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REPORT

Groundwater sustainability for irrigation in the semi-arid Konya Closed Basin, Türkiye, under climate change scenarios

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Abstract

Numerous aquifer systems are being overexploited to meet the ever-increasing water demands for domestic use, industry, and foremost, agriculture. In this study, the concept of net inflow is explored, combined with groundwater flow modeling to assess the impact of climate change and agricultural practices on the sustainability of groundwater resources. The net inflow concept aims to develop a relation between water level change and groundwater abstraction that can help in the management of groundwater resources. The study is applied to the water-stressed semi-arid Konya Closed Basin (KCB), an agricultural endorheic basin in central Türkiye. A groundwater flow model covering the entire basin, based on the MODFLOW/UZF programs, simulates vertical water flow in the vadose zone and Dupuit flow in the upper aquifer of the underlying subsurface system. The model was calibrated using crop cultivation area, crop water requirements, irrigation efficiency, and groundwater level observations from 29 long-term monitoring wells. Scenario analysis using the calibrated model combined with the net inflow concept and 17 high-resolution climate model projections from the EURO-CORDEX framework were used to examine the sustainability of the basin's groundwater resources. The scenarios considered different water management and irrigation practices co-developed with local stakeholders. Model results show that with the adoption of enhanced irrigation technologies only, groundwater levels will continue to decrease. By combining improved irrigation efficiency with reverting to traditional rainfed crops, it is shown that the overexploitation of groundwater can be mitigated, enabling the protection and more sustainable use of this critical resource.

Keywords Groundwater management · Numerical modeling · Net inflow · Climate change · Türkiye

Introduction

Aquifers are vast natural water reserves that are widely relied upon to meet domestic, industrial, and agricultural water demands. The global groundwater storage in the upper 2 km of the continental crust is estimated to be about 2.3×10^7 km^3 (Gleeson et al. 2016). Although not all this volume is readily accessible, it is nonetheless several orders of magnitude larger than the annual global groundwater recharge, which is estimated to be between $1.3–2.6 \times 10^4$ km^3 (Döll and Fiedler 2008; de Graaf et al. 2019; Berghuijs et al. 2022; Nazari et al. 2025). The accessibility of groundwater resources across all continents has led to an increase in groundwater extractions from about 310 km^3 in 1950 to 1200 km^3 in 2021, a fourfold increase (FAO, 2023). This translates to a per-capita increase of 23% from 124 m^3 in 1950 to 152 m^3 in 2021 (Loaiciga and Doh 2024). Much of the groundwater extractions are used for irrigation purposes to meet increasing demands for food production (Peña-Arancibia et al. 2020; Tulip et al. 2022; Xiang et al. 2022; Ben-Salem et al. 2023). Despite these vast reserves of water, orders of magnitude larger than annual extraction volumes when examined at a global scale, numerous groundwater systems, particularly in arid and semi-arid regions of the world, are under threat (Loaiciga and Doh 2024).

Climate change is expected to exacerbate these challenges. Observed, as well as projected, temperature rise is causing increased soil evaporation, leading to reduced soil moisture that, in many instances, will have to be compensated by increased groundwater extraction. At the same time, changes in precipitation patterns, such as more severe and extended droughts, will likely lead to a severe reduction in groundwater recharge, estimated to be as high as 25–40% reduction in some

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hotspots such as the Mediterranean basin (Jiménez Cisneros et al. 2014).

To mitigate these challenges, it is important to enhance the management of groundwater resources with the aim of significantly extending the life of stressed aquifer systems and ultimately reaching a state of sustainable groundwater use. Groundwater resources modeling plays an important role in achieving this goal (Karatzas 2017). Modeling can assess the impact of different policies or agricultural practices under different climate change scenarios on the sustainability of water resources (Kreins et al. 2015; D'Oria et al. 2019; Abrishamchi et al. 2020; Lyra and Loukas 2023; Noor et al. 2022; Chen et al. 2023; Xiang et al. 2022; Khadim et al. 2023; Feng et al. 2024; Singh 2024; Secci et al. 2024; Yifru et al. 2024). In this regard, the concept of net inflow has been proposed in recent years as an effective approach for examining the behavior of aquifer systems that are being heavily exploited (Butler et al. 2016; Butler et al. 2023). This concept, built on the principle of conservation of mass, examines the relationship between groundwater level change and groundwater extraction (described in more detail in the Model description section). Yet, as often noted (e.g., Healy and Cook 2002; Ebrahimi et al. 2016; Crosbie et al. 2019; Babaei and Ketabchi 2022; Gebru et al. 2024; Karunakalage et al. 2025), the inflows to an aquifer system, including the net recharge and environmental flows between subsurface units, are difficult to estimate. Moreover, while water levels are often regularly monitored, wells in many instances are not metered (Wang et al. 2020). Therefore, in this study, we explore the use of the net inflow concept in conjunction with a groundwater flow model to evaluate the impact of future agricultural practices. For demonstration, the approach is applied to the Konya Closed Basin (KCB), a highly stressed aquifer system located in central Türkiye (Tirol Kırçiçek et al. 2025). The analysis also considers the impact of climatic projections and their uncertainty on groundwater reserves.

The rest of the paper is organized as follows. The section titled "Site description" provides a detailed description of the KCB and the measures being considered to slow down the rapid drop in groundwater levels. The section "Model description" describes the model developed to simulate groundwater flows in the KCB. The concept of net inflow is also presented here. The section "Results" presents the scenario analysis results derived based on the groundwater model and the net inflow concept. The "Discussion" section concludes with a brief summary.

Site description

The KCB is located in the central Anatolian Plateau in Türkiye with elevation ranging from about 900 to 1100 m a.m.s.l. (Fig. 1). It is the largest endorheic basin in Türkiye, with an area of 50,000 km^2. The basin includes two subbasins separated by a plateau oriented in an east–west direction (Bayari et al. 2009). The two subbasins are relatively flat, consisting mostly of marl and limestone lacustrine deposits from the Quaternary period. High mountains form the boundaries of the basin (Roberts 1983). Until the last glacial period, the basin contained two large paleolakes that gradually dried up due to climate change (Kuzucuoğlu et al. 1999).

The hydrogeology of the basin consists of two major aquifer systems. The upper system comprises a shallow, productive freshwater aquifer, while the lower system represents a deep, confined aquifer containing saline to thermal groundwater. The shallow aquifer is primarily hosted in Neogene and Quaternary sediments, whereas the deeper aquifer is associated with the Paleozoic–Mesozoic karstic carbonate formations of the Taurus Aquifer Belt (TAB). The Neogene aquifer, which is several hundred meters in thickness, is the primary aquifer used for groundwater extraction. The deeper thermal aquifer is not accessed by any production wells because of a thick Paleogene rock layer about 100–200 m thick underlying the Neogene aquifer (Bayari et al. 2009). The general direction of groundwater flow is from the Taurus Mountains forming the southern boundary of the basin towards Lake Tuz in the northern subbasin, which represents the main discharge zone of the basin. Historical hydraulic head measurements from the early 1970s—when groundwater abstraction was still minimal—showed a decline in head from about 1100 m near the Taurus Mountains to roughly 905 m in the vicinity of the Lake Tuz, illustrating this south–north flow pattern (Bayari et al. 2009; Eren et al. 2024; Tirol Kırçiçek et al. 2025).

The basin has a semi-arid climate with an annual average precipitation of about 340 mm, mostly during winter and spring. Annual precipitation ranges from about 800 mm in the Taurus Mountains to less than 300 mm in the central eastern plains, while evaporation ranges from near zero in winter to about 282 mm in July (Yılmaz et al. 2021). As in other semi-arid endorheic basins, the KCB is sensitive to precipitation fluctuations, with water use largely dependent on groundwater (Tirol Kırçiçek et al. 2025).

The population of the KCB is approximately 3.2 million, with livelihoods heavily centered on agricultural activities. About one-third of all agricultural lands are irrigated; this proportion is growing in parallel with rising temperatures. Groundwater extraction in the KCB began in the 1960s (WWF 2014), initially through wells drilled by local authorities and non-profit community associations. Although the State Hydraulic Works (DSI) retains ultimate control over groundwater management, institutional fragmentation and limited inter-agency coordination have hampered effective enforcement and oversight. Over the past two decades, farmers have shifted away from rainfed wheat toward more water-intensive crops, especially sugar beet and corn, whose

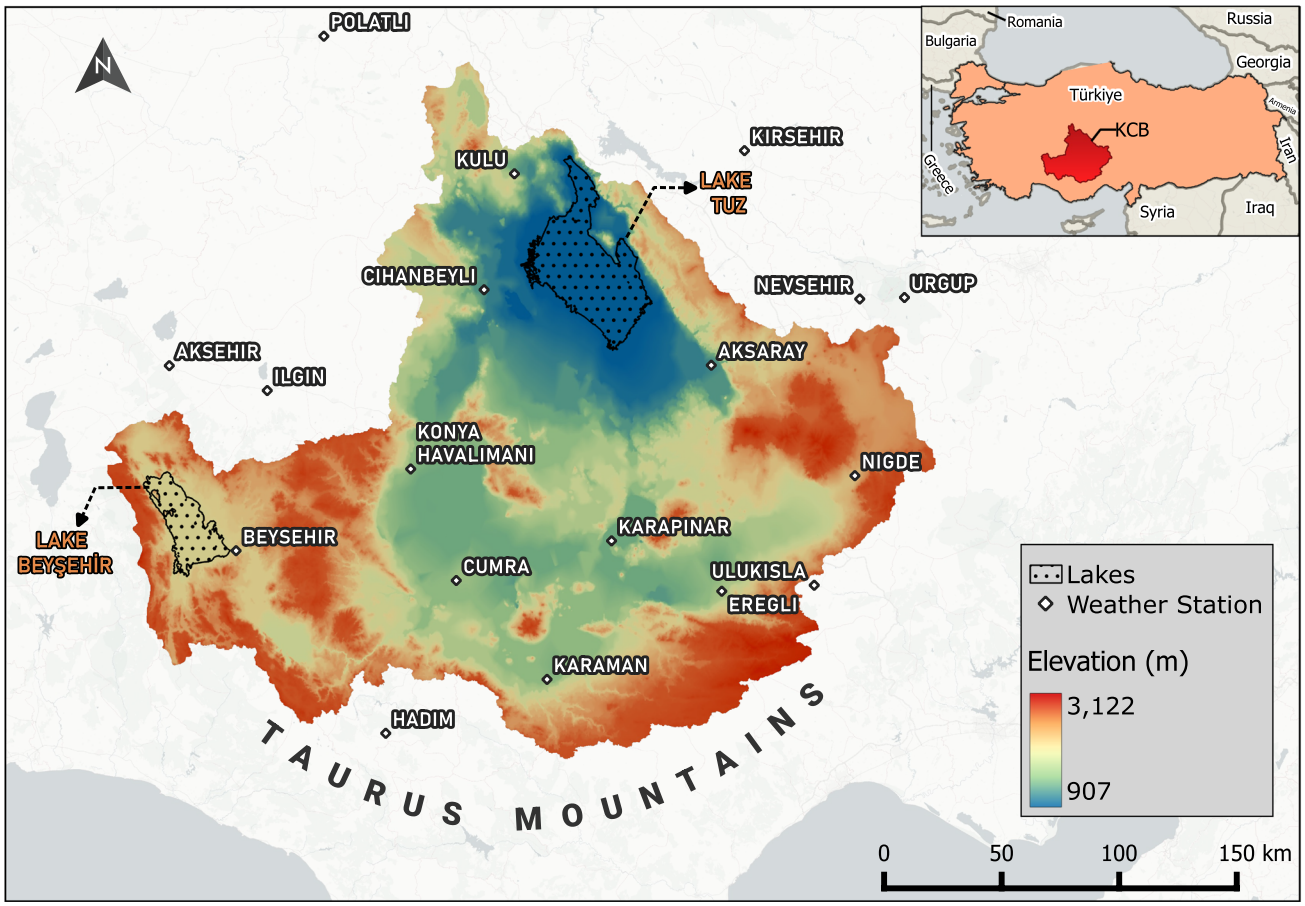


Fig. 1 Location of the Konya Closed Basin

water demands do not align well with the region's precipitation patterns, exacerbating groundwater depletion (Daloğlu Çetinkaya et al. 2025).

The basin has almost no perennial surface water bodies due to its semi-arid climate. There are two major lakes, Lake Tuz, which is now almost completely dry, and Lake Beyşehir, which provides limited water for local irrigation but primarily supplies drinking water. Consequently, surface water plays only a minor role in irrigation, with approximately 90% of all irrigation water drawn from groundwater sources. The priority use of surface water bodies is to meet domestic water demands in urban centers; irrigation water is supplied only when surplus water is available. Additional water transfers occur through the Mavi Tunnel project, which conveys water to the southern districts of the basin from the Taurus Mountains in the Göksu River Basin (an interbasin transfer) and from Lake Beyşehir, the largest yet fragile freshwater lake in the region.

Surface water supplies have become increasingly unreliable due to dry winters, causing farmers to depend more heavily on groundwater. Rising agricultural demand has accelerated, with the spread of pumping wells, creating a troubling "race to the bottom". This de facto open-access regime has led to a rapid increase in both registered and unregistered wells, estimated at over 100,000 (Daloğlu Çetinkaya et al. 2025) with roughly two-thirds being unregulated, and almost all unmetered. In recent years, in the absence of robust monitoring and enforcement, groundwater levels have steadily declined.

Until the early 2000s, flood irrigation with very low water efficiency dominated the basin. From the 2010s onward, government incentives encouraged the adoption of sprinkler and drip irrigation technologies, which, in theory, provide higher technical efficiency. However, in practice, improper operation often negates these potential gains, leaving actual irrigation efficiency low.

Model description

Input data

The hydrological model developed for the Neogene aquifer of the KCB is based on the MODFLOW/UZF computer

program. The program couples the unsaturated-zone flow (UZF) package (Niswonger et al. 2006), which simulates transient vertical water flow through the vadose zone, to the widely used MODFLOW (McDonald and Harbaugh 1988) program, which simulates saturated groundwater flow in the underlying aquifer. A schematic of the processes modeled by the coupled MODFLOW/UZF program is shown in Fig. 2. The program simulates the percolation of water applied to the ground surface in the form of precipitation or irrigation, explicitly accounting for evapotranspiration, downward percolation, and the potential return flow of excess irrigation water back into the aquifer. The water flux at the bottom of the vadose zone therefore represents the net recharge reaching the aquifer after accounting for evapotranspiration and percolation through the root zone. As such, the coupled program does not require defining the net recharge to the aquifer, which is often difficult to estimate. Moreover, the model accounts for lateral flow through the aquifer from the mountainous areas along the basin's edges to the agricultural regions in the basin's center.

As the KCB is an endorheic basin, no flow boundary conditions were imposed at the outer boundary. The flow domain was discretized into uniform 10×10 km cells. This spatial resolution was selected such that cells are smaller than the dimensions of all administrative districts within the basin (Fig. 3), ensuring that key hydrological and land-use patterns are adequately represented. Increasing the spatial resolution would not yield significantly different results given the scale of available data and the regional nature of the model. On the other hand, the use of a coarser grid would limit the model's ability to simulate water demand and irrigation applications.

Meteorological and water demand data were defined on a monthly basis, thus allowing for the growth of different crops such as wheat, which is cultivated in the winter, and corn, which is cultivated in the spring and harvested at the end of the summer. The computational time step was set to 1 day. The monthly precipitation imposed at the surface was spatially interpolated from 18 meteorological stations located within the basin and immediate surrounding areas (Fig. 1).

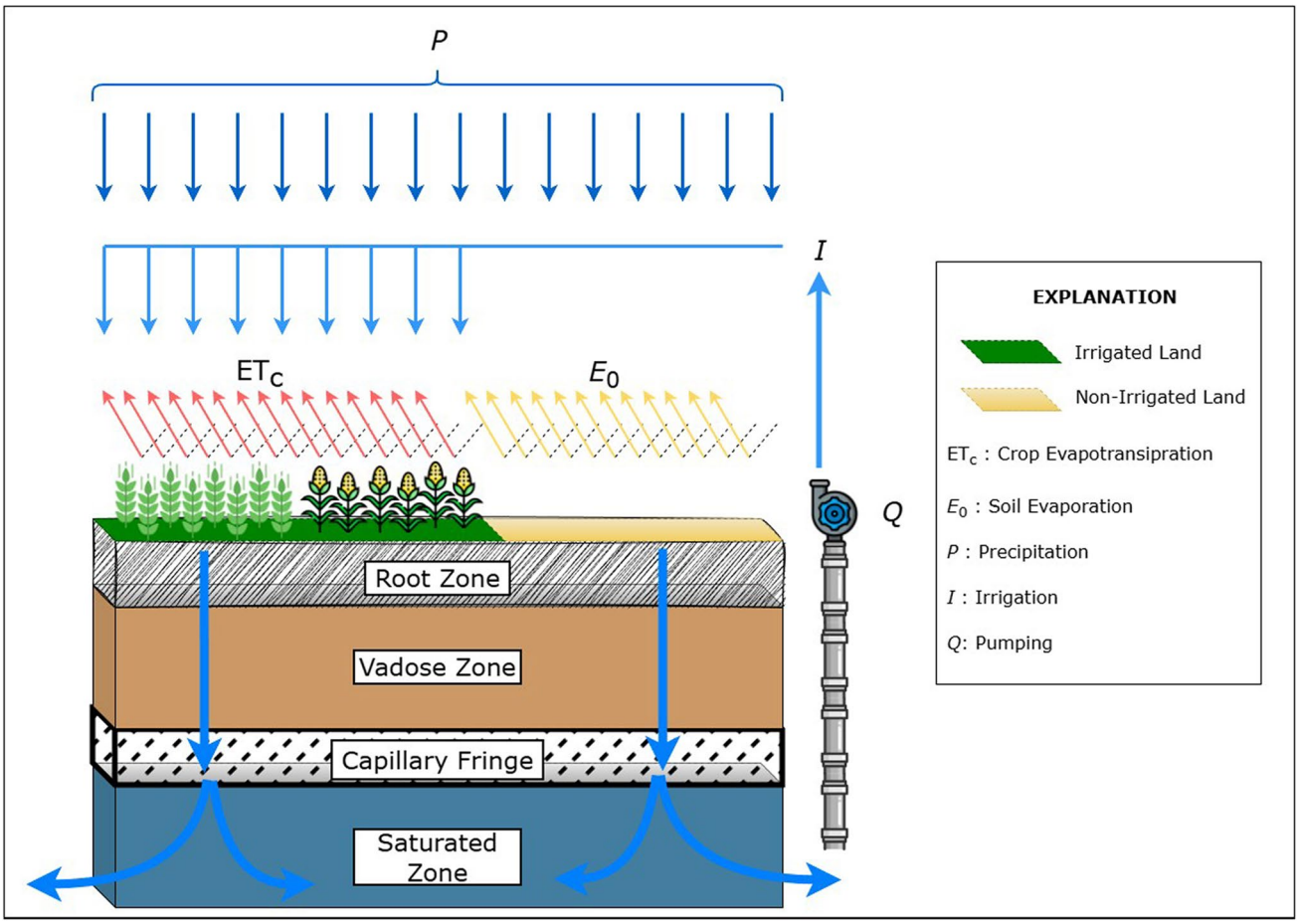


Fig. 2 Schematic representation of the MODFLOW/UZF model

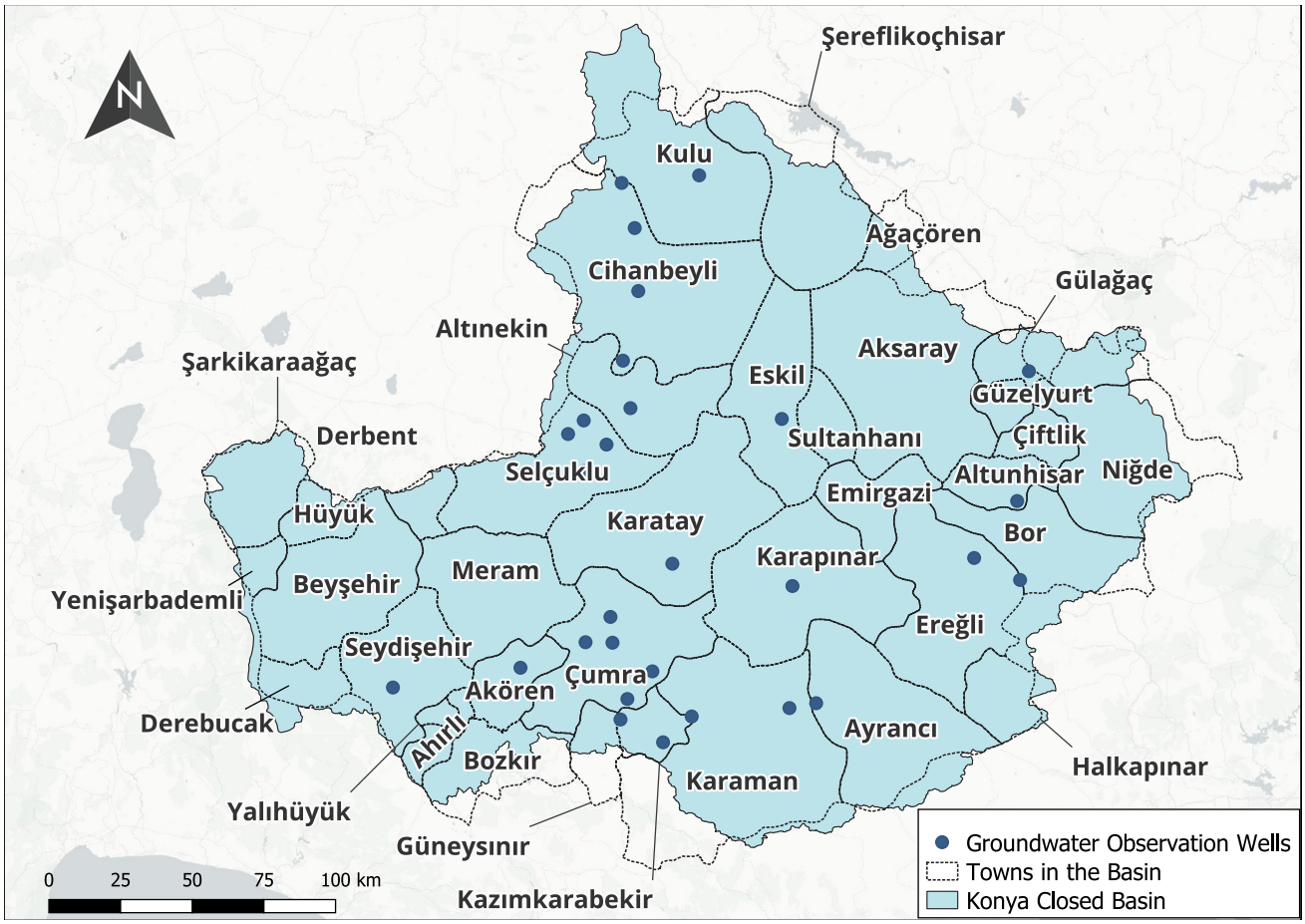


Fig. 3 Administrative districts within the KCB. Long-term observation wells used for model calibration are also shown

Figure 4a illustrates the spatial distribution of average annual precipitation across the KCB, highlighting the steep gradient between the wetter southern highlands and the drier central plains, while Fig. 4b illustrates interannual variability in basin-wide precipitation. Aquifer properties were determined from 81 pumping tests and geologic maps of the basin. The hydraulic conductivity varied between 1 and 150 m/day and was interpolated over the entire flow domain using ordinary kriging. A map of the interpolated hydraulic conductivity is shown in Fig. 4c.

Estimation of irrigation and groundwater extraction rates

As most groundwater extraction wells in the basin are not metered, the monthly groundwater extraction rates were estimated from the annual crop areas reported by the Turkish Statistical Institute (TUIK 2023) which documents the area of each crop for each district of Türkiye and the water requirement of each crop as defined for the Konya region (TAGEM 2017) on district basis (Fig. 3). The spatially and temporally variable water demand is thus calculated as follows:

$$D_i = \sum_{j=1}^{j=N} f_j \times \mathrm{WR}_{i,j} \tag{1}$$

where, D_i is the water demand of month i. This depends on the crop areas and the monthly water requirement of each crop. Here, f_j is the area cultivated with crop j, N is the number of cultivated crops and $\mathrm{WR}_{i,j}$ is the water requirement for crop j and month i.

The irrigation was calculated on a monthly basis as the water deficit, defined as the difference between the water demand and precipitation divided by the irrigation efficiency:

$$\Delta_i = \max(0, D_i - P_i) \tag{2}$$

$$I_i = \frac{\Delta_i}{\epsilon} \tag{3}$$

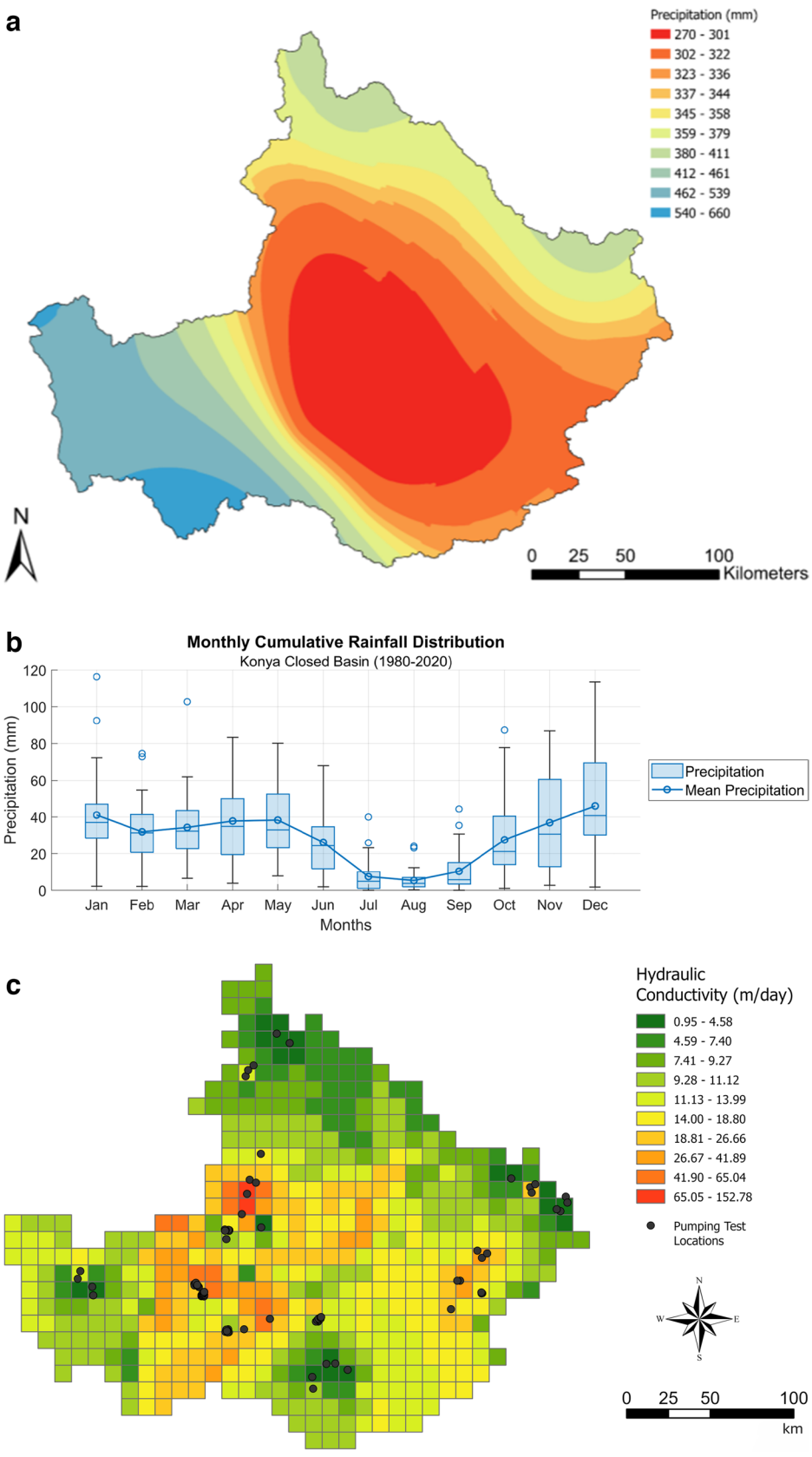


Fig. 4 Key model input parameters: **a)** Average annual precipitation; **b)** monthly precipitation; **c)** hydraulic conductivity estimated using kriging from the available 81 pumping tests. The locations of the pumping tests are also shown

where Δ_i and P_i are the water deficit and precipitation, respectively, for month i; $I_i$is irrigation during month i; and ϵ is irrigation efficiency.

The irrigation efficiency accounts for losses in the distribution system (Brouwer et al. 1989). Typical values of this parameter normally vary between 0.3 and 0.7, depending on the irrigation system utilized, such as drip irrigation or flood irrigation (Rai et al. 2017; Yoloğlu 2023). Finally, groundwater extraction is defined as the sum of groundwater extraction for domestic use and the groundwater extraction for irrigation. The above calculation was performed on a monthly basis for all model grids.

The model was calibrated for the period from January 2000 to December 2022 using monthly groundwater data from 29 long-term observation wells. The irrigation efficiency was defined as the main calibration parameter.

Scenario analysis

After calibration, the model was used to examine the sustainability of groundwater resources under different future agricultural practices and climatic projections. Three water management scenarios were developed based on input from farmers, non-governmental organizations (NGOs), and water authorities. Each scenario was simulated under two representative concentration pathways, RCP4.5 and RCP8.5, using climate projections for Konya region (Todaro et al. 2022) based on 17 regional climate model (RCM) and global circulation model (GCM) projections developed within the EURO-CORDEX framework. The EURO-CORDEX regional projections (EUR-11, ~12.5-km resolution) were selected for their fine spatial resolution and suitability for regional impact assessments. Derived through dynamic downscaling of CMIP5 global climate models, these projections are among the most widely adopted, extensively validated, and robust datasets available for assessing climate impacts at the regional scale (Coppola et al. 2021; Vautard et al. 2021). The considered scenarios are described below.

Business-as-usual scenario

The business-as-usual scenario assumes no significant changes in policy or behavior. It assesses the impact of climate change on the water resources of the basin while maintaining existing cropping trends (crop types and areas) until 2040. The present irrigation efficiency (0.65 determined from model calibration) is held constant for future years, reflecting the assumption that no major technological or management improvements will be introduced.

Increase in irrigation efficiency scenario

This scenario examines the potential effects of increasing irrigation efficiency on the water resources of the basin under future climate projections. All conditions were kept the same as in the business-as-usual scenario, except that efficiency was assumed to increase linearly from 0.65 (the current irrigation efficiency value determined from model calibration) to 0.80 between 2023 and 2028, and then remain constant at 0.80 thereafter. This higher efficiency level would correspond to adopting pressurized drip systems with minimal distribution losses, assuming farmers follow recommended irrigation practices and avoid over-irrigation.

Combination of corn phase-out and increased irrigation efficiency scenario

This scenario explores the potential effects of simultaneously increasing irrigation efficiency and reducing corn cultivation to 2005 levels. Irrigation efficiency was assumed to be the same in the "increase in irrigation efficiency" scenario. Regarding corn cultivation, a 5-year transition period (2023–2028) was assumed, gradually reducing corn acreage to its 2005 levels. The land no longer cultivated with corn is converted to wheat cultivation, the traditionally cultivated crop in the KCB, which has a considerably lower irrigation demand. This phased approach aims to reverse the significant rise in corn production observed over the last two decades. As in the previous scenario, future climate projections from the 17 high-resolution GCM-RCM combinations under RCP 4.5 and 8.5 were incorporated to estimate future precipitation.

Implementation of the net inflow concept

The net inflow concept is an aquifer water balance expression that attempts to relate the annual change in groundwater level to the annual extraction rate. The equation lumps all inflows/outflows into the aquifer system except the groundwater extraction:

$$S_Y \Delta H = \sum I - Q \tag{4}$$

where S_Y is the specific yield of the aquifer system,ΔH is the annual change in groundwater level, $\sum I$ is the sum of all inputs into the considered aquifer system, including the net recharge, return flow due to excess irrigation, and lateral flows, and Q is the annual groundwater extraction

The relationship between the annual drawdown and annual extraction is, in principle, non-linear, as the infiltration process through the vadose zone, including the

back infiltration of excess irrigation, is a highly non-linear process.

The net inflow concept does not introduce any assumptions beyond the groundwater balance already solved by the MODFLOW model. Rather, it represents a post-processing step in which the simulated inflow components are combined into a single "net inflow" term. The relationship between annual drawdown (ΔH) and annual extraction (Q) is then plotted for each simulation year (2000–2040) to illustrate the dynamic aquifer response under different scenarios.

The net inflow concept is introduced as a tool to help in the management of aquifer systems that are heavily exploited (Butler et al. 2023). The above equation can be applied to a subbasin of interest or to the entire basin. In this paper, the net inflow concept is applied to the entire basin as part of the scenario analysis. The goal here is to identify the scenario or set of conditions such that the groundwater extraction rate yields a near zero long-term change in water level. To account for climatic change uncertainty, the analysis is repeated for multiple climatic projections under both RCP scenarios.

Results

Irrigation water demand

Since groundwater-extraction wells in the KCB are not metered, irrigation water demand was estimated based on the cultivated area of each crop and its monthly water requirements. Crop area data were obtained from the Turkish Statistical Institute (TUIK 2023), which reports cultivation areas for each crop at the district level (Fig. 3). The annually varying crop distributions of each district were explicitly incorporated into the model.

Figure 5a shows the total area of the main crops. Figure 5b depicts the monthly water requirements for each crop recommended for the broader Konya region (TAGEM 2017). Winter crops, such as wheat, have their peak water requirements between January and July. In contrast, more recently introduced summer crops, particularly corn, require irrigation during the warmer summer months, thus relying heavily on groundwater to compensate for the region's dry summer climate.

The monthly irrigation water use was computed for each district separately based on the corresponding crop composition and local precipitation values. The total basin-wide agricultural water demand was then obtained by summing across all districts. Figure 5c presents the annual water demand for the entire basin, determined for the cultivated area and water requirement of each crop. The increase in water demand in recent years is largely driven by a shift to more water-demanding crops as well as an expansion in cultivated areas (Fig. 5a). By 2022, the land used for growing corn had expanded tenfold relative to its 2004 area. The spatially variable monthly groundwater extraction rates were calculated based on the water demand deficit and the irrigation efficiency, as described in the section "Estimation of irrigation and groundwater extraction rates".

Model calibration

Monthly groundwater level data (January 2000 to December 2022) from 29 observation wells located across the basin were used for model calibration, with the irrigation efficiency parameter treated as the main calibration parameter. Small changes in the local hydraulic conductivity were also made, especially in mountainous areas where pumping test data are lacking.

The irrigation efficiency (ϵ) values obtained after calibration were $\epsilon = 0.3$ for the years 2000–2004, $\epsilon = 0.4$ for the years 2005–2009, $\epsilon = 0.5$ for the years 2010–2014, and $\epsilon = 0.65$ for the years 2015–2022. These values correspond to an initial period of low efficiency due to the dominance of flood irrigation practices in the basin. The second period, with somewhat improved efficiency, is driven by greater farmer awareness of water scarcity. Government subsidies for drip irrigation were introduced in 2010, yielding a further increase in the irrigation coefficient for the 2010–2014 period. A final increase in the efficiency for 2015–2022 reflects further adoption of modern irrigation technologies.

Figure 6 compares the simulated groundwater levels with those observed at the 29 long-term monitoring wells for the years 2005, 2010, 2015, and 2020. The groundwater level data points lie near the first bisector for all years, indicating that the simulated values over the 23-year simulation period are generally consistent with observations. Groundwater depths in the basin average around 80 m, ranging from approximately 5–10 m below the surface in low-lying areas to more than 200 m in deeper zones. The coefficient of determination (R^2) for all control wells is 0.61. The mean absolute error (MAE) is 4.90 m, ranging between 1.59 and 10.39 m for different wells. The Nash–Sutcliffe efficiency (NSE), calculated as 1 minus the ratio of variance of the simulated heads to the variance of the observed heads, is 0.22 for the entire domain. Collectively, these statistics suggest that the model reasonably captures the major spatial and temporal variations in groundwater levels across the basin. Statistical analysis of residuals, defined as the difference between the observed and simulated monthly groundwater levels at the monitoring wells, is presented in the electronic supplementary material (ESM).

Figure 7 shows the initial groundwater levels at the beginning of the simulation and the groundwater levels at the end of the calibration process. Groundwater flows primarily from higher elevation recharge regions near the basin boundaries

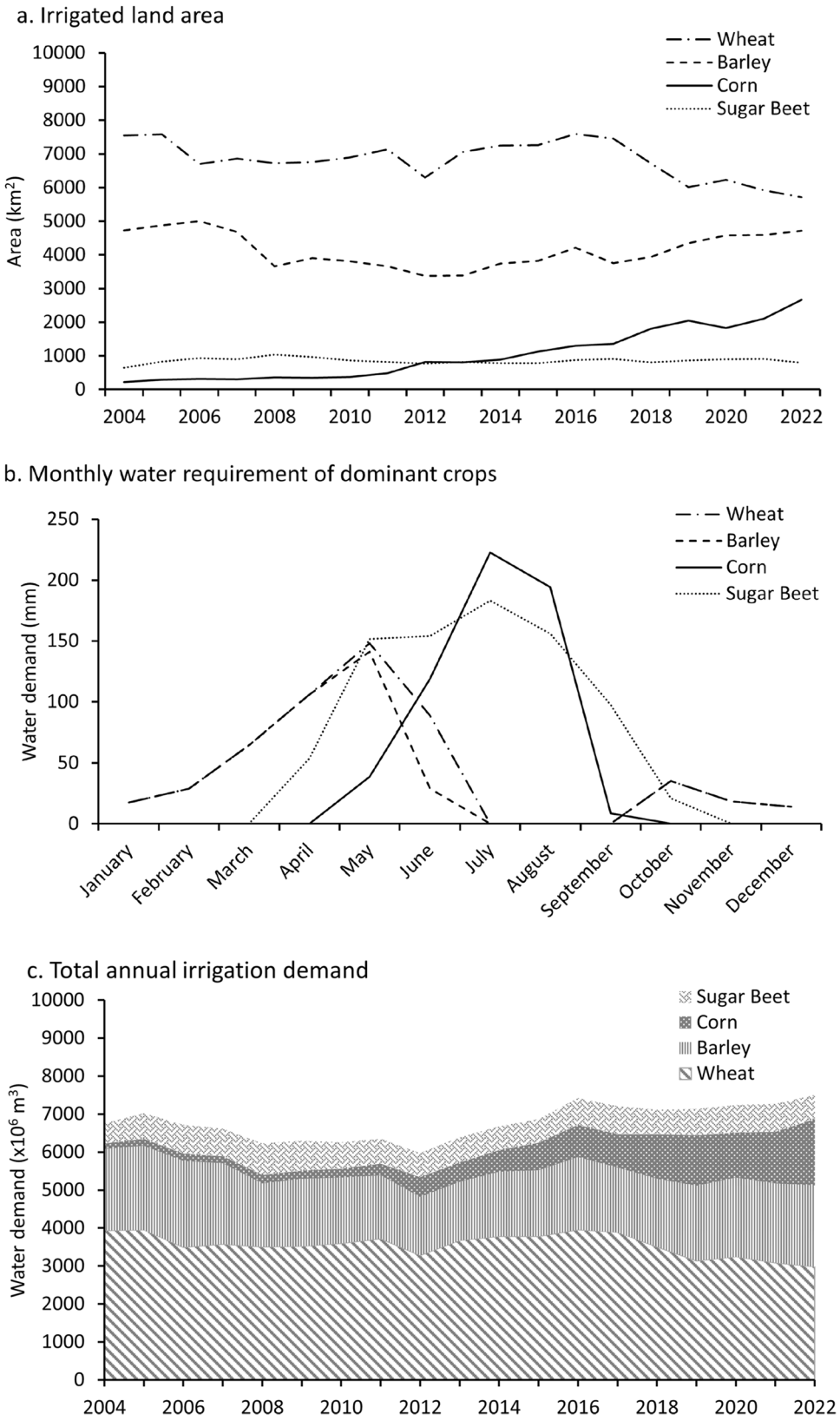


Fig. 5 Water demand calculation: **a)** irrigated area of major crops; **b)** monthly water requirement of different crops; **c)** Water demand of different crops for the KCB

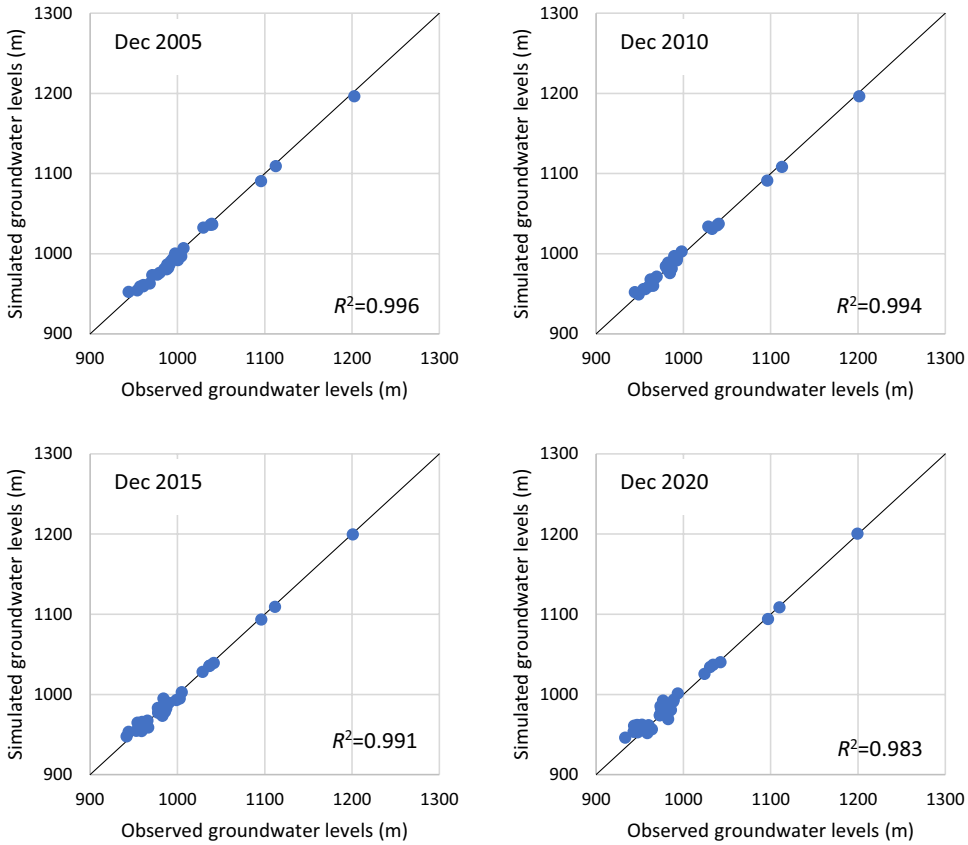


Fig. 6 Comparison of simulated and observed heads at groundwater monitoring locations

towards the central regions, where most of the agricultural activities are concentrated.

Model uncertainty

It should be noted that the developed model is associated with some uncertainties due to the limited availability data defining the hydrogeology and irrigation patterns of the KCB. This is often the case in many modeling studies, especially those covering a large area such as the KCB, which covers an area of about 50,000 km^2. The absence of detailed pumping data represents a major source of uncertainty. In this study, we attempted to indirectly estimate groundwater abstraction from the distribution of cultivated crops, which is well documented by the Turkish Statistical Institute (TUIK) at the district level (Fig. 3). Irrigation practices constitute another important source of uncertainty, as farmers often apply excess water than is required when supplies are abundant. Consequently, we have selected this parameter to be the main calibration parameter constrained by irrigation efficiency values from the literature (FAO, 2023) for different irrigation systems and by available information on irrigation patterns obtained from farmers, the State Hydraulics Work (DSI) and other stakeholders.

The aquifer hydraulic parameters were defined using data from the 81 pumping tests. These tests are primarily concentrated in cultivated regions of the basin, yet, on the whole they represent a relatively robust dataset for estimating the aquifer's transmissivity and storativity. Since the basin is closed, the aquifer transmissivity controls horizontal groundwater flow within the basin rather than the overall water budget.

Another key component of the model is the representation of flow through the unsaturated zone, which forms the transition between surface processes (precipitation and irrigation) and groundwater flow. The primary processes within the unsaturated zones are evapotranspiration and downward flow, which is described by the kinematic approximation of the Richard's equation and simulated by the UZF module. The coupling of the unsaturated and saturated flow model eliminated the need to define net recharge a priori. Instead, it requires the definition of the unsaturated hydraulic conductivity and the time-dependent evapotranspiration rates.

The current model benefited from data published by Türkiye's General Directorate of Agricultural Research and Policies (TAGEM 2017), which provides monthly crop evapotranspiration estimates at the district level for the entire country. These data serve as recommendations to guide farmers in irrigation practices. The Brooks–Corey formulation was used to characterize the unsaturated hydraulic conductivity. Based on soil characterization studies from the basin (Devrin Saygin et al. 2023; Nick et al. 2024), the

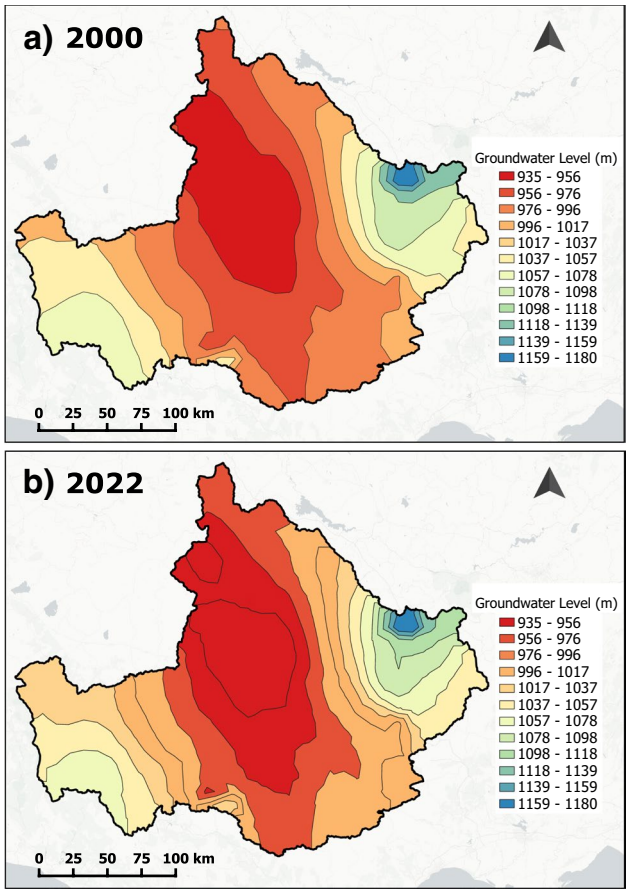


Fig. 7 Simulated groundwater level across the KCB for December 2022 at the end of the calibration period

residual saturation and pore-size distribution index were assigned values of 0.15 and 0.5, respectively. A vertical-to-horizontal hydraulic conductivity ratio of 0.1 was assumed to account for anisotropy in subsurface flow conditions. These parameters are particularly challenging to define, especially for large domains such as the KCB. A sensitivity analysis of the unsaturated zone parameters zone revealed that decreasing unsaturated hydraulic conductivity increases evapotranspiration and reduces recharge (Yoloğlu 2023). Further field efforts should be directed towards improving the characterization of the hydrogeologic properties of the vadose zone.

Overall, it is important to acknowledge that the model has some uncertainties, however it provides a plausible analysis tool for assessing the basin's water budget and internal flow dynamics, supporting water management decisions in the KCB.

Future water-use scenario

The calibrated model was used to evaluate groundwater use under different future scenarios that take into account climate projections under RCP4.5 and RCP8.5, changes in irrigation practices and cultivated crops, as described in the section "Scenario analysis". The results are evaluated in terms of the net inflow concept by plotting the spatially-averaged annual change in water level (ΔH) against the annual groundwater extraction volume Q (section "Implementation of the net inflow concept"). For sustainable use of the available groundwater resources, it is desirable that the long-term average drawdown remains near zero.

Figure 8 (a–c) shows the ΔH vs. Q plots for the (a) business-as-usual, (b) enhanced irrigation efficiency and (c) the rolling back of corn cultivated coupled with enhanced irrigation efficiency for the RCP 4.5 pathway. Figure 9 (a–c) shows the corresponding ΔH vs. Q plots for the same scenarios but for the RCP 8.5. In both sets of plots, the annual ΔH and Q are averaged over the entire domain. Past years are shown in red, while future years are shown in blue. For future years, the median of the 17 different GCM-RCM combinations is shown along with the upper/lower quartiles. The spread between the quartiles reflects the uncertainty due to variations in climatic projections. The dashed lines on the graphs represent the linear regression fit to all points, which depicts the spatially averaged relation between groundwater abstraction and annual average drawdown.

The historical data shown in Figs. 8 and 9 reveal that groundwater resources over the entire basin experienced a severe drop of about 0.9 m/year between 2000 and 2010 due to low irrigation efficiency, with irrigation about three times the total precipitation received by the basin. The years 2000–2003 experienced the largest drop in water levels, with annual average drawdown exceeding 1 m. In highly irrigated subregions of the basin, annual drawdowns exceeded 2 m. Between the years 2010 and 2015, and as a result of incentives, many farmers switched to more efficient irrigation technologies (higher irrigation efficiency). This led to a temporary slowdown of the drop in water levels. However, the switch to more water-demanding crops and expansion of irrigation lands led to a continued drop in groundwater levels starting from 2016, albeit at a lower rate than the rate that occurred in the years between 2000 and 2010. The drop in groundwater level, averaged over the entire basin and simulation period is estimated to be about 0.7 m/year.

For the business-as-usual scenario, the median rate of groundwater drop will continue to gradually increase in the coming years. For RCP4.5 and RCP8.5, the average annual drop in groundwater level between the years 2023 and 2040 ranged between 0.1 and 0.5 m, with an average of 0.28 m. The continued annual drawdown indicates that the system has not reached a sustainable state and that the benefits from the switch to more efficient irrigation systems in recent years are gradually eroding.

Even over the relatively short time horizon considered in this analysis, the uncertainty in climate projections

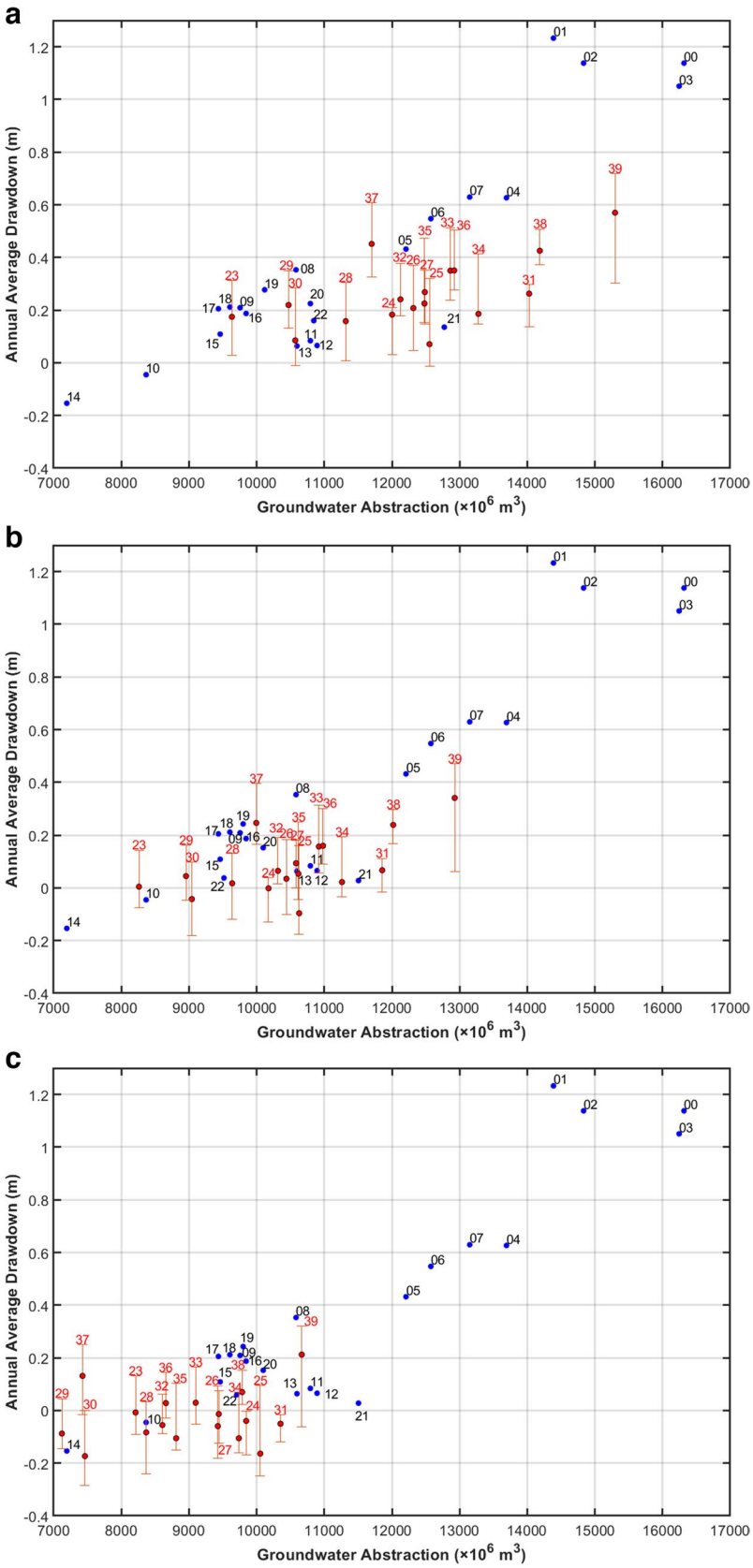


Fig. 8 Plots of annual drawdown vs. groundwater abstraction for climate projection RCP 4.5 and the scenario: (**a**) business-as-usual, (**b**) enhanced irrigation efficiency, and (**c**) enhanced irrigation efficiency coupled with a switch to traditional crops. Past years are shown in *blue*, future years in *red*. Median and upper/lower quartiles based on the 17 available high-resolution GCM-RCM combinations are shown for future years. The year is shown above each point

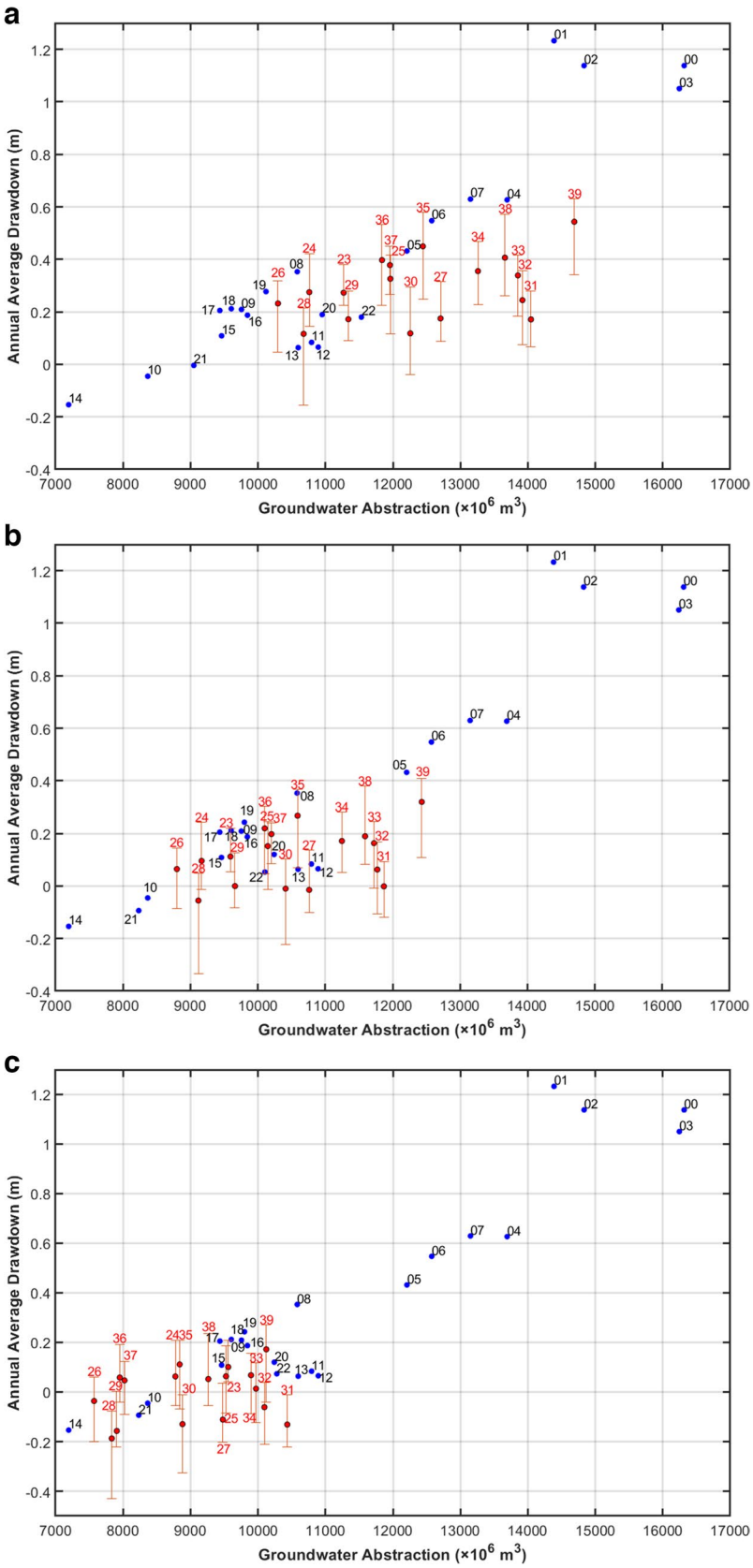


Fig. 9 Plots of annual drawdown vs. groundwater abstraction for climate projection RCP 8.5 and the scenario: (**a**) business-as-usual, (**b**) enhanced irrigation efficiency, and (**c**) enhanced irrigation efficiency coupled with switch to traditional crops

represented by the spread between the upper/lower quartiles remains substantial. The uncertainty in water availability, reflecting the variations between the different climate model projections, further complicates the management of groundwater resources in the basin.

The enhanced irrigation scenario assumes that the irrigation efficiency will gradually increase to 80% between 2023 and 2028, then remains constant. All other input parameters are similar to those in the business-as-usual scenario. Figures 8b and 9b show the plots of ΔH vs. Q for the enhanced efficiency scenario under RCP4.5 and RCP8.5, respectively. Between 2023 and 2040, the median annual drawdown ranges between + 0.25 m and – 0.19 m with an average of 0.06 m. Although this scenario predicts close to zero average drawdown, it is observed that the drawdown is increasing in the later years of 2035–2040. This suggests that the benefits of switching to more efficient irrigation by itself, while keeping current cropping trends unchanged, would be short-lived.

The last scenario considered in this study combines a return to traditional cropping patterns coupled with increased irrigation efficiency. Specifically, this scenario assumes that corn cultivation, which has expanded significantly in the last two decades, will be reduced to 2005 levels and replaced with wheat production. The irrigation efficiency is assumed to be similar to the previous scenario. Figures 8c and 9c show the corresponding plots of ΔH vs. Q for RCP 4.5 and 8.5, respectively. The median annual drawdown will be close to zero, with the drop ranging between + 0.18 m and – 0.18 m. Overall, this scenario shows that by combining advanced irrigation technology with change in cropping towards cultivating more traditional crops would lead to sustainable use of the groundwater resources in the KCB. However, the level of uncertainty due to variations in climatic projections remains high.

Discussion

The Konya Closed Basin is a semi-arid, water-limited environment where efficient use of its available water resources is crucial. With agriculture being the basin's primary activity, groundwater has become an essential resource buffering water deficits between precipitation and crop water demand. However, the longevity of this resource and the sustainability of agricultural activity in the region are increasingly in question.

To help manage this vital resource, a coupled unsaturated zone and groundwater zone model was developed for the entire basin. The advantage of coupling water flow through the unsaturated zone and in the aquifer is that the estimation of the net recharge, which is difficult to determine in the field, is avoided. Instead, the model calculates the temporal spatially variable net recharge from the applied irrigation, precipitation, and evapotranspiration. Over the years, a number of studies have examined the KCB's hydrogeology (Eren et al. 2024; Bayari et al. 2009; Kuzucuoğlu et al. 1999). Long-term groundwater monitoring has also been in place since the 1960s, reflecting the critical role of groundwater in the region's development. Nevertheless, constructing a robust groundwater flow model continues to pose challenges, mainly due to the prevalence of unlicensed wells and the lack of metering systems to track extraction rates. This shortfall in reliable data, which is widespread in groundwater management worldwide (Butler et al. 2016; Wang et al. 2020), complicates efforts to achieve accurate and comprehensive modeling of the aquifer system.

There are a number of studies in the literature that attempted to estimate extraction rates indirectly from proxy parameters. For example, Wang et al. (2020) and Chu et al. (2020) utilized electrical energy costs from agricultural areas to estimate groundwater extraction rates. An increasing number of studies have also used remote sensing data to successfully estimate changes in groundwater storage (see recent review by Adams et al. 2022). Techniques that can be used to monitor groundwater include gravimetric measurements from the GRACE missions that detect water changes (Rodell et al. 2018), surface deformation data such as InSAR and GNSS measurements, and airborne electromagnetic systems (AEM) that estimate changes in water table depths (Adams et al. 2022). Besides the differences in the parameters that these techniques monitor, they also differ in the accuracy and spatial and temporal resolutions they afford.

In this study, we estimated groundwater extraction indirectly based on (1) the cultivated area of each crop as reported by the Turkish Statistical Institute (TUIK), and (2) the recommended monthly water requirements of crops, which account for the climate of the Konya region (TAGEM 2017), and (3) irrigation efficiency. The irrigation efficiency is considered here to account for water losses through the irrigation systems and for farmers' tendency to exceed irrigation recommendations when excess water in the form of a shared groundwater resource is available. Given the lack of specific information about this parameter, it was selected as the primary calibration parameter, the long-term observed water levels as the calibration target. The irrigation efficiency was, however, constrained by published data on irrigation distribution systems (Brouwer et al. 1989) and by information acquired from multiple meetings and workshops held with stakeholders to better understand current practices and issues facing the agricultural sector, by far the largest user of water resources in the region.

The calibrated model was then used to assess a number of scenarios defined jointly with various stakeholder groups. The evaluation of scenarios was performed using the concept of net inflow (Butler et al. 2023), which relates annual

aquifer drawdowns to groundwater extraction. An advantage of presenting results using this concept is that it is relatively easy to understand, making it well–suited to share and discuss with stakeholders. Originally used to analyze highly monitored systems such as the High Plains Aquifer in the USA (Butler et al. 2016; Butler et al. 2023), in the current study, we have combined it with modeling results for assessing future scenarios. The current analysis applies the net inflow concept to the entire basin; however, it can equally be applied to critical sub-basins.

The analysis of the business-as-usual scenario clearly shows that the trend of declining groundwater heads will continue to increase in the coming years. This scenario illustrates that in the absence of any policy changes or initiatives aimed at improving irrigation technologies, the drop in groundwater levels will likely accelerate with potentially drastic impacts on irrigation and agricultural production of the basin. The underlying reason for this drop in groundwater levels is the expansion of agricultural land use and an increase in corn cultivation. This intensification of agricultural activities, with a focus on corn, is significantly contributing to the unsustainable depletion of groundwater resources.

The drop in groundwater level may cause an irreversible and harmful impact on socio-economic dynamics. A deeper water table means that farmers will need more electricity to pump water, creating a further financial burden on farmers. Small-scale farmers, particularly, would need to allocate a larger portion of their income to energy-related expenses in the future, rendering them particularly susceptible to the repercussions of policy-induced energy price hikes. Declining groundwater levels can also have adverse effects on aquatic systems that rely on groundwater for their functioning (Glanvile et al., 2023; Yılmaz et al. 2021).

Examination of the other scenarios suggests that increasing irrigation efficiency alone, even to an ambitious value of 0.8, may not suffice for sustainable groundwater use. Hence, a solution that relies solely on technological developments may not be sufficient. However, combining enhanced irrigation efficiency with the scaling back of corn cultivation, a water-intensive summer crop that has expanded significantly in recent decades, and replacing it with wheat, a traditionally cultivated crop more aligned with the semi-arid climate of Konya (Yılmaz et al. 2021), could halt and potentially reverse groundwater level declines in the basin. It should be noted, however, that both improving irrigation efficiency and modifying crop choices have important socio-economic implications. Higher-efficiency systems require significant upfront investment, technical know-how, and reliable energy access, which may pose challenges for smallholders. Similarly, shifting away from high-value or water-intensive crops such as corn could affect farm income, labor demand, and local market dynamics. The findings underscore the critical importance of adopting measures that address both agricultural policies and irrigation practices, while carefully considering their social and economic trade-offs, as these factors are pivotal in influencing the future trajectory of groundwater levels.

The results highlight the uncertainty stemming from the ensemble of 17 high-resolution GCM-RCM combinations used in this analysis (Figs. 8 and 9). The uncertainty in predicted drawdown is relatively large, reflecting the variation in precipitation among these models and their impact on aquifer recharge. The scenario analysis shows that by combining enhanced irrigation technologies with some adjustments in cropping practices, marked improvement in groundwater resource management of the basin can be achieved. Nonetheless, the ensemble of models highlights a wide range of possible conditions in the future and underlines the importance of flexible water management policies to adapt to these uncertainties.

Conclusions

This study developed a coupled unsaturated–saturated groundwater model for the KCB, a major agricultural region in Türkiye. By calibrating the model against long-term monitoring wells and incorporating downscaled climate projections (RCP4.5 and RCP8.5) from 17 GCM-RCM combinations (Todaro et al. 2022), we assessed how changes in cropping patterns and irrigation practices could influence groundwater levels. The findings, formulated in terms of the net inflow concept (Butler et al. 2023), reveal a persistent downward trend in groundwater levels over the past two decades. This decline will continue unless significant shifts in cultivation strategies and water use practices are adopted.

Of the various scenarios examined, a strategy that returns to traditional rainfall-aligned crop cultivation (winter wheat cultivation for the case of the KCB) combined with enhanced irrigation efficiency stands out as particularly promising. The simulations indicate that restoring the historic dominance of winter wheat, which aligns better with the basin's precipitation regime, together with the adoption of pressurized or drip irrigation systems, could substantially mitigate future groundwater declines and lead to sustainable groundwater use.

While the results presented here are specific to the KCB, the adopted approach supports robust, evidence-based management of stressed aquifer systems in agricultural settings. These methodologies can be extended to other regions worldwide, which face over-exploitation of groundwater resources and climate change.

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Data Availability Data are available upon request from the authors.

Declarations

Competing Interests The authors have no relevant financial or non-financial interests to disclose.

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