the main problems to be solved (Correia de Araujo et al., 2019).

In the European Union (EU), agriculture covers approximately 40 % of the land and accounts for 24 % of the water extractions (EEA, 2019, 2021). Since 1960, the total irrigated area in the EU has doubled, making agriculture the largest net water user, consuming 40 % to 60 % of the European net water use (EEA, 2021). In some countries, like Spain and France, agricultural water extraction has already affected groundwater bodies (EEA, 2021). In addition to this, countries in Central Europe have experienced droughts and heatwaves since the beginning of the 21st century (Ionita, 2020; Stein et al., 2016). These events have caused massive losses to the agricultural sector. The current losses in Europe are estimated to be €9 billion/year (Naumann et al., 2019). In the case of Austria, agricultural losses caused by drought averaged €123 million/year (2019), a figure higher than the combined agricultural losses from hail, frost, storms and floods (Leitner et al., 2020).

On a global scale, there is high confidence that climate change will increase the frequency of concurrent droughts and heat waves (IPCC, 2021). This situation is particularly alarming for the agricultural sector as 82 % of all damage caused by droughts is absorbed by agriculture (FAO, 2021). In Europe, the proportion of drought-related damage absorbed by agriculture lies between 39 % and 60 % (Cammalleri et al., 2020). Climate change is expected to further alter the water balance in Europe, and thus drought damage could further increase (Naumann et al., 2019; Samaniego et al., 2018). In Europe, the effect of increasing drought events on agriculture has already become noticeable. For example, it is estimated that cereal losses have increased 3 %/year because of drought (Brás et al., 2021) and that climate change will reduce wheat production by 6 % for each degree Celsius of temperature increase (Asseng et al., 2015).

As a result, agriculture in Central Europe requires climate change adaptation to increase its resilience to drought. Adaptation is especially important for agriculture to ensure food security (EEA, 2019) and ensure efficient supply and utilization of water resources (Turral et al., 2011). One method to promote adaptation is water demand management, which refers to measures implemented to reduce the amount of water needed to achieve a goal (Wang et al., 2016). This approach to climate change adaptation is particularly beneficial as it could maximize water efficiency and encourage sustainable use of local water resources. Climate change adaptation through water demand management involves the evaluation of adaptation measures using top-down impact modelling approaches (Ludwig et al., 2014; Montanari et al., 2013). Developing efficient adaptation measures, however, requires the integration of water management, hydrology, and agronomy (Turral et al., 2011). Because water management decisions are usually affected by large uncertainties, climate adaptation studies should include several climate change scenarios but also use several impact models to produce robust results (Huang et al., 2018).

Climate change adaptation through agricultural water management can be enhanced by understanding the risks and advantages of the proposed adaptation measures (Iglesias and Garrote, 2015). Because the water sector is so important for other sectors, management policies have to take into account their potential widespread impacts (Iglesias and Garrote, 2015). However, a common gap in water management is inadequate understanding of causal relationships in the system (Strosser et al., 2012). Additionally, water management has traditionally been based on historical data with the assumption that hydrological systems were stationary, but because of climate change, this approach is no longer viable (Ludwig et al., 2014). This means that water managers should include climate scenarios in their planning. Because of this, models that include the interactions between sectors and simulate the behavior of the system under climate change conditions could be particularly useful for water management.

This study presents an analysis of the Seewinkel region in Austria. In Seewinkel, agriculture relies on groundwater for irrigation and shares the land with a complex system of saline lakes. Scientific interest in Seewinkel is largely due to the region's semi-arid status and the importance of local agriculture and its water consumption patterns. Local stakeholders have already discussed several measures to adapt to climate change, and they were recorded by Kropf et al. (2021). Stakeholders mentioned the tradeoffs and synergies that adaptation could have based on their perceptions. However, no previous quantitative study has explored and confirmed the effects that these measures could have on the local irrigation water demand (IWD) and the local water resources under climate change scenarios. This analysis aimed to fill this gap and determine the effectiveness of the suggested adaptation measures in terms of (I) adapting agriculture to climate change by reducing its water demand and (II) preserving groundwater and the saline lakes ecosystem. The goal of this study was to reduce uncertainty regarding the effectiveness of adaptation measures to support stakeholders' science-based decision making for climate change adaptation.

This study explored the interactions between the local aquifer, the saline lakes ecosystem and agriculture, taking into account the effects of climate change on the system. This analysis considered causal relationships and a system with changing conditions. The rationale for this approach was to avoid the common oversights mentioned above. Previous studies of the region have analyzed historical trends in the aquifer water table (Magyar et al., 2021); the water balance of Lake Neusiedl (Soja et al., 2013); and used an integrated modelling framework to analyze the effects of adaptation (Karner et al., 2019; Mitter and Schmid, 2021). However, while the latter two studies yielded beneficial results for adaptation, they are limited to a 31-year horizon (2010–2040) and do not rely on climate model ensembles for their future projections. The most recent study in Seewinkel applied a large-scale hydrological model, the Community Water Model (CWatM) (Burek et al., 2020), coupled to a groundwater flow model, MODFLOW, to explore groundwater exchanges, groundwater recharge, and the effects of extractions and irrigation (Guillaumot et al., 2022). However, no previous study has evaluated the long-term effect of climate change adaptation measures while considering the causal relationship between agriculture, the aquifer, and the saline lakes. This study fills this research gap.

For the analysis, a novel hydrological model was developed based on system dynamics (SD) and calibrated using local observational data regarding the aquifer, the lakes and precipitation. The model presented in this study simulates the interactions between agriculture, the local aquifer, the saline lakes and the climate. The intention behind the development of an original hydrological model is to produce a model that can be used in place of advanced hydrological models, as spatially distributed and physically based models have high computational cost and require large amounts of data to be parametrized (Chen et al., 2022; De Niel et al., 2020). The model presented in this study runs with future climate projections provided by the World Climate Research program EURO-CORDEX initiative (Jacob et al., 2014) for three climate change scenarios: representative concentration pathways (RCPs) 2.6, 4.5, and 8.5. This is a step forward as previous studies of Seewinkel did not use climate model ensembles in their analysis. In this study, a scenario in which no adaptation is implemented (business-as-usual scenario; BAU) is compared against four adaptation scenarios. The adaptation measures are based on the measures suggested by stakeholders and the local government and recorded by Kropf et al. (2021).

2. Materials and methods

2.1. Case study

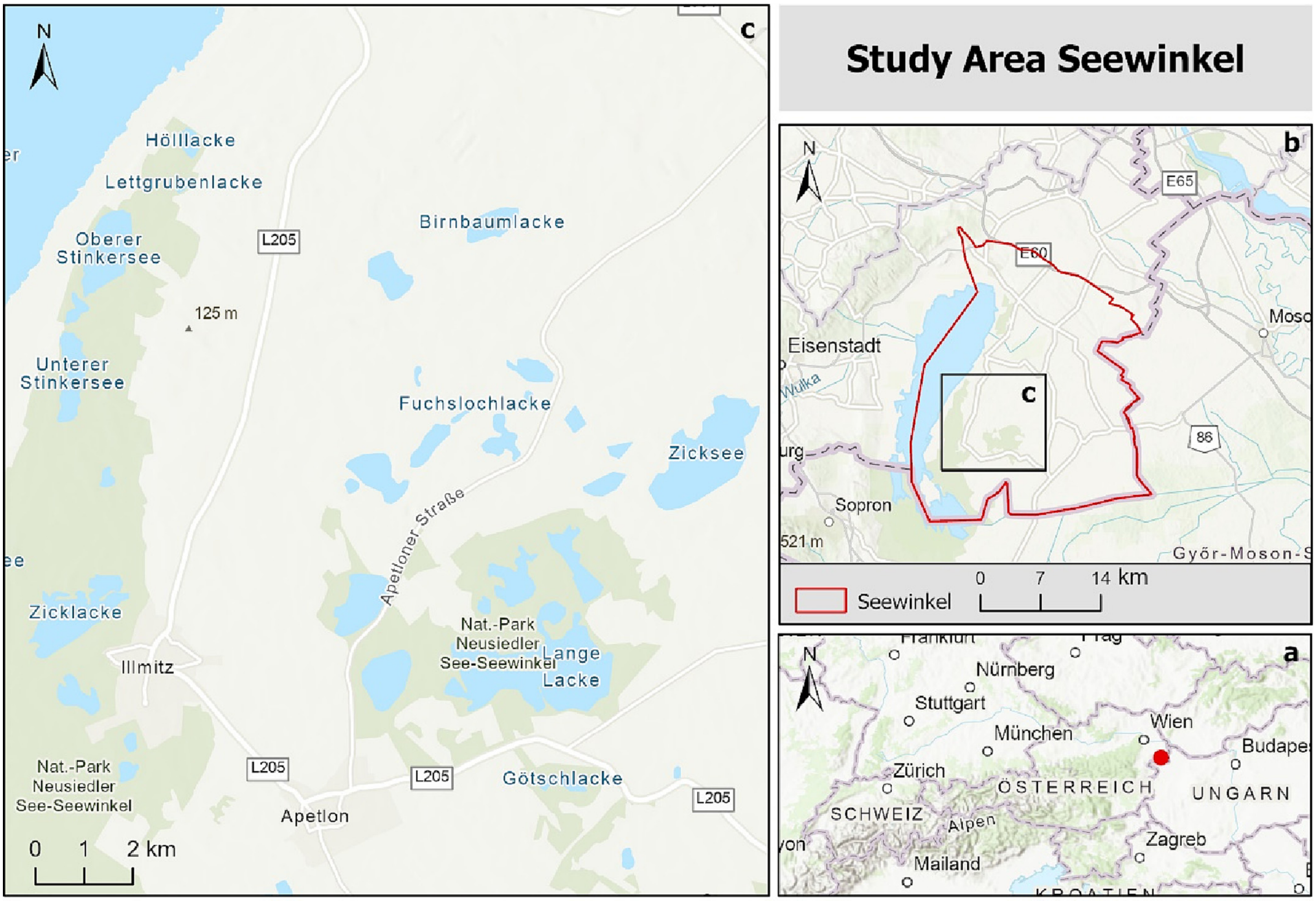
Seewinkel is a semi-arid region (Mitter and Schmid, 2021) located in the east of Austria in the state of Burgenland between Lake Neusiedl and the Austrian-Hungarian border (Fig. 1). The region is approximately 450 km^2, has an average annual temperature of 10 °C and has average annual precipitation of 600 mm (Kropf et al., 2021). The region is located west of Lake Neusiedl, the largest endorheic lake in Central Europe (Kropf et al., 2021) and also the largest lake in Austria (Soja et al., 2013). A vast majority of the land in Seewinkel is used for agriculture, 56 % for cropland, 6 % for grassland and 10 % for vineyards (Karner et al., 2019). Because of the semi-arid conditions, local agriculture relies on irrigation. Farmers extract water from the single local aquifer and irrigate using sprinkler systems for the crops and drip irrigation for the vineyards. Local crop production includes sugar beets, potatoes, corn, cereals, soya and sunflowers (Mitter and Schmid, 2021). While currently water demand is dominated by agriculture, demand by other sectors such as tourism and nature conservation is increasing (Mitter and Schmid, 2021).

Local agriculture shares the land with numerous saline lakes called “Salzlacken”. These saline lakes are a local habitat for amphibians, birds and florae (Krachler et al., 2012; Rechnungshof Österreich, 2020). Preserving the saline lakes is of vital importance for local biodiversity and tourism. The saline lakes are a fragile ecosystem that depends on groundwater (Magyar et al., 2021). Sinking groundwater levels could destroy these ecosystems, as a minimum groundwater level is necessary to maintain their hydro-chemical balance (Krachler et al., 2012). However, since the beginning of the 20th century, some of the lakes have been heavily modified and intentionally dried out. According to Krachler et al. (2012), maps from the middle of the 19th century show 139 saline lakes, but 80 of them have since been damaged beyond repair, leaving only 59 existing or worth considering for re-naturalization. The combined areas of the salt lakes fell from 3600 ha in 1858 to only 660 ha in 2006, which implies a loss of almost 82 % of this unique natural habitat (Rechnungshof Österreich, 2020).

Because Seewinkel is a semi-arid region, climate change in combination with human activities increases the risk of water stress (Magyar et al., 2021). Currently, groundwater extraction is regulated by water cooperatives (Magyar et al., 2021; Mitter and Schmid, 2021), but the aquifer is being exploited at 78 % of its sustainable yield (Bundesministerium für Landwirtschaft Regionen und Tourismus, 2021; Lindinger et al., 2021). Kropf et al. (2021) engaged local stakeholders in a multi-step cognitive mapping approach to discuss climate change adaptation. In the process, they recorded the stakeholders' perceptions and discussed adaptation measures. Among the most discussed measures were (I) adjusting the current crop rotation, (II) improving irrigation efficiency, and (III) artificial aquifer recharge. Artificial recharge is part of a governmental project, which includes the construction of a canal to bring water from the Moson-Danube River into the Seewinkel region to artificially recharge the aquifer.

2.2. Historical data

The SD model was calibrated using hydrological and climate data for the reference period 1981 through 2011. Groundwater level data recorded in boreholes and lake control-station data are available in the Austrian water portal (eHYD.gov.at) (Appendix 1). The lakes have measuring stations recording the fluctuations in the water depth at a daily scale. For the aquifer, daily groundwater level data from 70 measuring stations were normalized and averaged to get a single dataset.



Base Map: Topographic, ESRI | April 2023

Fig. 1. Map the study area. Seewinkel is located in East Austria (a) more specifically, east of Lake Neusiedl and west of the Austrian-Hungarian border (b). The region is known for its saline lakes (c).

The Austrian water portal also provided precipitation data from seven weather stations located inside the basin for the same reference period (1981–2011) (Appendix 1). Because the model is not spatially distributed, precipitation was averaged at a monthly basis for the whole region. There were no significant differences between the weather stations as the region is very small and flat. The potential evapotranspiration data were calculated by using the CWatM (Burek et al., 2020) using the Penman-Monteith equation (Monteith, 1965).

2.3. Climate projection data

To simulate the region's conditions under climate change, this study used EURO-CORDEX data (Jacob et al., 2014) for three RCP scenarios. The RCPs represent three possible climate change futures as proposed in the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. These scenarios depend on the amount of greenhouse gases emitted in the coming decades. This study considered three RCPs, RCP 2.6, RCP 4.5 and RCP 8.5, as they represent the best, intermediate and worst climate change scenarios. The RCP 2.6, RCP 4.5 and RCP 8.5 scenarios represent futures in which the global mean surface temperature rises up to 2 °C, 2 °C to 3 °C and >4 °C, respectively.

For climate services purposes, the EURO-CORDEX community recommends use of the largest possible model ensemble in order to achieve robust results (Benestad et al., 2021). Consequently, a multi-model ensemble was used for each RCP (Appendix 2). Each model ensemble member was fed individually into the SD model. Monthly near-surface temperature, precipitation and potential evapotranspiration data were used for each RCP. Near-surface temperature and precipitation were taken directly from the ensemble members. Potential evapotranspiration was calculated from daily near-surface temperature, maximum near-surface temperature and minimum near-surface temperature using the method of Hargreaves and Samani (1985) (Hargreaves and Samani, 1985) provided by the Python package xclim (Logan et al., 2021). Spatial averages over the Seewinkel region were calculated with pyweights function.

The direct use of climate data as inputs for impact models, however, is not recommended, as regional climate model outputs may still have considerable systematic biases that could produce inaccurate results (Mendez et al., 2020). Imperfect conceptualization, discretization and spatial averaging within grid cells leads to bias errors between climate models and observations (Soriano et al., 2019). Therefore, most climate change impact studies require an additional processing step with bias correction methods before the regional climate model data can be used so their statistical properties are more similar to the ones observed (Galmarini et al., 2019; Mendez et al., 2020).

Because of this, the climate data were bias adjusted by application of the correction method using standard deviation presented by Bouwer et al. (2004) in Eq. (1). By application of this method, the climate data were corrected against the observed average and for the observed variance. The chosen baseline period was 1981–2005, as 1981 is the first year for which complete observational data are available and 2005 is the last year of the historical period of the climate models.

$$a'_{cm,j} = \frac{\left(a_{cm,j} - \bar{a}_{cm,j}\right)}{\sigma_{cm,j}} \times \sigma_{obs,j} + \bar{a}_{obs,j} \tag{1}$$

where $a'_{cm,j}$ is the corrected climate parameter of a particular month "j". $a_{cm,j}$ is the uncorrected simulated climate parameter. $\bar{a}_{cm,j}$ is the average simulated climate parameter over the baseline period. $\sigma_{cm,j}$ is the standard deviation of the simulated parameter over the baseline period. $\sigma_{obs,j}$ is the standard deviation of the observed climate parameter over the baseline period, and $\bar{a}_{cm,j}$ is the average observed climate parameter over the baseline period.

2.4. SD and the SD model

SD is a method developed by Jay Forrester during the 1950s to model complex systems and the interactions within them. The method has proven useful for the simulation of complex environmental and water problems (Phan et al., 2021; Zomorodian et al., 2018). SD has been used extensively as a tool for water management as the interactions between hydrological systems, society and the environment can be built into the models. For example, SD has been implemented to improve water resources management (Correia de Araujo et al., 2019; Dong et al., 2019; Kotir et al., 2016; Mirchi et al., 2012; Sun et al., 2017), groundwater management (Barati et al., 2019), river management (Hassanzadeh et al., 2014; Rubio-Martin et al., 2020) and water management for climate change adaptation (Gohari et al., 2017).

Phan et al. (2021) performed a review of 169 studies applying SD for water resources management and found that SD has several disadvantages. First, modelers face difficulties during the model development, calibration and validation because of the discrepancies between scales. Second, non-linearities, delays and feedbacks cause uncertainties and dynamic complexities. Third, SD has limitations in dealing with spatial dynamics and the incorporation of qualitative perspectives. However, SD models also offer several advantages that are usually exploited to support water management. First, SD models can integrate information provided by stakeholders. Second, SD models assist decision makers to answer "what if" questions by simulating measures for water-related problems under different possible scenarios. Third, SD models usually compute results relatively quickly compared to other modelling methods (Zomorodian et al., 2018). This is a strong advantage of SD models over purely hydrological models or hydro-economic models, which are computationally intensive.

For the reasons mentioned above, SD models are well suited to test adaptation measures and support climate change adaptation. The SD model (Fig. 2) developed in this study is a deterministic lumped model with a monthly time step and is forced with precipitation and evapotranspiration data because, according to Magyar et al. (2021), the main drivers of the monitoring wells in Seewinkel are precipitation and evapotranspiration. The model consists of six stocks.

The first stock represents water stored in the upper soil layers. The soil infiltration is modeled based on the curve number method (Eqs. (2), (3) and (4)) (Boonstra, 1994). First, a curve number was selected based on the physical characteristics of the region. Then, Eq. (2) was used to calculate the maximum soil water retention capacity (S) in millimeters.

$$S = \frac{25,400}{CN} - 254 \tag{2}$$

Runoff (Q) was calculated using Eq. (3). According to the curve number method, runoff only begins if precipitation is >20 % of S. This initial accumulation of 20 % accounts for water intercepted in surface depressions or by vegetation (Bos et al., 2009). With the runoff (Q) and precipitation (Pp) values, infiltration is calculated with Eq. (4).

$$Q = \frac{(Pp - 0.2S)^2}{(Pp + 0.8S)} \text{ if } Pp > 0.2S \tag{3}$$

$$\text{Infiltration} = Pp - Q \tag{4}$$

Infiltration fills the soil reservoir, and water is stored in that stock. Water leaves the soil stock either by evapotranspiration or as aquifer recharge. Potential evapotranspiration is satisfied by the water stored in the soil reservoir; thus, actual evapotranspiration can be smaller than potential evapotranspiration. Aquifer recharge happens only when the water stored in the soil is equal to or greater than S. Once water exceeds S, the excess leaves as recharge.

The second stock represents the aquifer. Water enters the aquifer stock as recharge and leaves by either baseflow or extractions. The relationship between the aquifer stock and the baseflow follows a linear behavior (one recession coefficient), shown in Eq. (5). Because aquifers are not empty stocks but rather layers of water-bearing materials such as gravel, sand or

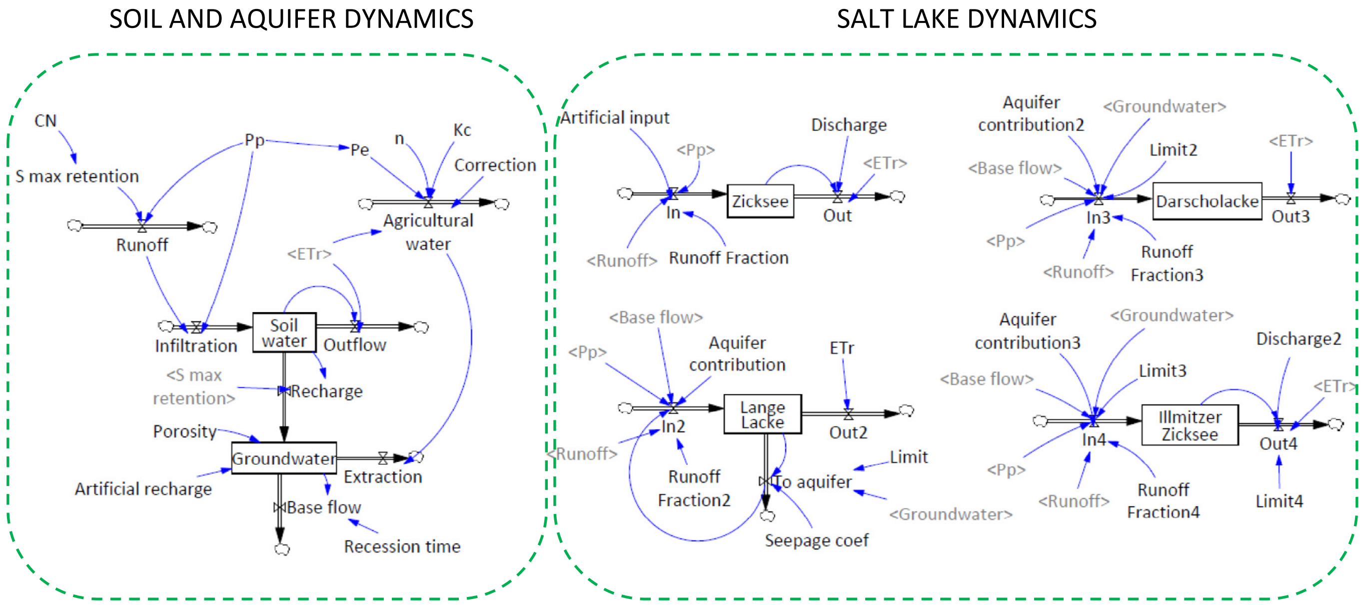


Fig. 2. The SD model with its two sub-models. The sub-model on the left simulates the soil and aquifer dynamics as well as the IWD. The sub-model on the right models the lake dynamics. CN is the curve number, Pp is the average monthly precipitation, Pe is the effective precipitation, ETr is the average monthly evapotranspiration, Kc is the crop factor and η is the irrigation efficiency.

permeable rocks, the model considers porosity as a factor. The aquifer dynamic behavior is governed by Eq. (6).

$$\text{Baseflow} = \text{Groundwater} * \text{Recession time} \qquad (5)$$

$$\text{Groundwater} = \frac{(\text{Recharge} - \text{Extraction} - \text{Baseflow})}{\text{Porosity}} \qquad (6)$$

In Seewinkel, the agricultural industry is the only sector extracting water from the aquifer. Because of this, the influence of agricultural water extraction on the aquifer's dynamics is included in the model (Fig. 2). Because of unavailability of data needed to determine irrigation water extractions, the monthly IWD was calculated using an irrigation demand Eq. (7) based on Brouwer and Heibloem (1986), Shen et al. (2013) and Wang et al. (2016). The equation requires data on monthly evapotranspiration (ETP) and precipitation (Pp) data. The effective precipitation (Pe) is calculated based on Pp with Eq. (8) as provided by Brouwer and Heibloem (1986). The crop factor (Kc) is related to the crop type, the irrigation efficiency (η) represents the efficiency of the implemented irrigation method and a correction factor (cf).

$$\text{IWD} = \frac{(\text{ETP} * \text{Kc}) - \text{Pe}}{\eta * \text{cf}} \qquad (7)$$

$$\text{Pe} = 0.8 * \text{Pp} - 25 \text{ if Pp} > 75 \qquad (8)$$

$$\text{Pe} = 0.6 * \text{Pp} - 10 \text{ if Pp} < 75$$

The crop factor (Kc) is unique for every crop and changes over the growing season. Kc values are usually available in manuals. In this study, the values were obtained from Brouwer and Heibloem (1986). As stated before, the main crops in Seewinkel are potatoes, sugar beets and corn. Because these crops have quite similar crop factors and vegetation periods, an average value was taken to simulate the crop water demand of the combined crop rotation (Appendix 2).

As previously mentioned, the irrigation efficiency (η) is needed to calculate the IWD. According to Howell (2003), common irrigation methods, for example, sprinkler irrigation, have efficiencies of 60 % to 85 % with average efficiency of 75 %. In contrast, water-saving irrigation methods like drip irrigation have efficiencies of up to 95 %. In the case of Seewinkel, farms rely on the moving big gun method, which has an efficiency of 55 % to 75 % with an average efficiency of 65 %. This last value was selected to calculate the IWD of the study area.

The remaining four stocks represent the four largest saline lakes. These lakes are the Zicksee, the Lange Lacke, the Darscholacke and the Illmitzer Zicksee. The dynamic behavior of the saline lakes (Fig. 2) is based on the extensive descriptions reported by Krachler et al. (2012). The lakes receive water from precipitation and runoff and from the aquifer. Their common characteristic is that water mainly leaves the lakes through evaporation, which explains their saline nature. In some special cases, water leaves the lakes through discharge or infiltration. Since the beginning of the 20th century, each saline lake has been managed and modified in different ways. In the Lange Lacke, for example, water flows in both directions. Once the aquifer level drops, water flows from the lake into the aquifer. The Zicksee, on the other hand, receives an annual artificial recharge of around 300,000 m^3 coming from a well next to the lake.

2.5. SD model calibration

The SD model was calibrated using the historical data and the optimization tool in the software Vensim developed by Ventana Systems. Vensim is a software designed to build and run SD models. The software optimizes user-defined model parameters to match historical observational data. Simulations are repeated until the parameters provide results that match the historical data. For the calibration, monthly observational data of the groundwater and lake fluctuations were used (reference period 1981–2011). For the aquifer, the data of 70 measuring boreholes were converted into anomalies and averaged to obtain an overview of the aquifer behavior. In the case of the saline lakes, each of the lakes included in the model has a measuring station.

After the calibration, a goodness-of-fit analysis was performed using three coefficients commonly implemented in hydrological modelling. The coefficient of determination (R^2) is widely applied to test the goodness-of-fit of hydrological models (Moriasi et al., 2015; Onyutha, 2022). However, several studies have highlighted that R^2 does not quantify the model bias and is insensitive to additive and proportional differences between observations and simulations (Legates and McCabe, 1999; Onyutha, 2022). For this reason, three coefficients were used to test the goodness-of-fit: R^2, the Nash-Sutcliffe efficiency (NSE) (Nash and Sutcliffe, 1970) and the normalized root mean square error (nRMSE) as implemented by Guillaumot et al. (2022).

The NSE describes the relative magnitude of the residual variance compared to the observational data variance. Generally, models with a NSE ≥ 0.50 are classified as satisfactory. NSE values of <0.2, 0.2–0.4, 0.4–0.6, 0.6–0.8, and >0.8 are considered insufficient, sufficient, good, very good, and excellent, respectively (Okiria et al., 2022). At a watershed level, models with a $R^2 > 0.40$ and a NSE > 0.45 are considered satisfactory (Moriasi et al., 2015).

After the calibration, the SD model developed in this work was able to reproduce the yearly and seasonal variations of the groundwater level. For the groundwater, the model had a $R^2 = 0.73$, NSE = 0.73 and nRMSE = 52.3 %, compared to observational data. Fig. 3 shows the output of the model compared to the observational data. In the case of the saline lakes, the model had a $R^2 = 0.56$, NSE = 0.54 and nRMSE = 68.1 % for the Lange Lacke; $R^2 = 0.60$, NSE = 0.6 and nRMSE = 63.7 % for the Zicksee; $R^2 = 0.44$, NSE = 0.31 and nRMSE = 83.3 % for the Darscholacke and $R^2 = 0.19$, NSE = −0.29 and nRMSE = 113.2 % for the Illmitzer Zicksee.

Based on the coefficients, the model outputs for the aquifer, the Lange Lacke, the Zicksee and the Darscholacke were satisfactory. However, the model outputs for the Illmitzer Zicksee were not satisfactory. The observational data for the Illmitzer Zicksee were incomplete and were reconstructed with interpolation. The process, however, did not yield acceptable outputs. The model was particularly advantageous to simulate the aquifer's behavior. As previously mentioned, Guillaumot et al. (2022) applied the hydrological model CWatM (Burek et al., 2020) coupled to a groundwater flow model, MODFLOW, in Seewinkel. Their model was able to simulate the aquifer fluctuations and achieved an nRMSE = 52.2 %. This means that the SD model and CWatM were equally capable of modelling the fluctuations of the aquifer in Seewinkel.

2.6. Simulating adaptation scenarios

Five adaptation scenarios were simulated based on a business-as-usual scenario (BAU) and the adaptation measures suggested by local stakeholders as presented by Kropf et al. (2021). These scenarios were as follows: (1) no adaptation measures implemented (BAU), (2) shift to less water-demanding crops (CROP), (3) improve irrigation systems to increase irrigation efficiency (IRRI), (4) artificial recharge (RECH), and (5) a combination of the CROP and IRRI scenario (COMB) (Appendix 3). These measures were selected for two reasons. First, according to the stakeholders, CROP, IRRI

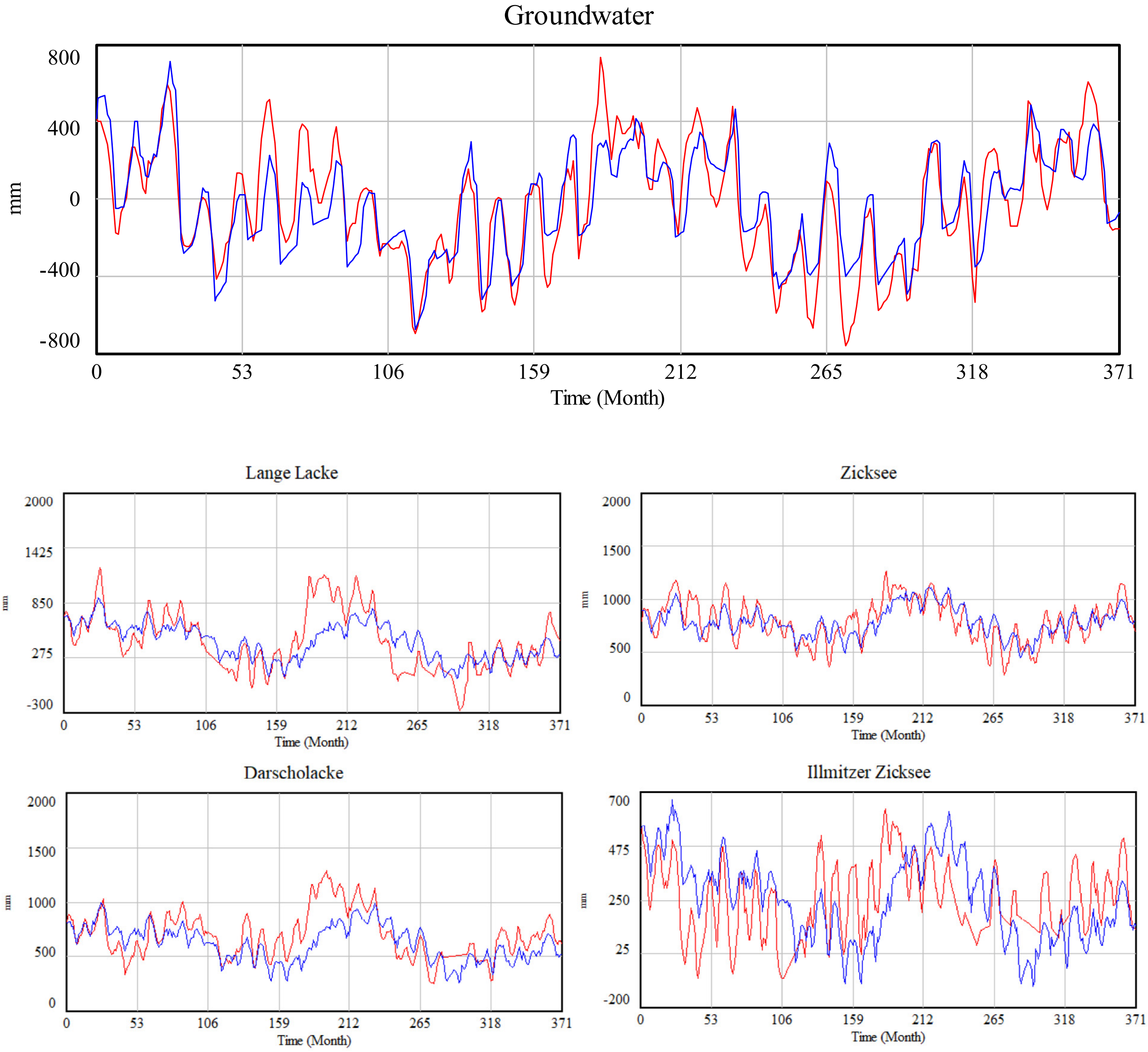


Fig. 3. Output of the model (in blue) and the observational data (in red) for the Seewinkel aquifer showing the deviations around the historical mean (zero) and for the four lakes considered by the model.

and RECH had the highest number of synergies and tradeoffs, with RECH being the most controversial (Kropf et al., 2021). Second, these measures were selected to determine whether the stakeholders' perceptions were accurate. According to Kropf et al. (2021), stakeholders believed that a change to drought-tolerant crops on larger areas could increase the demand for groundwater for irrigation. Some stakeholders also believed that increasing irrigation efficiency would have a small effect in reducing groundwater use for agriculture. The local government planned to implement a project to artificially recharge the aquifer. However, some stakeholders opposed that project, believing that changing crops would be more effective.

To simulate the implementation of an adaptation measure or two adaptation measures in combination, one or more parameters were changed. In BAU, the simulations were run with no changes in the model parameters to simulate the present conditions. In CROP, the crop factors (Kc) and the growing periods were adjusted to simulate a new crop rotation consisting of faster-growing crops with a lower water demand (Appendix 4). The hypothetical crop rotation was based on less water-demanding crops such as sorghum, millet, soybeans, barley and lentils in place of the three most grown crops (potatoes, sugar beets and corn). In IRRI, the irrigation efficiency was increased to simulate a shift into more water-efficient irrigation methods. A shift to irrigation with lateral move spray heads, which has an average efficiency of 85 % (Howell, 2003), was simulated by changing the efficiency in the irrigation demand Eq. (7) from 0.65 to 0.85.

RECH simulated the implementation of artificial aquifer recharge, a measure similar to a project proposed by the government of Burgenland. The project proposed the construction of a canal to connect Seewinkel to the Moson-Danube, an arm of the Danube in Hungary. The water brought into the region could be used to artificially recharge the aquifer in Seewinkel. RECH simulated a scenario in which 3.75 M m^3/month (ca. 6.54 mm/month) would be diverted via the canal into Seewinkel and used to recharge the aquifer (ORF, 2021). Finally, COMB simulated a scenario in which farms adapt to climate change by combining IRRI and CROP. To simulate this scenario, the irrigation efficiency was increased to 0.85 and the Kc changed to simulate the less water-demanding crop rotation mentioned above.

Simulations were done using the Python library PySD to run the calibrated SD model. PySD is a tool that facilitates the integration of data science and SD models (Houghton and Siegel, 2015). Traditionally, SD models can run only one simulation at a time, meaning that only one input dataset and one output dataset can be computed per simulation. The modeler would have to manually change the input dataset to compute new results. However, with PySD it is possible to run simulations with input datasets composed of data ensembles. This means that the model can be run multiple times, each time with a new input dataset. The results can then be automatically saved, processed and properly displayed. PySD allowed the SD model to be run with each RCP data ensemble to simulate five possible adaptation scenarios. In total 15 simulations were done using the multi-model ensemble climate projections.

3. Results

The modelling results are presented in this section. The dynamic behavior of irrigation demand (Fig. 4), the aquifer level (Fig. 5) and the salt lake depth (Fig. 6) were used as reference parameters to compare the effectiveness of the adaptation scenarios. BAU represented the baseline to which IRRI, RECH, CROP and COMB were compared. The ranking of the adaptation scenarios based on the simulation results is also presented in this section.

3.1. Irrigation demand under climate change and adaptation scenarios

In BAU, the average IWD was 5.2 % less for RCP 4.5 than for RCP 2.6 and 2.5 % less for RCP 8.5 than for RCP 2.6 (Fig. 4). In regards to the adaptation scenarios, for all RCPs, COMB was the most efficient scenario and reduced the IWD by an average of 40 % compared to BAU. For all RCPs, IRRI was almost as effective as CROP, and IRRI and CROP each reduced the IWD by an average of 23 % compared to BAU. RECH had a direct effect on the available water but did not influence the IWD or the decisions taken by farmers. Only CROP and IRRI or a combination of these reduced the IWD.

3.2. Aquifer level under climate change and adaptation scenarios

For all RCPs, the aquifer showed an average drop below the historical average (zero) of 0.90 m in BAU (Fig. 5). For RCP 2.6, the aquifer level was stable over time. For RCP 4.5 and RCP 8.5, the aquifer level increased after 2060 (Fig. 5). However, in BAU, the average groundwater volume was 21.8 % less for RCP 4.5 than for RCP 2.6 and 20.7 % less for RCP 8.5 than for RCP 2.6.

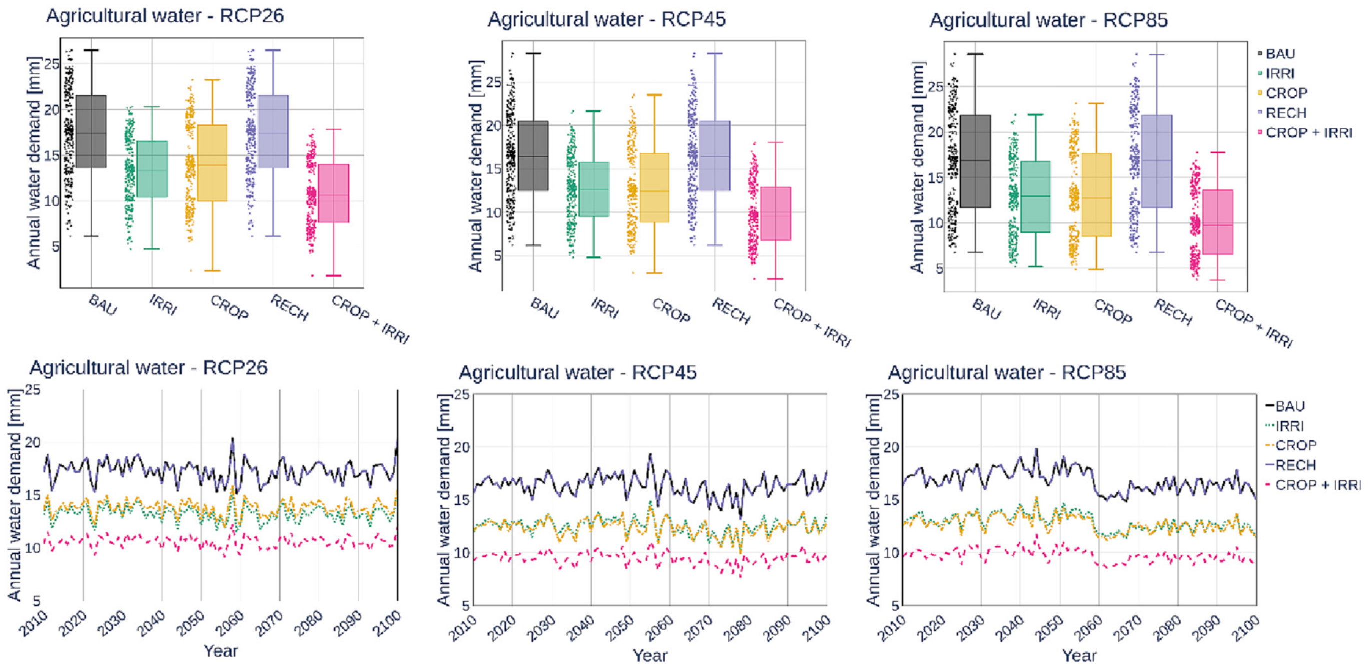


Fig. 4. Average annual IWD under three RCP scenarios and four adaptation scenarios for the reference period (2010–2100).

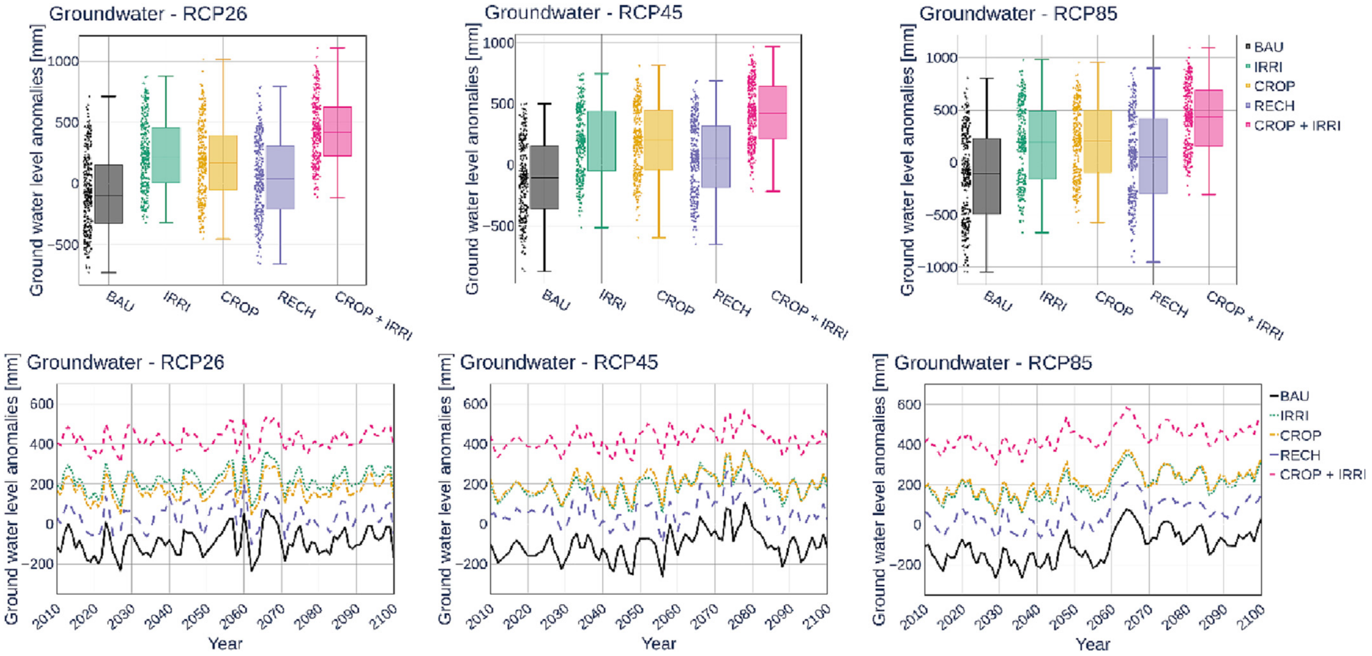


Fig. 5. Aquifer level under three RCP scenarios and four adaptation scenarios for the reference period (2010–2100). The zero represents the historical average of the aquifer.

All of the adaptation scenarios promoted an increase in the ground water level (Fig. 5). The most effective scenario was COMB, which promoted an average increase in the stored volume of about 0.43 m above the historical average (zero) (0.52 m above BAU) for all RCPs. IRRI and CROP followed; each of these scenarios promoted an average increase of 0.20 m above the historical average (0.3 m above BAU) for all RCPs. Lastly, RECH was the least effective, promoting an average increase of 0.06 m above the historical average of the aquifer (0.15 m above BAU) for all RCPs.

3.3. Salt lake depth under climate change and adaptation scenarios

For RCP 2.6 and RCP 4.5, the salt lakes depth decreased until 2060 when this trend changed to a drastically incremental trend (Fig. 6). For RCP 8.5, the Darscholacke and the Lange Lacke completely dried out before 2030 and remained dry up until 2060, after which they recovered. For RCP 8.5, the Illmitzer Zicksee dried out in the decade of 2050. The Zicksee did not dry out under any of the RCPs, possibly because it is the only lake that receives a continuous artificial recharge as it is no longer connected to the aquifer. Nevertheless, the Zicksee also showed a drastically increase after 2060.

The effectiveness of the adaptation scenarios differed by lake. In the Darscholacke (Fig. 6, first row), for all RCPs, the most effective adaptation scenario was COMB, followed by CROP, IRRI and RECH. In the Lange Lacke (Fig. 6, second row), for RCP 2.6, the most effective scenario was CROP, followed by RECH, IRRI and COMB. For RCP 4.5, the most effective scenario was CROP, followed by IRRI and COMB and lastly RECH. For RCP 8.5, the scenarios seemed to have no positive effect. The adaptation scenarios did not affect the Zicksee (Fig. 6, third row) as it is not connected to the aquifer. The Illmitzer Zicksee (Fig. 6, fourth row) was not considerably affected by any of the adaptation scenarios.

3.4. Ranking of the adaptation scenarios

Climate change adaptation scenarios in Seewinkel should be equally beneficial for the natural resources and the local agriculture. Therefore, the ranking was based on their effectiveness in terms of improving the resilience of the different water bodies and reducing the IWD. The adaptation scenarios were ranked on a scale from 1 to 4, with 1 being the most effective adaptation scenario and 4 the least effective for that particular parameter under a particular RCP (Table 1). When a scenario had no effect on a parameter, the scenario was ranked 5. The Zicksee was excluded from the ranking as none of the scenarios had any effect under any RCP. The Illmitzer Zicksee was also excluded as the model had a poor performance simulating this lake.

Table 2 presents the results after the ranking. For RCP 2.6, COMB was the most effective scenario, followed by CROP and IRRI, tied for second place, and finally RECH. For RCP 4.5, COMB was the most effective scenario, followed by CROP, IRRI and RECH. For RCP 8.5, COMB was again the most effective scenario, followed by CROP, IRRI and RECH. The scores of the adaptation scenarios under the different RCPs were added to obtain a value representing effectiveness under all climate change scenarios. After this addition, CROP had a score of 27, IRRI of 33, RECH of 47 and COMB of 20, meaning that COMB was the most beneficial for both the water bodies and irrigation demand, followed by CROP, then IRRI and lastly RECH.

4. Discussion

4.1. Effectiveness of the adaptation scenarios

The results of this study offer new insights into the interactions between agriculture, the aquifer and the saline lakes in Seewinkel under climate change. It is also the first study to use climate model ensembles for three RCPs (2010–2100). Previous studies have studied the relationship between land use, irrigation and net benefits (Karner et al., 2019) and the relationship between water pricing, land use, water extractions and net benefits (Mitter and Schmid, 2021). While these studies yielded useful results, they were based on stochastic climate scenarios, were limited to 31-year horizons and did not show the effect on the aquifer and the lake volumes. Because this study is based on model ensembles, the results represent the most probable scenario based on all available climate models.

The results of this study confirm that changes to the demand side are the most effective approach to reduce the IWD and preserve the local water resources. This has been observed by previous studies in the region. Mitter and Schmid (2021) found that setting the price of water at 0.7 €/m^3 could stop groundwater extractions for irrigation in Seewinkel. However, this would cause a shift in land use and decrease the net benefits of agriculture. Heumesser et al. (2012) implemented a study in Marschfeld, a region close to Seewinkel, and concluded that increasing water prices either delays

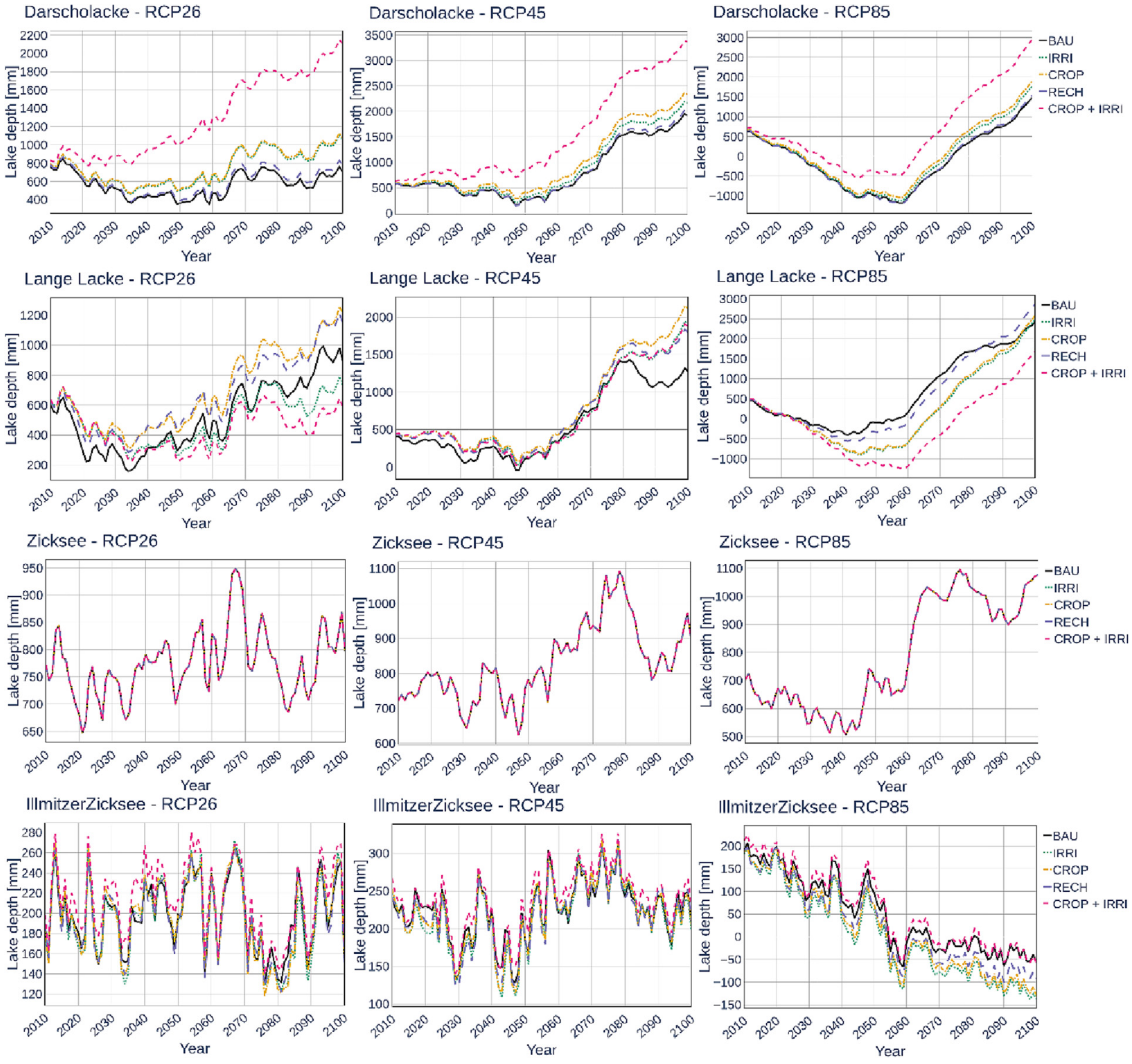


Fig. 6. Salt lake depth under three RCP scenarios and four adaptation scenarios for the reference period (2010–2100).

the adoption of efficient irrigation methods or makes the adoption not profitable at all. The negative backlash of pricing, however, could be avoided by promoting adaptation through more sustainable agricultural practices. As shown by the results of this study, considerable water savings can be achieved with proper irrigation (Chartzoulakis and Bertaki, 2015; Haj-Amor and Acharjee, 2021). Additionally, the results of this study show that improving irrigation efficiency can increase farmers' adaptive capacity (Datta and Behera, 2022; Heumesser et al., 2012; IPCC, 2022). The results of this study also show that changing or diversifying the crop rotation increases the resilience of farms by reducing their water needs and helps them adapt to climate change (Iqbal and Aziz, 2022; Teixeira et al., 2018; Turral et al., 2011; Wang et al., 2023).

The results of this study showed that for RCP 4.5 and RCP 8.5 compared to RCP 2.6, the IWD decreased but so did the stored volume of the aquifer. In BAU, the average IWD was 5.2 % less for RCP 4.5 than for RCP 2.6 and 2.5 % less for RCP 8.5 than for RCP 2.6. Compared to the results of studies

Table 1
Adaptation measures ranked by how effective they were in terms of improving the resilience of the water bodies or reducing the IWD under the three RCP scenarios.

RCP	Scenario	Aquifer	Irrigation demand	Darscholacke	Lange Lacke	Score
RCP 2.6	CROP	3	3	2	1	9
	IRRI	2	2	2	3	9
	RECH	4	5	3	2	14
	COMB	1	1	1	4	7
RCP 4.5	CROP	2	2	2	1	7
	IRRI	3	3	3	2	11
	RECH	4	5	4	3	16
	COMB	1	1	1	2	5
RCP 8.5	CROP	2	2	2	5	11
	IRRI	3	3	2	5	13
	RECH	4	5	3	5	17
	COMB	1	1	1	5	8

Table 2
Adaptation scenarios ranked by how effective they were in terms of improving the resilience of the water bodies or reducing the IWD under the three RCP scenarios, based on a total score across all RCPs.

Scenario	RCP 2.6	RCP 4.5	RCP 8.5	Score
CROP	9	7	11	27
IRRI	9	11	13	33
RECH	14	16	17	47
COMB	7	5	8	20

using stochastic scenarios, however, the results using RCPs showed only small changes. According to Mitter and Schmid (2021) a wetter and a dryer scenario would respectively cause changes of −50.2 % and 26.5 % in the IWD in comparison to a scenario with conditions similar to the current. The results of the study reported here showed that such a strong reduction of the IWD could be achieved only in the COMB scenario, where the IWD was reduced by 40 % in comparison to BAU. In contrast, Karner et al. (2019) concluded that a wetter and a dryer scenario would cause the IWD to increase by almost 50 % and decrease by 60 %, respectively. They stated that in a dry scenario, water demand for irrigation would be limited and the irrigated land would be smaller. Besides the reduction in the IWD, the results of this study showed a decrease in groundwater volume. In BAU, the average groundwater volume was 21.8 % less for RCP 4.5 than for RCP 2.6 and 20.7 % less for RCP 8.5 than for RCP 2.6. The results also showed that the majority of the salt lakes substantially recover after 2060 and also suggested that the region will become wetter. The decrease in the IWD and the recovery of the salt lakes might be explained by an increase in precipitation. This increase was observed in RCP 4.5 and RCP 8.5. By the end of the century, the region would receive a higher cumulative precipitation, with 860 mm and 2114 mm more precipitation in RCP 4.5 and RCP 8.5, respectively, compared to RCP 2.6.

In regards to the stakeholders' perceptions of adaptation, the results of this study have helped clear up some misconceptions regarding the adaptation measures. As previously mentioned, according to Kropf et al. (2021), stakeholders in Seewinkel believed that a change to drought-tolerant crops on larger areas could increase the demand for groundwater for irrigation, a belief that this study has proven to be incorrect. The results of this study showed that changing crops reduced the IWD by 23 % in comparison to BAU for all RCPs. This reduced the pressure on local water resources and promoted an increase of 0.20 m above the historical average of the aquifer (0.3 m above BAU) for all RCPs. Changing crops was also an effective measure to promote conservation of the saline lakes. However, implementing these changes has additional challenges. Kropf et al. (2021) found that stakeholders in Seewinkel perceive that a new crop rotation could have economic trade-off such as an increase in the workload or need for investments in new farming equipment. Additionally, for new crop rotations to be successful, they should be compatible with the market demand, promote soil formation and be economically sustainable (Drastig et al., 2016; Schipper, 2020; Valencia Cotera et al., 2022). Crop rotations incompatible with the market demand could make farmers more economically vulnerable, thus causing maladaptation. Designing a new crop rotation for Seewinkel consisting of less water-demanding crops that are also economically feasible represents a research opportunity for future studies.

Moreover, according to Kropf et al. (2021), some stakeholders in Seewinkel believed that increasing the irrigation efficiency would have only a small effect in reducing groundwater use for agriculture, a belief that this study has proven to be incorrect. The results showed that by increasing the irrigation efficiency, farmers in Seewinkel could strongly reduce their IWD by an average of 23 % compared to BAU for all RCPs. The results also showed that the implementation of more efficient irrigation methods could promote an average increase of 0.20 m above the historical average of the aquifer (0.3 m above BAU) for all RCPs and was an effective measure to promote conservation of the saline lakes. However, this is only valid under the conditions that farmers keep the same cropping pattern and not expand their irrigated area. This could allow them to continue using irrigation to cope with dry periods while at the same time reduce the pressure on the local aquifer. However, changing the current irrigation systems would require a strong investment. In Austria, subsidizing these systems could promote their implementation and support farmers (Heumesser et al., 2012). It is also important to consider that reluctance to improve the efficiency of irrigation could ultimately prove to be economically unsustainable, mainly because intensive irrigation could lead to higher energy use, which in turn causes higher emissions (Zhao et al., 2018) and increases production costs (Valencia Cotera et al., 2022). The increase in emissions would be especially high in Seewinkel, where the majority of the water pumps are powered using fossil fuels (Kropf et al., 2021). Because of this, relying only on current irrigation methods could cause a rebound in vulnerability as agriculture might become unprofitable. Further analysis is required to study the economic and energy cost of irrigation in Seewinkel under climate change. These future studies could also propose viable ways to promote and incentivize a shift to more water efficient irrigation methods.

Finally, according to Kropf et al. (2021) stakeholders in Seewinkel who oppose artificial recharge believed that changing crops would be more effective, a belief that this study has confirmed. Artificial recharge has proven to be an effective method to promote sustainable groundwater use and increase aquifer reserves (Javadi et al., 2021; Prabhu and Venkateswaran, 2015). The results of the study reported here showed that artificial recharge was the least effective single measure to increase and protect water resources in Seewinkel. If this measure is implemented, it could still, however, improve the state of the aquifer and the salt lakes. Artificial recharge could increase the aquifer level by 0.06 m above the historical average of the aquifer (0.15 m above BAU) and was effective under all RCPs. However, this is the only measure that does not reduce the IWD, and it could be the most expensive. While this measure only improved the local water resources, it could also help improve the resilience of farms by increasing the water supply. Artificial recharge has potential benefits beyond increasing the aquifer stored volume. For example, it could reduce the concentration of nitrate pollutants in the aquifer (Cao et al., 2022). In contrast, the project plans to bring water from the Moson-Danube, which could cause a shift in vulnerability or a degradation of the common good, two types of maladaptation (Juhola et al., 2016). This project might also require large investments, which might be better used to support farmers implementing changes to their irrigation systems and crop rotations.

4.2. Strengths and drawbacks of the SD model

The SD model presented in this study had a good performance simulating the water cycle and the effect of the IWD on the aquifer. As previously mentioned, in comparison to the hydrological model, CWatM, the SD model presented in this study was equally capable of simulating the aquifer fluctuations. Both models achieved an nRMSE = 52 %. Additionally, the R^2 of 0.73 and the NSE of 0.73 indicated a high correlation between observations and simulations. This represents the main advantage of the model as a modest lumped hydrological model performed as well as CWatM. However, the SD model was not able to simulate the lake behavior with the same degree of accuracy as CWatM. The correlation between observations and simulations for the Lange Lacke, the Darscholacke and the Zicksee were acceptable, but the model performed poorly for the Illmitzer Zicksee, and this lake had to be excluded from the analysis. This represents the first weakness of the model. However, the study's objective was to understand trends and behaviors; therefore, the lakes' correlations were deemed acceptable.

Additionally, the model has other two opportunities for improvement. First, the curve number method (also known as Soil Conservation Service curve number method) used in the model to calculate runoff might not be the best approach. The curve number method is limited to certain land use types and does not describe the spatial variability of runoff (Bartlett et al., 2016). However, it was decided to implement the curve number method as the Seewinkel region is small, flat and the vast majority of the land in this region is used by agriculture. Thus, uniform conditions were assumed. Second, the model did not consider irrigation return flow. Irrigation return flow is the fraction of irrigation water that percolates and returns to the aquifer, and it can be anywhere from 2 % to 86 % of the irrigation water (Sadik et al., 2022). Guillaumot et al. (2022) did include irrigation return flow in the analysis. Despite these two shortcomings, the SD model yielded excellent results. However, these two points still leave room for improvement.

The main objective of the SD model was to serve as a tool to compare climate change adaptation strategies. Therefore, its intention was not to entirely substitute for hydrological models. However, the results have shown that the model is useful to perform water management analyses for climate change adaptation. In this regard, the model offers several advantages. First, the SD model allows the user to quickly test and evaluate the effect of climate change adaptation measures at a local scale. Second, thanks to the implementation of PySD, the model can be run using climate model ensembles to reduce uncertainty about the future climate scenarios. Third, because of its modular design, the model could be coupled to other SD sub-models to create larger, more sophisticated models. Fourth, the SD model could be reused and recalibrated for other similar regions. Because of these advantages, the model could serve as the foundation for similar future research.

Finally, it should be considered that developing a complete water resources management model is a highly challenging task, and it is extremely challenging to include all factors, feedbacks and relationships (Phan et al., 2021). The authors believe that the model presented in this study offers an acceptable reflection of the current trends in Seewinkel, but they encourage others to expand the boundaries and overcome the limitations of the model with further research.

5. Conclusion

The novel hydrological SD model presented in this study was successful in simulating the interactions between agriculture water extractions and the local water resources. After the calibration, the model had the same accuracy as the advanced hydrological model CWatM in simulating the groundwater fluctuations. The model was also able to simulate the dynamic behavior of three saline lakes with a lower but acceptable accuracy. The analysis of water management measures for climate change adaptation under three RCP scenarios yielded new insights for the region and helped verify the stakeholders' perceptions. The results showed that the most efficient way to adapt agriculture and reduce groundwater extractions is a combination of measures, more specifically, a change to a new crop rotation with an improvement of irrigation methods. In the model, when these measure were applied jointly, the IWD decreased by an average of 40 % and the aquifer increased its stored volume by an average of 0.52 m across RCPS compared to BAU. These measures were also beneficial for two of the saline lakes. Artificial recharge was the less beneficial measure as it did not have any effect on the IWD and it increased the aquifer's stored volume by only 0.15 m across RCPs compared to BAU. Despite these novel results, a socio-economic analysis is still required as adaptation usually requires high investments that farmers are not always ready to make.

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CRediT authorship contribution statement

Rodrigo Valencia Cotera: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Writing – original draft. **Luca Guillaumot:** Conceptualization, Data curation, Supervision, Writing – review & editing. **Reetik-Kumar Sahu:** Conceptualization, Supervision, Writing – review & editing. **Christine Nam:** Supervision, Writing – review & editing. **Ludwig Lierhammer:** Data curation, Writing – review & editing. **María Máñez Costa:** Supervision, Writing – review & editing.

Data availability

Data will be made available on request.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

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