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ESTIMATION OF AQUIFER RECHARGE OF THE SEMI-ARID KONYA CLOSED BASIN IN TÜRKIYE UNDER CLIMATE CHANGE

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Abstract: Irrigated agriculture in semi-arid closed basins depends heavily on groundwater, yet the feedbacks between irrigation practice and aquifer recharge remain poorly quantified. The Konya Closed Basin, one of Türkiye's most productive agricultural regions, exemplifies this challenge: with intensive largely unregulated irrigation withdrawals exceeding aquifer recharge leading to rapid declines of groundwater levels. This study develops a coupled unsaturated-saturated flow model based on the MODFLOW/UZF framework to estimate spatiotemporal recharge dynamics across the basin and to assess the sensitivity of recharge and the overall water budget to changes in irrigation efficiency, cropping patterns, and future climate. The model explicitly captures the complex non-linear processes governing water infiltration through the vadose zone and evapotranspiration, with groundwater extraction estimated from historical cultivated areas and crop water demands. Future hydroclimatic conditions were projected using seventeen regional climate models within the EURO-CORDEX framework. Projected climate change through 2040 is modest, so irrigation management and cropping decisions emerge as the dominant controls on recharge dynamics. Moreover, recharge is spatially variable, governed principally by the spatial distribution of precipitation, crop type, and vadose zone hydraulic properties. The highest recharge rates are concentrated in the Beyşehir Lake catchment and along the Taurus Mountain forming the southern basin boundary. Temporally, recharge exhibits somewhat steady rates relative to surface water application, a pattern attributed to the buffering capacity of the thick unsaturated zone, which dissipates and delays peak infiltration signals. Scenario analyses demonstrate that improvements in irrigation efficiency and transitions away from water-intensive summer crops such as corn, while effective in reducing consumptive water use, exert limited influence on irrigation return flow recharge, owing to the dominance of evapotranspiration losses during the summer irrigation period. Recharge rates are estimated at approximately 20–40% of total water application, placing the basin at the upper end of values reported for irrigation-intensive semi-arid regions. These findings underscore the importance of accurate recharge quantification as a prerequisite for sustainable groundwater resource governance in water-scarce, agriculturally dependent semi-arid basins.

Keywords: Groundwater recharge, Irrigation return flow, Semi-arid basin, MODFLOW/UZF, Climate change projections, Agricultural water management

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1. Introduction

Groundwater constitutes an indispensable resource sustaining irrigated agriculture across semi-arid regions where precipitation is insufficient to meet crop water demand. Despite its critical role, the dynamics linking irrigation practice, land use change, and aquifer recharge remain poorly understood at the basin scale. In endorheic basins where water balances are particularly sensitive to human intervention, this knowledge gap carries direct consequences for long-term agricultural sustainability. The Konya Closed Basin in south-central Türkiye exemplifies this challenge, as the country's most productive agricultural region, yet its underlying aquifer system is experiencing rapid and spatially heterogeneous decline driven by decades of intensive, largely unregulated groundwater extraction. A structural shift in cropping patterns in the past 2 decades from relatively low water-demand winter wheat toward summer corn, has further amplified groundwater withdrawals particularly during the months when evaporative demand peaks and natural recharge from precipitation is minimal (Daloğlu Çetinkaya et al., 2025). Understanding how recharge responds to these changing agricultural pressures and to a warming climate is a prerequisite for sustainable water management in the basin.

Groundwater recharge is the net downward flux of water through the unsaturated zone to the water table, representing the residual of infiltration after evapotranspiration and soil moisture storage change are accounted for (Scanlon et al., 2002). In semi-arid settings, this residual is small, episodic, and spatially concentrated rather than diffuse, a point established early in the recharge literature (Sanford, 2002). Due to its high spatial and temporal variability, the nonlinear nature of

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infiltration processes, and the inherent limitations of available measurement techniques, aquifer recharge remains one of the most challenging components of the water balance to estimate. Unlike other water balance components such as precipitation or streamflow, recharge cannot be measured directly at the basin scale but must instead be inferred indirectly from hydrological or numerical methods (Scanlon et al., 2002; Healy, 2010; Babaei and Ketabchi, 2022; Gebru et al, 2024; Türkseven et al., 2026). Recent continental-scale work by Lee et al. (2025) further shows that recharge mechanisms themselves shift with climate and landscape setting, reinforcing the need for site-specific, process-based estimation rather than generalized assumptions. Gee and Hillel (1988) demonstrated that simple estimates based on fixed fractions of annual precipitation are fundamentally misleading particularly in arid and semi-arid environments, because they ignore the plant and soil factors that govern vadose zone dynamics. Their critique remains pertinent as the ~10% recharge-to-precipitation ratio commonly assumed for semi-arid regions is not a physical law but a convenient approximation whose validity has not been rigorously tested against site-specific process models (Scanlon et al., 2006). This study focuses on the estimation of the recharge rate for the Konya Closed Basin, using a physically based coupled model to derive recharge as an emergent outcome of soil, climate, and irrigation dynamics rather than as an assumed input.

Representing recharge accurately in groundwater models requires matching the boundary condition type to the physical setting. Sanford (2002) argues that in arid and topographically elevated regions where the water table is deep, recharge is climate-controlled and best represented as a specified-flux boundary condition, whereas in humid, low-relief settings it is lithology-controlled and better handled with a constant-head condition. In a large semi-arid basin like Konya, with a deep vadose zone across the central plain and permeable highland margins supplying lateral groundwater flow, the coupled unsaturated-saturated modeling approach is an appropriate framework, one that explicitly simulates the transmission of surface water fluxes through the vadose zone before they register as recharge to the aquifer. The MODFLOW/UZF model used in this study is designed for this purpose, dynamically computing recharge as a function of surface water application, infiltration, evapotranspiration, and soil hydraulic properties rather than prescribing it as a fixed value (Niswonger et al., 2006).

The challenge of estimating recharge is compounded when land use is dominated by irrigated agriculture. Over-irrigation generates return flows (back recharge) that can temporarily augment aquifer recharge beyond what precipitation alone would produce. Scibek and Allen (2006) demonstrated in their linked climate-recharge-groundwater modeling study that irrigation return flow increased recharge by 10 to 20% in an agricultural valley aquifer, with the effect concentrated in the summer months when extraction and evaporative demand are highest. This seasonal amplification of recharge through irrigation return flow has management implications that are counterintuitive, improvements in irrigation efficiency, while reducing consumptive water use at the field level, simultaneously suppress back recharge. The Konya Closed Basin, where a structural shift from winter wheat to water-intensive summer crops such as corn has already intensified summer groundwater demand, provides a test case for quantifying this efficiency-recharge trade-off. Similar dynamics have recently been documented in other semi-arid, irrigation-dependent settings; Bouimouass et al. (2025) found that traditional irrigation in Morocco's High Atlas sustains recharge to the Haouz aquifer even as streamflow declines, underscoring the sensitivity of irrigation-driven recharge to both water-delivery practices and climatic trends.

The interaction between cropping systems, irrigation practice, and recharge dynamics must also be understood in the context of land use change. Mensah et al. (2022), reviewing over 200 studies on integrated hydrological modeling under land use and climate change, found that changes in agricultural land cover consistently alter groundwater recharge patterns, and that integrated modeling approaches coupling land surface and groundwater dynamics are essential for capturing these effects. The spatially distributed recharge approach used in this study, in which recharge is computed independently for different soil-vadose zone-depth combinations across the basin, follows methodological principles also demonstrated by Navarro-Farfán et al. (2024), who showed that distributed recharge representation captures spatial heterogeneity, particularly in basins with variable geology and land use.

Projecting recharge under climate change adds a further layer of complexity. Smerdon (2017), synthesizing six major reviews of groundwater and climate change published between 2011 and 2016, identified the variability between General Circulation Models as the dominant source of uncertainty in future recharge projections. For the semi-arid Mediterranean region, including the Konya Basin, the climate projections point toward drying trends and increased evaporative demand, conditions that will intensify pressure on already-stressed aquifer systems (Todaro et al., 2022). This pattern is consistent with observed declines in semi-arid basins elsewhere; Noori et al. (2023) documented a marked reduction in groundwater recharge across Iran linked to warming and reduced precipitation, a trajectory with direct relevance to the Konya Basin's projected hydroclimatic future. Because recharge in the basin is already governed by a delicate balance between winter precipitation and summer irrigation demand, even modest shifts in this balance could compound the effects of ongoing groundwater depletion, making it essential to evaluate recharge under future climate alongside

management scenarios. Despite this body of work, physically based recharge estimates that explicitly separate natural and irrigation-return components remain rare for irrigation-dominated semi-arid basins, where the two pathways are most likely to interact and where management decisions have the greatest leverage over aquifer sustainability. The present study develops a coupled unsaturated-saturated flow model based on MODFLOW/UZF for the Konya Closed Basin to address three interrelated objectives: (i) estimate spatiotemporal recharge patterns under historical conditions and identify the controlling factors; and (ii) quantify the effect of irrigation efficiency improvements and crop pattern changes on recharge and the overall aquifer water budget and (iii) estimate recharge as a fraction of surface water application. The model and its calibration framework were first introduced in Yoloğlu et al. (2026), where the MODFLOW/UZF implementation was used to examine groundwater sustainability through the net inflow concept, a relationship between water level change and groundwater abstraction that integrates all inflow and outflow components of the aquifer budget (Butler et al., 2016). While Yoloğlu et al. (2026) examined groundwater sustainability through the net inflow concept, the present study isolates the recharge component of the water balance. Whereas the earlier study treated recharge implicitly, within the broader inflow-outflow budget used to assess sustainability, the present study analyzes recharge as the primary object of investigation, including its spatial distribution, its governing mechanisms, and its response to irrigation efficiency and cropping scenarios under both historical and projected future climate. Focusing on recharge explicitly allows for a process-based assessment of aquifer replenishment capacity and its sensitivity to irrigation efficiency transitions and crop pattern changes, dimensions that are lost when recharge and abstraction effects are modeled together. The results are intended to inform water governance decisions in a basin where the long-term sustainability of irrigated agriculture depends on closing the gap between what farmers extract and what the aquifer can sustainably supply.

2. Materials and Methods

2.1. Study Area

The Konya Closed Basin is located in the south-central Anatolian Plateau and covers approximately 50,000 km^2, making it one of the largest endorheic basins in Türkiye (Figure 1). Its southwestern margin is fed by Beyşehir Lake, the largest freshwater lake in Türkiye, which supplies water to the basin via the Çarşamba Canal irrigation network. The climate is semi-arid continental, with cold dry winters and hot summers. Mean annual precipitation ranges from approximately 250 mm in the central plain to over 500 mm in the surrounding highlands, with the highest totals recorded along the southern boundary in the Taurus Mountains. Critically, the bulk of the precipitation occurs in winter months outside the growing season of most crops (Kartal and Nones, 2024). This seasonal mismatch between precipitation and crop water demand is the primary structural driver of irrigation dependence across the basin. Evaporation ranges from near zero in the winter months to about 282 mm in the month of July (Yılmaz et al., 2021).

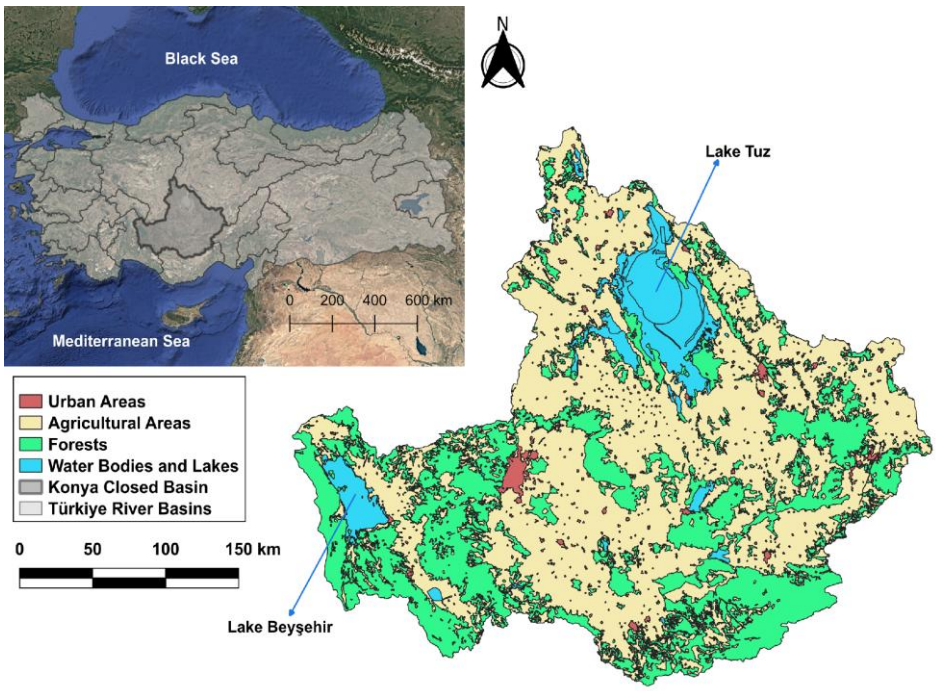
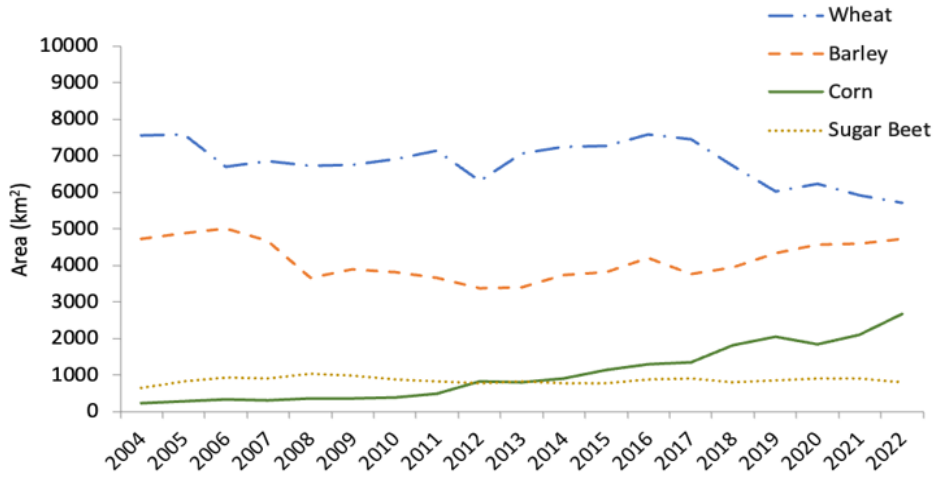
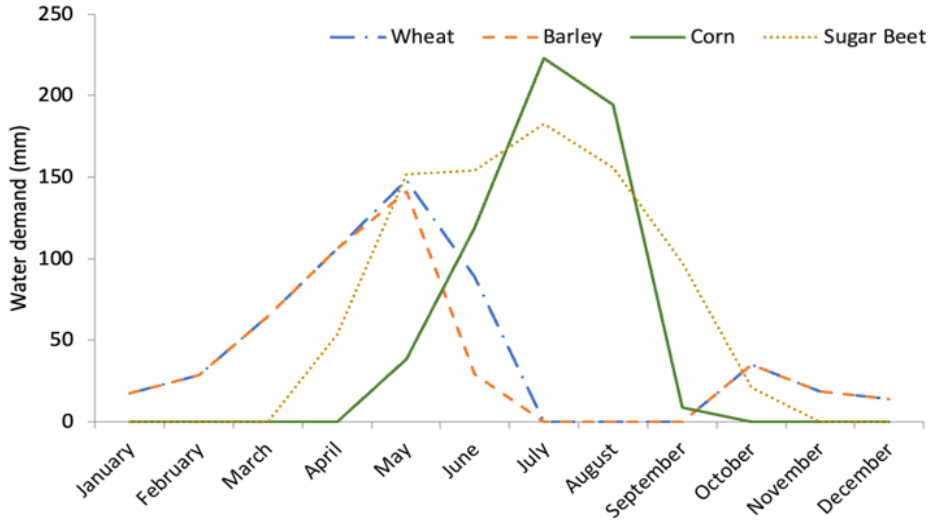


Figure 1. Location map of the Konya Closed Basin (KCB) within central Türkiye, showing the basin boundary, major settlements, and the two lakes, Lake Tuz and Lake Beyşehir. Basin boundary and land use data are derived from CORINE.



b. Monthly water requirement of dominant crops



c. Total annual irrigation demand

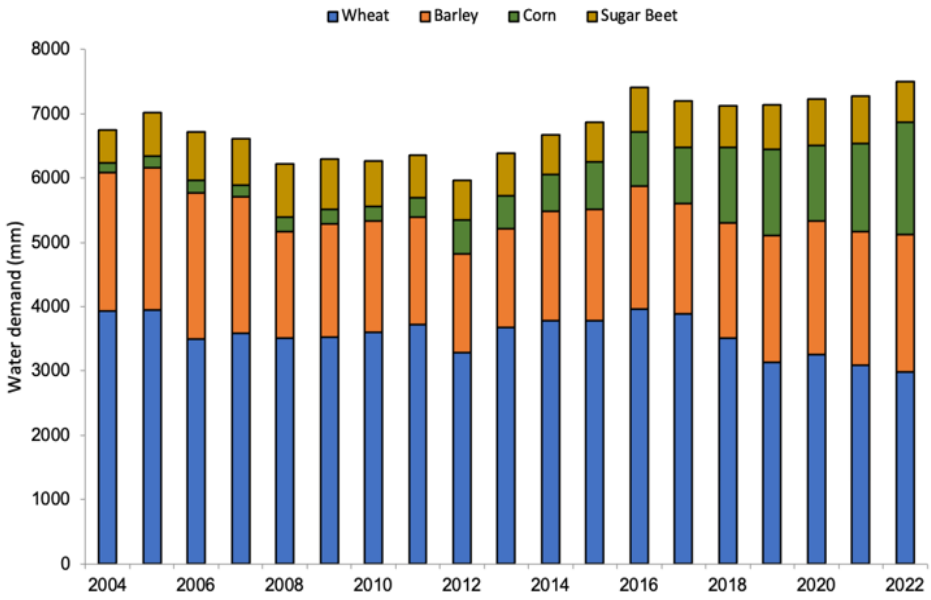


Figure 2. a) Irrigated land area, (b) monthly crop water requirement, and (c) annual irrigation demand, illustrating the changes in crop patterns and the associated variation in irrigation water requirements and overall demand. Crop areas are from the Turkish Statistical Institute (TUIK, 2023); monthly crop water requirements are from TAGEM (2017) for the Konya region.

The basin is underlain by a multi-layered alluvial aquifer system comprising Quaternary and Neogene sediments deposited across the central plain (Bayari et al., 2009). The unsaturated vadose zone between the land surface and the water table plays a critical role in how surface inputs (whether from precipitation or irrigation) are transmitted to the aquifer (Niswonger et al., 2006). Intense agricultural production defines the basin's water management challenge (Yılmaz et al., 2021). The dominant crops include wheat, sugar beet, and corn, but the past two decades have seen a pronounced structural shift away from winter wheat toward corn, a summer crop with substantially higher consumptive water use (Figure 2a). By 2022, the land cultivated with corn had expanded tenfold relative to its 2004 area. This transition has increased groundwater demand during the summer months when evaporative demand peaks and natural recharge from precipitation is negligible (Figure 2b and 2c). Irrigation is supplied through a combination of surface water infrastructure fed by Beyşehir Lake and Mavi Tünel and an expanding network of private groundwater wells (Daloğlu Çetinkaya et al., 2025). The majority of these wells are unregulated, making direct measurement of abstraction infeasible and requiring the indirect estimation approach described in Section 2.2.

The cumulative effect of expanding irrigated area, the crop shift toward more water-intensive varieties, and recurrent dry periods has been a sustained decline in groundwater levels across the central plain (Tirol Kırçiçek et al., 2025). Depletion is spatially heterogeneous, most severe where well density and irrigation intensity are highest, while the highland margins exhibit comparatively stable or seasonally recovering water tables (Yoloğlu et al., 2026). These contrasting dynamics, recharge-generating uplands versus extraction-dominated lowlands, motivate the spatially distributed modeling approach adopted in this study.

2.2. Model Framework for MODFLOW/UZF

Groundwater flow in the Konya Closed Basin was simulated using MODFLOW, the US Geological Survey's modular finite-difference groundwater flow model (Harbaugh et al., 2000), coupled with the Unsaturated Zone Flow (UZF1) package (Niswonger et al., 2006). The modeling methodology is briefly described below.

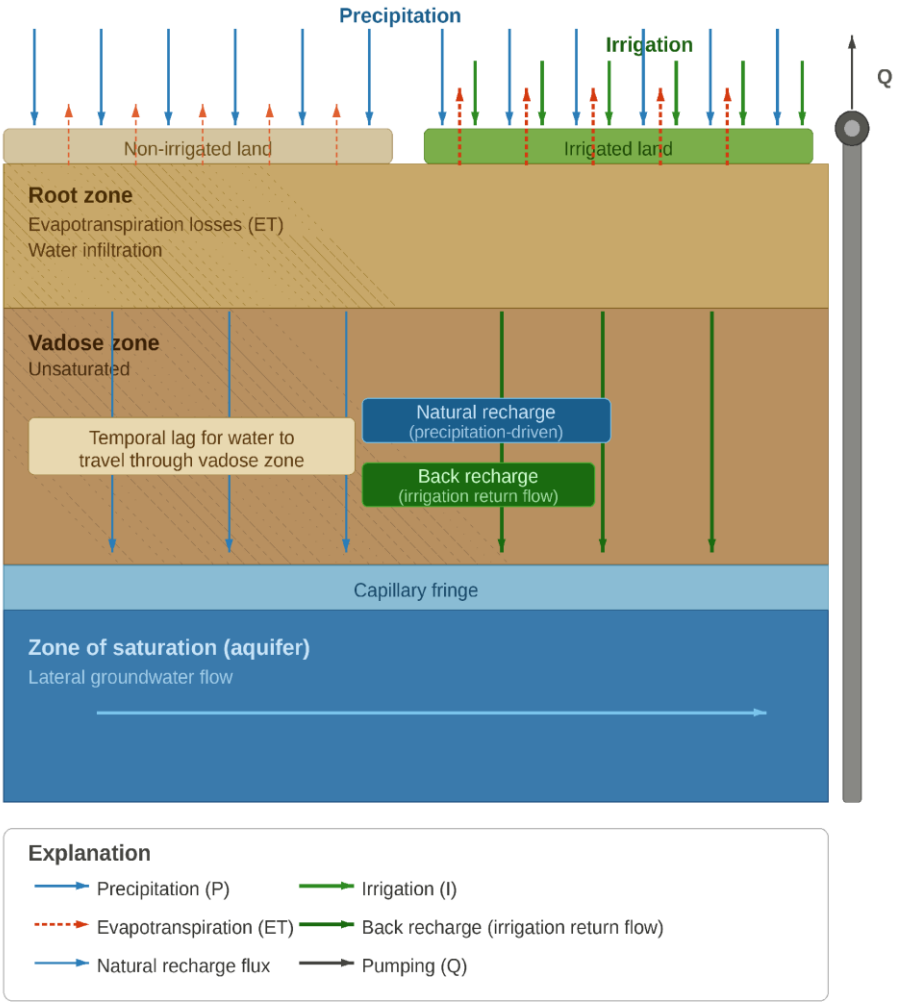


Figure 3. Conceptual diagram of the coupled unsaturated–saturated flow (MODFLOW/UZF) model, showing the surface water inputs (precipitation, irrigation), the vadose-zone processes (evapotranspiration, downward percolation, return flow of excess irrigation), and the resulting net recharge flux to the underlying saturated aquifer.

The model domain covers the entire Konya Closed Basin (~50,000 km^2), discretized into uniform 10 × 10 km grid cells. As the basin is endorheic, no-flow boundary conditions were imposed along the outer basin boundary. Meteorological and water-demand inputs (precipitation, crop water requirements) were defined on a monthly basis to capture seasonal cropping cycles, while the model was run at a daily computational time step to resolve the vadose-zone flow dynamics simulated by the UZF package.

Standard MODFLOW implementations represent recharge as a prescribed upper boundary flux, whereas the UZF1 package removes this limitation by simulating one-dimensional vertical water movement through the unsaturated zone using a kinematic wave approximation to Richards' equation (Niswonger et al., 2006). Infiltration at the land surface is routed downward through the vadose zone, subject to evapotranspiration losses and soil moisture storage changes, before reaching the water table. Recharge is therefore an emergent model output rather than a prescribed boundary condition, a distinction that is particularly critical in irrigated semi-arid basins where both precipitation and irrigation water are spatially and temporally variable and must percolate through a deep, heterogeneous vadose zone before contributing to aquifer replenishment.

This architecture is well suited to capturing the two recharge mechanisms central to the Konya Closed Basin. The first is natural recharge, driven by precipitation, predominantly in the winter and spring months, infiltrating through permeable highland margins and transmitted downward before contributing to lateral groundwater flow toward the central plain. The second is back recharge, irrigation return flow that percolates below the root zone during the growing season. Because both pathways are governed by vadose zone dynamics, a model that prescribes recharge as a boundary condition cannot distinguish between them or resolve their seasonal variability. The UZF1 package addresses this by routing all surface water inputs through the unsaturated zone explicitly, allowing natural and irrigation-induced recharge components to be separated in the model output (Figure 3) (Niswonger et al., 2006).

The subsurface is represented as a single unconfined aquifer layer underlain by an impermeable basement, consistent with the hydrogeological structure of the alluvial plain. Aquifer hydraulic conductivity was determined from 81 pumping tests and interpolated over the entire basin using ordinary kriging. Estimated hydraulic conductivity values varied from 1 to about 150 m/d (Figure 4a). Vertical flow through the vadose zone is parameterized in each active model cell using the Brooks-Corey relationships (Brooks and Corey, 1964), with unsaturated zone hydraulic properties informed by soil characterization studies conducted within the basin. Residual saturation and the porosity distribution were set to 0.15 and 0.5, respectively, following Deviren Saygın et al. (2023) and Nick et al. (2024). Subsurface anisotropy was represented through a vertical-to-horizontal hydraulic conductivity ratio of 0.1.

Sensitivity analysis of unsaturated zone parameters indicated that recharge estimates are particularly responsive to unsaturated hydraulic conductivity where lower conductivity values slow water percolation through the root zone, thereby increase evapotranspiration losses within the vadose zone and correspondingly reduce the fraction of infiltrated water that ultimately reaches the aquifer (Yoloğlu et al., 2026). This sensitivity underscores the importance of the soil parameterization choices described above and points to vadose zone characterization as a priority for future field campaigns in the basin.

The model was calibrated and validated against long-term groundwater level observations from 29 monitoring wells distributed across the basin for the period 2000–2022. Calibration targeted the reproduction of observed water table trends across the central plain and highland margins, with groundwater extraction estimated indirectly from crop cultivation areas and water requirements given the absence of metered withdrawal data (see Section 3.2). The main calibration parameters were the pumping efficiency and the hydraulic conductivity. The calibration statistics indicate an overall coefficient of determination (R^2) of 0.58 calculated across the 29 available monitoring wells. The mean absolute error (MAE) averaged 4.90 m, with individual well errors ranging between 1.59 m and 10.39 m. For the entire model domain, the Nash–Sutcliffe efficiency (NSE), defined as one minus the ratio of the variance of simulated hydraulic heads to that of observed hydraulic heads, was calculated to be 0.22. Taken together, these performance metrics show that the model captures the observed data well.

Building on the validated framework, we focus in this study on examining the spatiotemporal distribution of the recharge relative to the components of the aquifer water budget.

2.3. Irrigation and Agricultural Water Demand Estimation

Accurate quantification of groundwater extraction is a fundamental challenge in the Konya Closed Basin, where the vast majority of irrigation wells are unmetered and individual withdrawal volumes cannot be directly measured. This governance gap, documented in detail in Daloğlu Çetinkaya et al. (2025), means that abstraction cannot be obtained from monitoring records and must instead be estimated indirectly.

In this study, groundwater extraction is estimated from crop-based water demand calculations. Historical crop cultivation areas are obtained from the Turkish Statistical Institute (TÜİK) database (TÜİK, 2023), and crop water requirements are derived from TAGEM (General Directorate of Agricultural Research and Policies) standards (TAGEM, 2017). Spatially distributed irrigation demand is subsequently computed at the district (*ilçe*) level, as the product of each crop's

cultivated area and its monthly water requirement, adjusted for irrigation efficiency. The model also accounted for groundwater extraction for domestic use.

Crop water requirements vary substantially across the growing season, reflecting the phenological cycle of the dominant crops (Figure 2b). This seasonal variability impacts directly the total monthly irrigation demand (Figure 2c), with peak demand concentrated in the summer months of June through August when corn and sugar beet, the most water-intensive crops in the basin, reach their maximum evapotranspiration requirements.

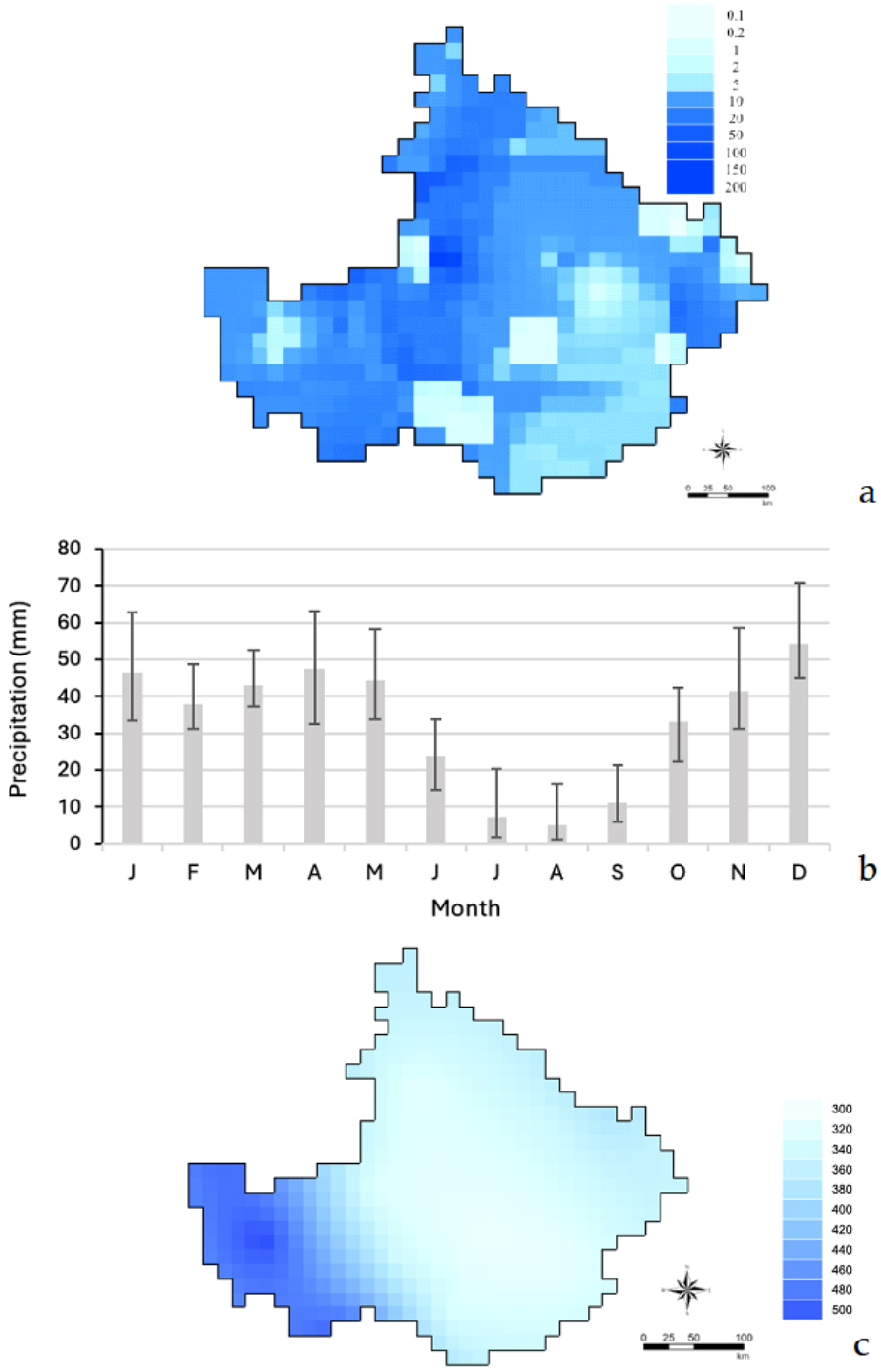


Figure 4. a) Hydraulic conductivity (m/day) estimated using ordinary kriging from 81 pumping tests distributed across the basin; b) monthly average precipitation (mm), showing minimum and maximum values across 18 meteorological stations for 1980–2022; c) spatial distribution of average annual precipitation (mm) for 1980–2022, interpolated using kriging method.

2.4. Historic Climate and Future Projections

Historical climate records from multiple stations across the basin (1980–2022) confirm the seasonality that governs both natural recharge and irrigation demand.

Precipitation is concentrated in winter and spring (November–May), with minimal values through the summer months (Figure 4b). Precipitation is also spatially variable; stations in the southwestern margins near Lake Beyşehir record higher annual totals than the arid central plain (Figure 4c). Cold winters and hot dry summers further amplify evaporative demand during the growing season.

Future climate conditions were adopted from seventeen regional climate models from the EURO-CORDEX framework under RCP4.5 and RCP8.5 (Todaro et al., 2022). The EURO-CORDEX regional projections (~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. Prior to use in the model, the climate projections underwent bias correction using observed data from 18 meteorological stations located in the Konya Basin (Todaro et al., 2022). Projected changes in both temperature and precipitation across the basin remain relatively modest through 2040. Monthly precipitation and temperature data from each model were used to drive the calibrated MODFLOW/UZF model, producing an ensemble of projected recharge time series. RCP8.5 was adopted as the more policy-relevant, no-mitigation pathway, and 2040 was selected as the analysis horizon because, as shown below, projected climate change over this near-term period remains modest, allowing the relative influence of management interventions to be isolated from long-term climatic drift. Given the limited climate change through the near-term horizon, this study focuses on projections to 2040 for RCP 8.5 projections.

3. Results and Discussion

3.1. Spatial Distribution of Recharge

The coupled vadose zone groundwater model produces spatially distributed monthly recharge across the Konya Closed Basin that reflects the interplay of three spatially and temporally variable factors: surface water application (composed of both precipitation and irrigation), the spatial distribution of irrigated agricultural land including the type of crops and irrigation efficiency, and the hydraulic conductivity and thickness of the vadose zone which controls the rate of water percolation. Figure 5 depicts the spatial distribution of the monthly recharge for the year 2020, exemplifying the complex factors influencing the recharge. Two distinct spatial regimes emerge over the annual cycle, each governed by a different recharge mechanism. During winter and late spring (January–May), precipitation is the dominant driver of recharge and its spatial distribution closely follows the basin's topographic and climatic gradients (Figure 4b and 4c). The southwestern margins of the basin, in proximity to Lake Beyşehir and the Taurus highland front, receive substantially higher precipitation than the relatively arid central plain due to mountain effects and Mediterranean climatic influence (Orhan et al., 2024). This spatial gradient in precipitation is pronounced, with the inland sections of the basin receiving considerably less rainfall than the highland periphery (Figure 4c). This translates into elevated recharge rates concentrated along the basin's southwestern margins during winter months, while the central plain contributes comparatively little. The higher elevation areas also contain fewer irrigated agricultural land, meaning that during this period recharge is almost entirely precipitation-driven.

In the summer months, precipitation declines significantly across the basin. However, the summer months are the growing season for many of the crops. With higher temperatures and evapotranspiration rates, natural recharge from rainfall decreases significantly (Figure 4). Instead, recharge is mostly attributed to irrigation return flows, excess applied water percolating below the root zone, generating back recharge**.** The spatial pattern of this back recharge signal is not uniform across the basin, however, as irrigation application varies between districts according to the dominant crop type cultivated in each. As shown in Figure 2b, corn and sugar beet cultivation, which drives the highest summer irrigation demand, is not uniformly distributed across the basin, and districts with higher coverage of these crops generate proportionally greater back recharge during July and August. This signal peaks in July and August, coinciding with maximum crop water application for summer crops, particularly corn, which has substantially higher consumptive water demand than the winter wheat it had progressively replaced across the basin (Figure 2c). The spatial distribution of hydraulic conductivity further controls this pattern, as coarse alluvial deposits in the central plain facilitate faster transmission of irrigation return flows to the water table, amplifying the back recharge signal in these areas (Figure 4a).

3.2. Recharge Under Future Management Scenarios

To assess how changes in agricultural water management affect aquifer recharge, three scenarios are examined following the framework established in Yoloğlu et al. (2026), to which the reader is referred for a full scenario description. Briefly: (1) business as usual (BAU), in which current irrigation practices and cropping patterns continue unchanged; (2) adoption of enhanced irrigation efficiency (S1), in which gradual adoption of more efficient technologies reduces irrigation application rates; and (3) enhanced efficiency combined with phased corn reduction to 2004 levels (S2), in which improved efficiency is accompanied by a shift away from summer corn toward less water-intensive winter crops such as wheat.

Under BAU, the monthly water application and precipitation lines reveal a seasonal structure (Figure 6a). Precipitation is the dominant surface water input

during winter and spring, peaking in January and December, and declining significantly into the summer months of June–September. Irrigation application fills the crop water demand deficit, as it begins in April, peaks in July, and returns to zero by October. The two inputs thus alternate across the year, together maintaining a near-continuous surface water supply to the land throughout the annual cycle. Peak surface water application is estimated to occur in the months of April and May when water demand peaks. Despite this seasonal alternation in the source of surface water inputs, estimated recharge remains spread across all months with slightly lower values in the summer months when temperatures and evapotranspiration rates are higher.

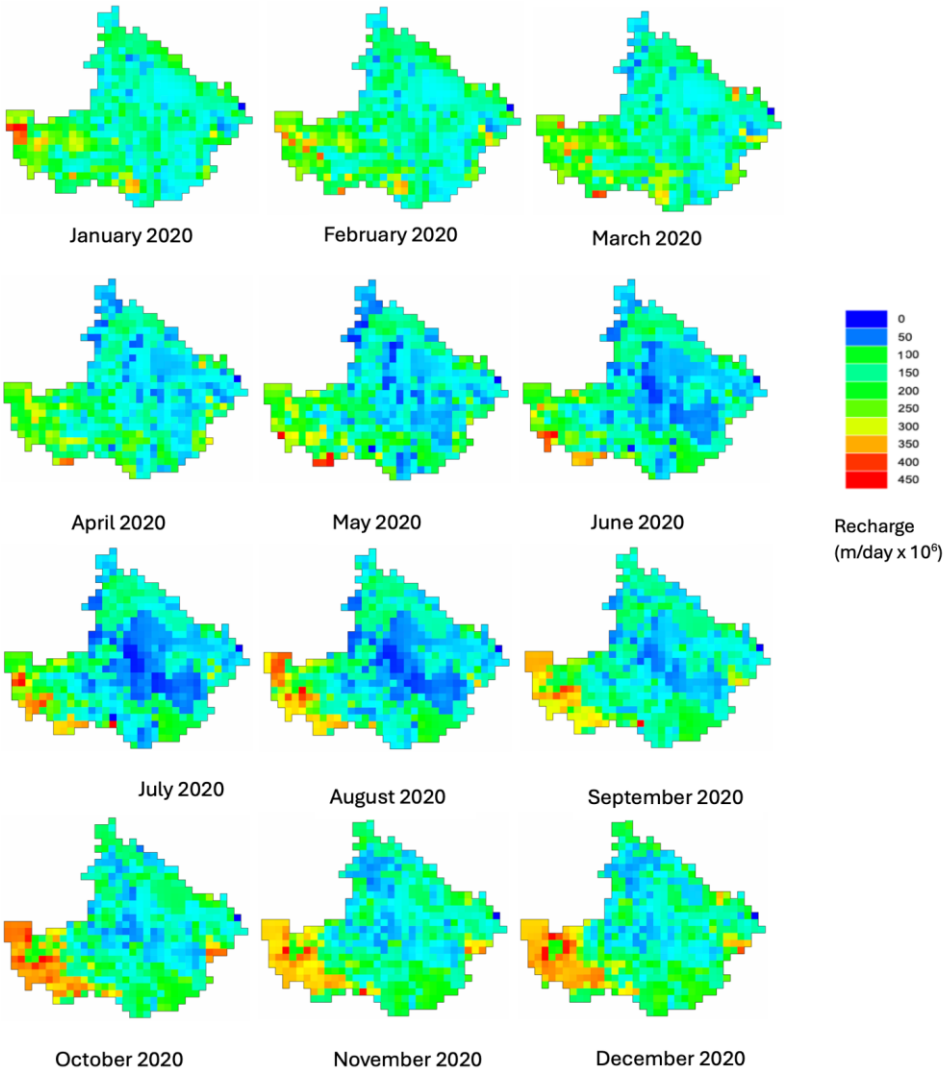


Figure 5. Spatially distributed monthly recharge rates (m/day x 10^6) across the Konya Closed Basin for 2020.

This near uniformity reflects the buffering effect of the deep vadose zone in the Konya Closed Basin, where the depth to water table reaches as much as about 200 m in some regions, which attenuates the seasonal signal in surface inputs before it reaches the water table.

Under the enhanced irrigation efficiency scenario (S1), the seasonal structure of precipitation is unchanged, while irrigation application is reduced compared to BAU, reflecting the water savings achieved through more efficient application technologies (Figure 6b). The corresponding recharge pattern for scenario S1 is similar to that of the BAU scenario, albeit with slightly lower rates due to the lower surface water application rates of S1 relative to BAU. This result demonstrates that efficiency improvements result in less back recharge; however, the decreased irrigation demand under S1 more than compensates for the diminished back recharge. The higher annual irrigation demand of this scenario relative to net recharge (Figure 6b) means stable groundwater levels are not achieved under this scenario, although some improvement is seen relative to the BAU scenario (Figure 6a). The most pronounced differences emerge under the corn phase-out combined with enhanced efficiency scenario (S2), which produces a shift in the seasonal distribution of irrigation application (Figure 6c). The summer irrigation peak, particularly July, August, and September, is reduced compared to both BAU and S1, as corn, an irrigation-intensive crop in the basin, is progressively replaced by winter crops with lower and earlier-season water demands.

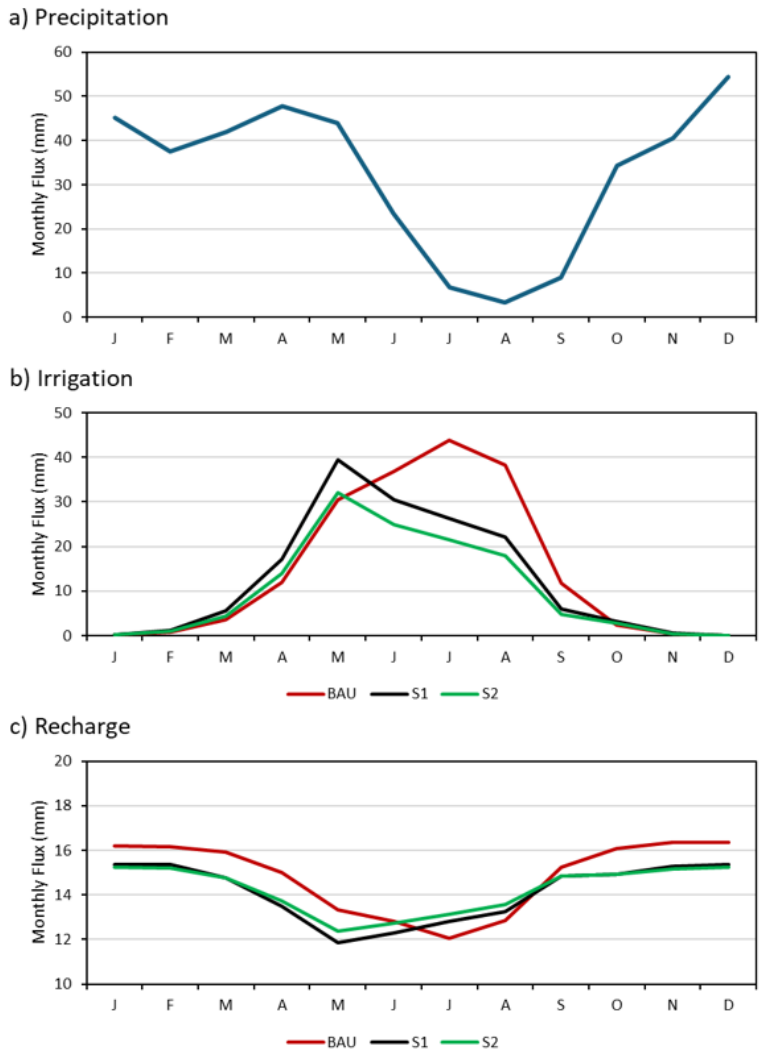


Figure 6. Mean monthly precipitation, irrigation application, and recharge (mm) under three management scenarios for the Konya Closed Basin under RCP8.5 projections: Business as Usual (BAU, current cropping and irrigation efficiency held constant to 2040); Enhanced Irrigation Efficiency (S1, irrigation efficiency increased from 0.65 to 0.80 between 2023 and 2028); and Corn Phase-Out with Enhanced Efficiency (S2, S1 efficiency gains combined with a 2023–2028 transition of corn acreage back to 2004 levels, replaced by wheat).

Figure 7. Fraction of annual recharge to total surface water application (precipitation and irrigation) for three management scenarios (Business as Usual, BAU; Enhanced Irrigation Efficiency, S1; and Corn Phase-Out with Enhanced Efficiency, S2) over the period 2005–2040. Each line represents the median ratio across the seventeen EURO-CORDEX regional climate model ensemble for RCP8.5 projections.

The irrigation curve is seen to shift downwards and to earlier months reflecting the reduced corn and enhanced irrigation efficiency. Monthly recharge rates under S2 show a slight reduction through the summer months compared to BAU, consistent with the reduced irrigation inputs during this period. With annual recharge close to the groundwater extraction rate, groundwater levels for this scenario stabilize, suggesting that through the combination of enhanced irrigation technologies and reverting to historical cropping patterns, near stable conditions can be achieved. Taken together, the three scenarios reveal an important asymmetry in the recharge response to agricultural management interventions.

Efficiency improvements alone reduce irrigation application but leave recharge largely unchanged, while the combination of efficiency improvements and crop diversification away from summer corn produces a measurable reduction in summer back recharge. In both cases, the effect on total annual recharge is modest relative to the magnitude of changes in surface water application, consistent with the vadose-zone buffering described in Section 3.1.

This muted recharge response contrasts with the broader "irrigation efficiency paradox" literature, which typically reports the opposite: efficiency gains sharply reducing basin-scale recharge, since decreased deep percolation and return flow undercut on-farm water savings (Grafton et al., 2018; Scott et al., 2014; Xiong et al., 2021). This has been documented in the Eastern Snake Plain Aquifer and the Souss and Tensift basins of Morocco (Grafton et al., 2018). The KCB's comparatively weak response appears basin-specific, driven by the storage and travel-time buffering of its unusually thick vadose zone (average water-table depth ~80 m).

The relative importance of climate versus management can be judged directly from the magnitudes involved. Projected climate change between 2023–2040 is modest under both pathways, small relative to the basin's ~340 mm mean annual precipitation. Management scenarios (S1, S2), by contrast, produce much larger changes in irrigation application, which account for most of the variation in recharge (Figure 7). This suggests that, over the near-term horizon considered here, recharge is more sensitive to management decisions than to the projected climate signal, though climate change would be expected to play a larger role beyond this study's time horizon.

3.3. Fraction of Recharge to Surface Water Application

The ratio of annual recharge to total surface water application (precipitation and irrigation) provides a useful metric for understanding the basin's recharge dynamics (Figure 7). Across the simulation period (2005–2040), the ratio fluctuates between approximately 0.22 and 0.42, remaining substantially above the range typically reported for non-irrigated semi-arid regions (Gee and Hillel, 1988; Scanlon et al., 2006). In irrigated regions, recharge has been reported to represent 1–25% of the combined precipitation and irrigation input (Scanlon et al., 2006), and the Konya Closed Basin falls within the upper range. The relatively high recharge of the Konya Closed Basin is also attributed to the significantly reduced evaporation rates in winter months when a large proportion of the precipitation occurs.

This range is broadly consistent with, though at the lower end of, values reported for other irrigation-dominated alluvial systems. In northwestern Bangladesh, irrigation return flow alone was estimated to contribute up to 98% of dry-season recharge, with roughly a third of applied irrigation returning to the aquifer (Tulip et al., 2022). In the Po Plain of northern Italy, surface-water irrigation return flow was found to dominate recharge, contributing a median of 64% of total recharge in irrigated areas (Caschetto et al., 2025). Comparisons across western U.S. basins similarly show recharge-to-precipitation ratios spanning roughly 1–49%, with the higher values associated with more permeable alluvial systems such as California's Central Valley, where irrigation return flow is also a major recharge component. In contrast, recharge in the North China Plain has been shown to depend on crop type and irrigation amount rather than following a fixed fraction. The KCB's estimated recharge fraction (22–42%, Figure 7) falls within the range reported for other alluvial, irrigation-dominated semi-arid systems, while remaining below the highest values reported for more permeable, less arid basins such as the Central Valley.

BAU scenario applies the highest irrigation water and therefore shows the lowest recharge ratio. S1 reduces water application through efficiency improvements, while S2 applies the least water, through the combined effect of efficiency gains and corn phase-out with the highest recharge to surface water application ratio. Since recharge remains relatively stable across all three scenarios, the divergence in the ratio is driven by differences in the surface water application. Each line in the figure represents the median ratio across the seventeen EURO-CORDEX climate model runs for RCP8.5.

4. Conclusion

Groundwater recharge constitutes a critical component of the water balance with profound implications for the long-term sustainability of agricultural systems, particularly in arid and semi-arid regions where irrigation demand consistently exceeds natural precipitation. Nevertheless, quantifying recharge remains inherently challenging, reflecting the complexity of the processes governing infiltration and percolation, including the spatiotemporal distribution of precipitation, crop type and their seasonal water requirements, and vadose zone hydraulic properties.

To address this challenge, a physics-based saturated–unsaturated flow model was developed for the Konya Closed Basin, a major semi-arid agricultural region of Türkiye critically dependent on groundwater for irrigation. The model was constructed using the MODFLOW computer program that simulated

groundwater flow in the saturated zone, coupled with the UZF1 module to simulate variably saturated flow through the vadose zone.

Model results demonstrate that recharge rates are spatially heterogeneous across the basin, reflecting the diversity of crop types and the hydraulic heterogeneity of the aquifer system. Temporally, recharge rates are marginally higher during winter months, when evapotranspiration demand is low relative to summer months when elevated temperatures and crop water uptake substantially reduce percolation. The subdued temporal variability in recharge is attributed to the attenuating effect of the thick vadose zone, which dampens and delays peak recharge signals.

Scenario simulations reveal that while improvements in irrigation efficiency and transitions away from water-intensive crops reduce total water application particularly during summer, the corresponding reduction in recharge is minimal. This finding indicates that the majority of excess irrigation water is lost through evaporation, with only a small fraction returning to the aquifer as irrigation return flow. Model results also indicate that recharge to the Konya Closed Basin aquifer system amounts to approximately 25–30% of total surface water application. This relatively high recharge fraction reflects the relatively high recharge rates in the winter months when most of the precipitation occurs with minimal evapotranspiration, and the high irrigation rates applied in the summer months in the Konya basin.

These findings provide a quantitative basis in support of the sustainable governance of groundwater resources in the Konya Closed Basin. The results can help in the determination of sustainable irrigation allocations in support of the long-term viability of the agricultural sector, which constitutes the principal economic activity of the region.

Author Contributions

The percentages of the authors' contributions are presented below. All authors reviewed and approved the final version of the manuscript.

	O.C.Y.	I.D.Ç.	N.K.C.
C	10	40	50
D	10	40	50
S		20	80
DCP	30	35	35
DAI	60	10	30
L	20	50	30
W	10	60	30
CR	10	30	60
SR	10	60	30
PM		50	50
FA		50	50

C= concept, D= design, S= supervision, DCP= data collection and/or processing, DAI= data analysis and/or interpretation, L= literature search, W= writing, CR= critical review, SR= submission and revision, PM= project management, FA= funding acquisition.

Conflict of Interest

The authors declared that there is no conflict of interest.

Ethical Consideration

Ethics committee approval was not required for this study because there was no study on animals or humans.

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