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RESEARCH

Quantifying future water-saving potential under climate change and groundwater recharge scenarios in Lower Chenab Canal, Indus River Basin

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Abstract

Quantifying water-saving potential (WSP) is crucial for sustainable water resource management in canal command areas and river basins. Previous studies have partially or fully ignored the importance of groundwater in WSP assessments, particularly in irrigated areas. This study is aimed at quantifying WSP in the Lower Chenab Canal (LCC) command area of the Indus River Basin, Pakistan, under various scenarios of future climate change and groundwater recharge. These quantifications are conducted using an empirical model based on the Budyko theory. The model was forced using observed, remote sensing, and CMIP6 future climate data for two Shared Socioeconomic Pathways (SSP245 and SSP585) and their ensembles (cold-dry, cold-wet, warm-dry, and warm-wet) for possible futures. The results showed that the average WSP in the LCC command area was 466 ± 48 mm/year during the historical period (2001–2020). The WSP is projected to decrease by – 68 ± 3% under the warm-dry ensemble scenario (SSP245 and SSP585) and – 48 ± 13% under the ensembled cold-wet scenario by 2100. The results also demonstrated that WSP could be increased by up to 70 ± 9% by artificially recharging 20% of the abstracted groundwater per year in the LCC command area by the late twenty-first century. Our findings highlight the importance of adopting artificial groundwater recharge to enhance the WSP and sustainably manage water resources in the LCC command area. Policymakers should consider these findings when deciding on water resource management in the Indus River Basin.

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1 Introduction

Water-saving potential (WSP) is a key indicator of irrigation efficiency, and its quantification is crucial for ensuring future freshwater availability and sustainable water resource management in river basins worldwide. Freshwater availability is under significant pressure due to the growing global population and increasing demands for food and energy (Hafeez and Awan 2022; Immerzeel et al. 2020; Pritchard 2017). Future climate changes are anticipated to further exacerbate this situation, intensifying the pressure on available water resources (Huss and Hock 2018; Nepal and Shrestha 2015; Yang et al. 2016). Conservation, judicious use of water, and adaptation are potential ways to mitigate and reduce the impacts of anthropogenic and climate forcings (Simons et al. 2020). WSP refers to the amount of water that can be conserved through water-saving approaches. It is a critical indicator of irrigation efficiency, representing the amount of water that can be conserved through various water-saving strategies. These strategies can encompass a wide range of approaches (Pande and Moharir 2021), including technological innovations such as precision irrigation and drought-resistant crop varieties, changes in irrigation practices, water pricing policies, and education programs to promote water conservation among farmers. A high WSP suggests substantial scope for improving water use efficiency and saving water for other uses. The concept of WSP acquires particular significance in the context of a river basin due to the interlinked nature of water resources. Alterations in irrigation methods at one location within the basin can dramatically influence downstream regions, thereby impacting water availability for other users and ecosystems (Grafton et al. 2018). The scope of WSP is a complex interplay between groundwater and surface flows in the Indus River Basin (Awan and Ismaeel 2014; Cheema et al. 2014; Malakar 2021). Quantifying WSP in the Indus Basin would highlight its importance in ensuring future freshwater availability and guiding sustainable water resource management. The intricate irrigation systems and varied water users within the Indus Basin pose challenges and opportunities to enhance water use efficiency and realize the WSP.

Previous studies have often ignored the role of groundwater recharge in enhancing WSP, leading to an incomplete understanding of the factors influencing WSP (Jägermeyr et al. 2015). The sustainable use of water resources is threatened by the unsustainable withdrawal of water due in part to a lack of policies promoting and incentivizing the use of accurate and cautious water withdrawal techniques (Hellegers et al. 2022; Scott et al. 2014; World-Bank 2016; Yasin et al. 2021; Zhang et al. 2022). Therefore, there is a need for an assessment framework that can accurately quantify the WSP. Including groundwater recharge in such a framework will significantly enhance our understanding of WSP, leading to improved water conservation and management practices.

The WSP assessment framework requires information about all water components of the hydrological cycle in a given area, including surface water, groundwater, and precipitation, as well as the fraction of water that is lost to evaporation (Ahmad et al. 2021; Jensen and Allen 2016; Zhang et al. 2022). In cases where data on a particular river basin is scarce, satellite-derived datasets can be used to evaluate the spatial and temporal variations of key hydrological parameters such as precipitation (Duan et al. 2021), evapotranspiration (Peña-arancibia et al. 2020), runoff, soil moisture changes, and storage change (Poortinga et al. 2017; Simons et al. 2016). However, satellite estimates still have limited abilities to compute water withdrawals; alternatively, the remote sensing data coupled with the hydrological models have good potential for evaluating the irrigation dynamics (Arshad et al. 2022; Cheema et al. 2014; Droogers et al. 2010; Pena-Arancibia et al. 2016; Santos et al. 2007). Some large-scale hydrological models can facilitate computing the WSP of the total available water flow to the system (Jägermeyr et al. 2015). However, the complexity of these models and the large amount of data required for parameterization and force can result in significant output uncertainty. Furthermore, these assessments are typically limited to the global or basin scale and do not consider the potential for determining WSP at the level of individual irrigated regions, such as canal command areas (CCAs).

Empirical models, known for their simplicity and accuracy, can be further improved by including groundwater in their calculations. Using empirical models based on Budyko's theory, combined with observed, remote sensing, and future climate data, has received limited attention in the scientific community for quantifying WSP and projecting future changes. Budyko's theory divides precipitation into evapotranspiration and streamflow based on the water-energy balance (Condon and Maxwell 2017; Sposito 2017; Xu et al. 2013) and has proven effective in the development, constraint, and validation of water balance models (Chen et al. 2020b, 2013; Gentine et al. 2012; Poortinga et al. 2017; Zhang et al. 2008). While initially developed for natural river systems in dynamic equilibrium, with precipitation as the sole source of water supply, this approach has been reformulated and extended to assess the water balance of systems with anthropogenic influence (Chen et al. 2020b; Greve et al. 2016; Wang et al. 2016). The approach has been applied and tested successfully in various river basins, including the Heihe River Basin (Du et al. 2016), the Tarim Basin (Han et al. 2011), the Indus Basin (Simons et al. 2020), and the Lower Jordan (Gunkel and Lange 2017), representing diverse environments such as irrigated and arid climates. However, the Budyko theory–based empirical models have yet to be applied in predicting future variations in WSP at the CCA scale, particularly when including groundwater in the true water-energy balance. Information on groundwater recharge and abstraction could improve our understanding of WSP in the context of future climate change.

This study is aimed at quantifying the WSP in the Lower Chenab Canal (LCC), a major irrigation system in the Indus River Basin, under different climate change and groundwater recharge scenarios. To do this, we use an empirical model based on Budyko's theory. We force our model with in situ meteorological (temperature and precipitation) observations, remote sensing data, and CMIP6 climate projections. Our specific objectives are as follows: (1) to determine the historical WSP in the Lower Chenab Canal using this Budyko theory–based empirical model; (2) to project future variations in WSP using CMIP6 future climate data under cold-dry, cold-wet, warm-dry, and warm-wet projections; and (3) to investigate the impact of groundwater recharge on projected WSP under different water management scenarios. By providing quantitative information on projected WSP, this study is aimed at assisting in developing policies to promote sustainable water resource management through adequate groundwater recharge practices in the region.

2 Materials and methods

2.1 Study area

The study area covers the entire Lower Chenab Canal (LCC) in the Rachna Doab, Punjab, Pakistan. The LCC takes off from Khanki Headworks and distributes water to the eastern and western sides of the LCC through seven branch canals—Sagar, Upper Gugera, Rakh, Mian Ali, Jhang, Lower Gugera, and Burala (Fig. 1). The LCC delivers average discharge of 440 m^3/s at Khanki Headworks and thereby irrigating ~ 1.22 million ha of agricultural land. Rabi (October to March) and Kharif (April to September) are the two major cropping seasons (Awan and Ismaeel 2014). The major growing crops included wheat, sugarcane, rice, and cotton. The region's climate ranges from arid to semi-arid, with an annual rainfall of ~ 400 mm, of which more than 70% falls during the monsoon season (Mujtaba et al. 2022). However, spatiotemporal variabilities between rainfall and evapotranspiration highlight the need for artificial irrigation in the studied region. Over the past decades, climate change–induced changes in temperature and rainfall increased annual water consumption by 7 to 11% in the LCC (Awan et al. 2016). Thus, considering the impacts of climate change and the heightened water demand, sustainable artificial irrigation is of utmost importance for the future of the LCC region.

2.2 Data collection

Table 1 provides a detailed description of the data used in this study. The data from six meteorological stations (Fig. 1) was incorporated into the CHIRPS algorithm to improve satellite rainfall estimates for the LCC region. Data on the Budyko parameter ω was taken from a study by Xu et al. (2013). These ω values indicate the irrigation effects on water and vegetation during this period.

The actual evapotranspiration (ET_a) and potential evapotranspiration (ET_p) values (2606 ± 101 and 942 ± 168 mm/year, respectively) were estimated using remote sensing data (MOD16A2.006) (Fig. 2). The polynomial relationship was derived between the spatially distributed grid values. The developed statistical relationship was used for projected calculations of ET_a in the future (2015–2100) using CMIP6 temperature data.

2.3 Development and parametrization of the empirical model

2.3.1 Empirical model based on the Budyko hypothesis

In this study, the Budyko hypothesis (BH)-based empirical model was developed for dividing the actual evapotranspiration (ET_a) into green and blue water (ET_g and ET_b). The BH establishes an empirical relationship between ET_a, ET_p, and P for those river basins that have dynamic equilibrium and experience minor changes in water storage (Sposito 2017). The initial Budyko equation has been subjected to re-formulation many times to account for variations in watershed

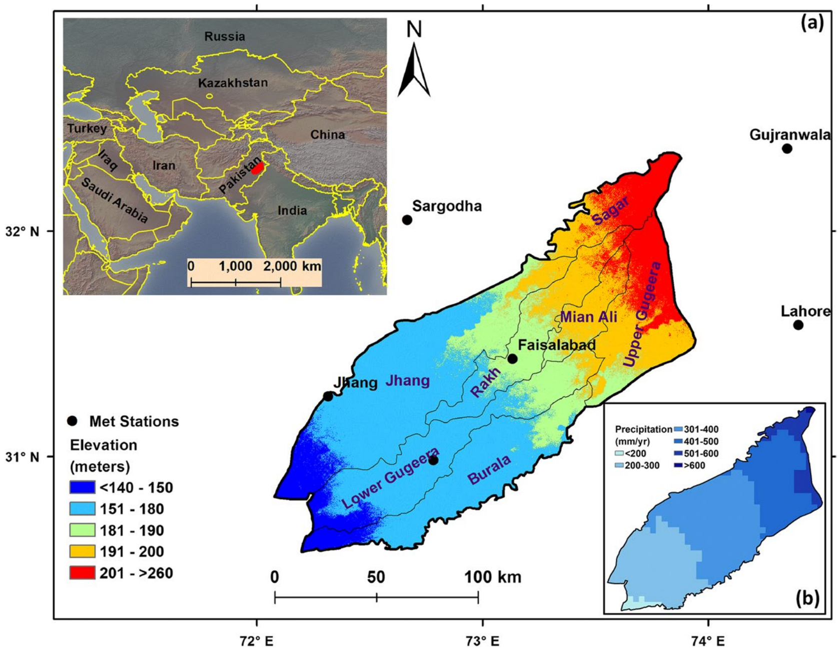

Fig. 1 **a** The geographic location of the Lower Chenab Canal command areas, Rachna Doab, Pakistan (source: Punjab Irrigation Department), and meteorological stations. **b** Spatial distribution of average annual precipitation (2001–2020)

Table 1 Details of the data used in the current research

Dataset	Description	Reference
Observed meteorological data	Precipitation and temperature; 1985–2020	Pakistan Meteorological Department
Observed canal inflows	Head discharge; 2001–2020	Water and Power Development Authority (WAPDA)
Climate Hazards Group InfraRed Precipitation with Station data (CHIRPS) V2.0	0.05°; daily; 1985–2020	Climate Hazards Center, UC Santa Barbara; https://chc.ucsb.edu/data/chirps
MOD16A2.006	Actual evapotranspiration (ET_a) and potential evapotranspiration (ET_p), Terra Net Evapotranspiration 8-Day Global 500 m; 2001–2020	NASA LP DAAC at the USGS EROS Center; https://lpdaac.usgs.gov/products/mod16a2v006/
CMIP6 future climate data	Precipitation and temperature (min, max); 1985–2100 1. BCC-CSM2-MR: Beijing Climate Center (BCC) Climate System Model (T266) Medium Resolution, hereafter BCC 2. CNRM-CM6-1: Centre National de Recherches Meteorologiques—Climate Model Version 6, hereafter CNRM 3. GFDL-CM4: Geophysical Fluid Dynamics Laboratory-Climate Model version 4, hereafter GFDL 4. IPSL-CM6A-LR: Institut Pierre Simon Laplace-Climate Model Version 6, hereafter IPSL	https://esgf-node.llnl.gov/projects/cmip6/

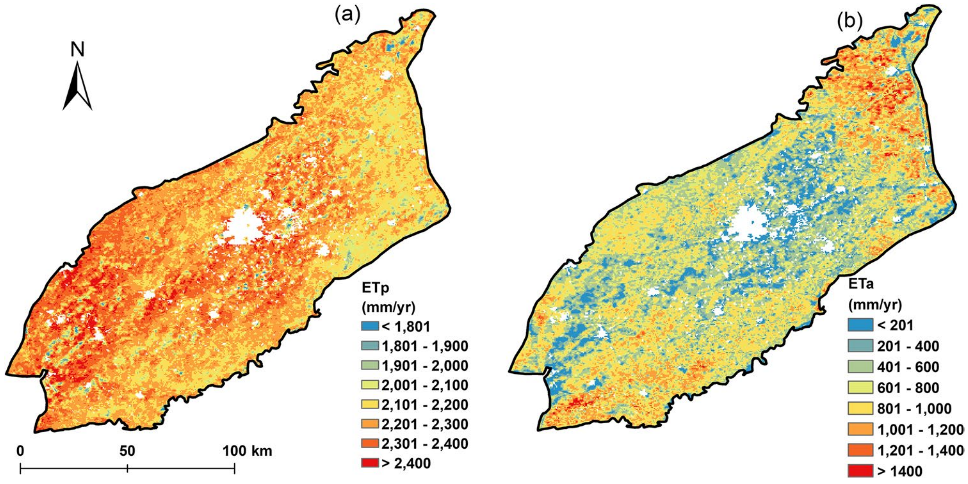

Fig. 2 MODIS **a** potential (ET_p) and **b** actual ET (ET_a) based on MOD16A2.006 product in LCC for 2001–2020

boundary conditions. The present study employs Budyko re-formulation that was developed by Fu (1981):

$$\frac{ET_a}{P} = 1 + \frac{ET_P}{P} - \left(1 + \left(\frac{ET_P}{P}\right)^{\omega}\right)^{1/\omega} \tag{1}$$

where ω, the Budyko parameter, helps describe the Budyko curve's shape, and it can be taken as an integrated catchment characteristic influenced by certain catchment-specific properties, including land cover, vegetation, climate, and soil hydraulics (Condon and Maxwell 2017; Li et al. 2013). The higher values of ω describe the higher green water (ET_g) for the same ET_p/P ratio (the aridity index), and consequently, it demonstrates the elevated basin's capacity to store water for evapotranspiration. Thus, the ω parameter acts as an indicator to reflect the synthetical influence of basin characteristics on ET (Chen et al. 2020a).

Using the Budyko equation with adjusted total water supply, the groundwater contribution for the LCC is estimated as follows on a multi-annual time scale:

$$\frac{ET_a}{P_{adj}} = 1 + \frac{ET_P}{P_{adj}} - \left(1 + \left(\frac{ET_P}{P_{adj}}\right)^{\omega}\right)^{1/\omega} \tag{2}$$

The conventional definitions of blue and green water describe that these are the components of actual evapotranspiration (ET_a) (Falkenmark and Rockström 2006) from the surface, groundwater resources, and rain-dependent and represented with ET_b and ET_g, respectively.

$$ET_b = ET_a - ET_g \tag{3}$$

ET_b is also called incremental evapotranspiration (Hoogeveen et al. 2015) or secondary evaporation (van Dijk et al. 2018), whereas ET_g corresponds to the net precipitation available for the irrigation consumption (Jensen and Allen 2016).

2.3.2 Calculations of WSP

The WSP is a metric quantifying the amount of water that can be conserved through efficient management, determined by the unconsumed portion of the total available water within a specific region, often factoring in the complex interplay between groundwater and surface water flows. Simons et al. (2020) re-introduced the concept of consumed fraction (CF), which is the ratio between the amount of irrigation water consumed and total water withdrawal, indicating irrigation efficiency over an area. Here, the equation that calculates CF takes the following form:

$$CF = ET_b/Q_T \tag{4}$$

where Q_T refers to the water withdrawals from surface and groundwater resources. An overview of the workflow of the whole approach is presented in Fig. 3.

According to the actual conditions in LCC, Q_T consists of two types of inflow:

$$Q_T = Q_s + Q_{gw} \tag{5}$$

where Q_s indicates the surface water volume diverted at the main canal head. Q_{gw} is the pumped groundwater, including non-consumed flows and fossil groundwater abstraction. We assume 35% of the canal water will be used after deducting losses. In the case of groundwater, losses were taken as 20% for the calculation. These losses include conveyance and application losses and losses due to infiltration and deep percolation (Ahmad and Majeed 2001; Khan et al. 2021; Mujtaba et al. 2022; Rizwan et al. 2018). The groundwater component can also be considered additional water because it includes drainage from CCA upstream,

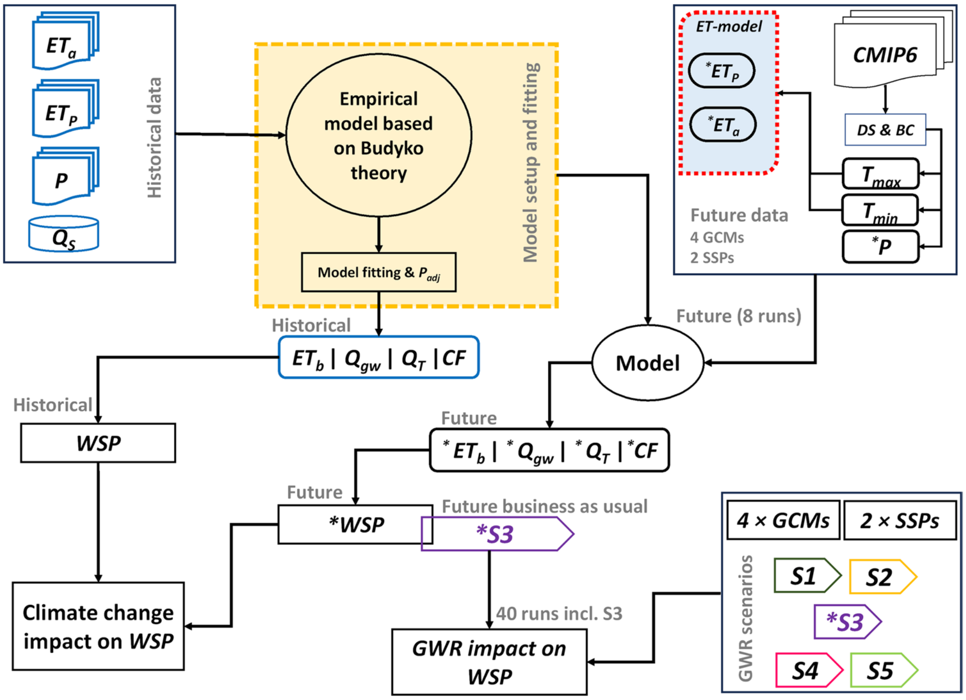

Fig. 3 Flowchart of the methodology for assessing the impacts of climate change and groundwater recharge (GWR) scenarios on water-saving potential (WSP). ET_a = actual ET, ET_p = potential ET, P = precipitation, Q_s = canal diversions, ET_b = blue ET, ET_g = green ET, Q_{gw} = groundwater contributions, Q_T = total water, CF = consumed fractions, DS = downscaling, BC = bias correction, T_{max} = projected max temperature, T_{min} = projected min temperature, *projected values based on CMIP6 and empirical models. $S1 = -20\%$ groundwater abstraction (compared to actual values), $S2 = -10\%$ groundwater abstraction (compared to actual values), $^*S3$ = business-as-usual scenario (nothing changes), $S4 = +10\%$ groundwater recharge (compared to actual values), $S5 = +20\%$ groundwater recharge (compared to actual values)

penetrating through the surface and subsurface ways. We assumed that groundwater constitutes a significant part of the overall water supply.

The WSP is computed as the difference between the total surface and groundwater supply and the water consumed by irrigation:

$$WSP = Q_T - ET_b \tag{6}$$

The developed empirical model fitted by estimating the adjusted precipitation (P_{adj}) to close the actual water-energy balance in the command area. The P_{adj} is the sum of precipitation and total water withdrawals in the command area.

$$P_{adj} = P + Q_T \tag{7}$$

Here, $1 - ET_a/P_{\text{adj}}$ corresponds to the runoff fraction R_f. By subtracting P from P_{adj}, we get the estimation of Q_T required to quantify WSP. The empirical model was parametrized and fitted for the historical period. Then, it was forced with CMIP-6 climate data to project future variations in WSP (Eyring et al. 2016).

2.4 Future predictions

The climatic data were extracted from four GCMs (namely, BCC, CNRM, GFDL, and IPSL) of CMIP6 for two Shared Socioeconomic Pathways (SSPs): SSP245 and SSP585 (Table 1). The data from representative grids were downscaled and bias-corrected using CMhyd software (https://swat.tamu.edu/software/cmhyd/) before applying it to the empirical model (details in Supplementary material). We categorized the GCMs based on the projected future (Table 2) that they represent (i.e., cold-dry, cold-wet, warm-dry, and warm-wet), following the multi-perspective approach proposed by Shafeeque and Luo (2021).

The downscaled and bias-corrected temperature data were used to calculate the ET_p using the Hargreaves model as follows:

$$ET_P = 0.0023 \times 0.408R_a\left(T_{max} - T_{min}\right)^{0.5} \times (T + 17.8) \tag{8}$$

The ET_p was then used to estimate ET_a (actual evapotranspiration) based on the empirical Budyko model that was parametrized using historical data.

The LCC flows are controlled by the gauge at the Khanki Headworks; therefore, future inflows from the Khanki Headworks gauge were taken as constant based on the average flow during 2001–2020. The groundwater contributions were calculated using the Budyko framework for the projection period using projected precipitation, ET_p, and discharge. Future CF and WSP were calculated using predicted values of ET_b and Q_T. In addition, the uncertainties in the projected ET_p and ET_a data were assessed by comparing the MODIS ET_p and ET_a values from the overlapped historical period (i.e., 2015–2020) (Supplementary Fig. S7).

2.5 Assessing the impact of artificial groundwater recharge on WSP

To thoroughly examine the future WSP in the LCC command area influenced by the artificial groundwater recharge, we designed a comprehensive methodological framework involving five distinct water management scenarios (Fig. 3):

1. Scenario 1 ($S1$): reduction of groundwater abstraction by 20% compared to the actual rate
2. Scenario 2 ($S2$): reduction of groundwater abstraction by 10% from the actual rate
3. Scenario 3 ($S3$): business-as-usual scenario, maintaining the existing groundwater abstraction practices without any changes
4. Scenario 4 ($S4$): enhancement of groundwater recharge by 10% compared to the actual rate
5. Scenario 5 ($S5$): enhancement of groundwater recharge by 20% compared to the actual rate

Table 2 Projected changes in temperature (ΔT) and precipitation (ΔP) in Lower Chenab Canal (LCC) based on selected GCMs from the CMIP6 archive. The changes were calculated by averaging the first and last decade of twenty-first century. Rank coding: for ΔT, 1 and 2 = cold and 3 and 4 = warm; for ΔP, 1 and 2 = dry and 3 and 4 = wet

Scenario	GCM	ΔT (°C)	ΔP (%)	Rank ΔT	Rank ΔP	Projection
ssp245	BCC	2.3 ± 0.42	3.0 ± 17	1	1	Cold-dry
	CNRM	30. ± 0.54	18 ± 43	2	3	Cold-wet
	GFDL	4.1 ± 0.44	9.0 ± 43	4	2	Warm-dry
	IPSL	3.1 ± 0.39	23 ± 20	3	4	Warm-wet
ssp585	BCC	4.2 ± 0.62	13 ± 27	1	2	Cold-dry
	CNRM	5.7 ± 0.53	65 ± 55	2	4	Cold-wet
	GFDL	6.5 ± 0.40	10 ± 39	3	1	Warm-dry
	IPSL	6.5 ± 0.44	29 ± 38	4	3	Warm-wet

Each scenario was methodically evaluated under two SSPs (SSP245 and SSP585) using four GCMs (Table 1). This approach generated 40 distinct computational runs, providing a broad and robust dataset for our study. The chosen methodology enabled us to holistically assess and quantify the impact of artificial groundwater recharge on WSP under the spectrum of potential future climate change.

3 Results

3.1 Historical water-energy balance and WSP

During the historical period (2001–2020), the annual ET_g and ET_b were 358 ± 75 and 584 ± 142 mm/year, respectively. Annual ET_g (Fig. 4), which follows a relatively smooth spatial pattern, correlated fairly with the rainfall gradient (Fig. 1(b)). ET_b becomes influenced by many factors, including cropping patterns, canal operations, groundwater pumping behavior, soil salinity, and groundwater quality, and therefore is significantly heterogeneous.

Given the Budyko theory, Fig. 5 corresponds with the anticipated behavior of an irrigated system, thereby indicating that the water consumption rate cannot be adequately accounted for solely by the natural water supply originating from precipitation. In Fig. 5, the theoretical lines (black dotted) describe that the values of ET_a are associated with P in Eq. 5. In the case in which unadjusted precipitation and ET_g were used, the LCC lies well above the Budyko curve (blue-dashed line) (Fig. 5a). The high aridity indices (ET_p/P) plotted on the x-axis demonstrate the arid climate in the LCC.

Figure 5b shows the results of the Budyko curve when the observed Q_s (402.28 mm/year) was added to the supply side of both ratios. It is observed that the aridity index and the ET/P ratio or water limit decrease when Q_s is added to the water supply, indicating the wetter climate of the land surface (Fig. 5b). Consequently, a considerable shift of all the points toward the Budyko lines has been noted. It is important to note that these are annually averaged values for the historical period (2001–2020). The water-energy balance represents the equilibrium state between evapotranspiration and precipitation in a region, influenced by climate, soil type, vegetation, and topography (Shafeeque et al. 2022b; Xu et al. 2013). The actual water-energy balance is typically visualized through the Budyko curve, which showcases the intertwined relationships between climatic, hydrological, and ecological processes, while an ideal water-energy balance would place most data points within the area confined by the red, black-dotted, and blue-dashed lines (Fig. 5), indicating that the precipitation and canal diversions sufficiently account for the total water supplied to the crops. However, most data points fall outside this ideal region (Fig. 5a, b), suggesting that additional water sources contribute to ET_a beyond precipitation and canal water diversions (in the case of Fig. 5b). The empirical model simulated a true water-energy balance in the LLC when forced by P_{adj} (Fig. 5c).

A relatively large volume of Q_{gw} is computed (average 648 ± 192 mm/year) (Fig. 6a). The average annual Q_T in LCC was 1050 ± 182 mm/year (Fig. 6b), which substantially exceeded ET_b for maintaining all the hydrological processes of the Budyko hypothesis. The adjusted precipitation (P_{adj}) was calculated as 1008 ± 242 mm/year for 2001–2020 in LCC. The average CF in LCC, weighted according to Q_T, is 0.55 ± 0.05, with higher values in Jhang, Lower Gugera, and upper parts of Burala branch canals (Fig. 6c). Finally, the Q_T and ET_b were used to assess the WSP in LCC. The average annual WSP was calculated as 466 ± 48 mm/year, with higher values in the head (Sagar and Upper Gugera) and tail (lower parts of Burala branch canal) tributaries in the southern part of LCC (Fig. 6d).

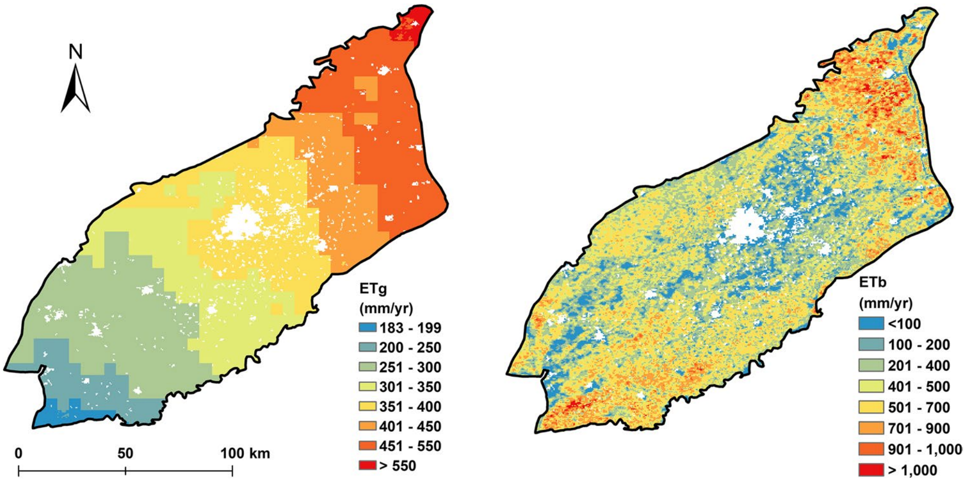

Fig. 4 ET_g and ET_b calculated from ET_a using the empirical model based on the Budyko theory in LCC for 2001–2020

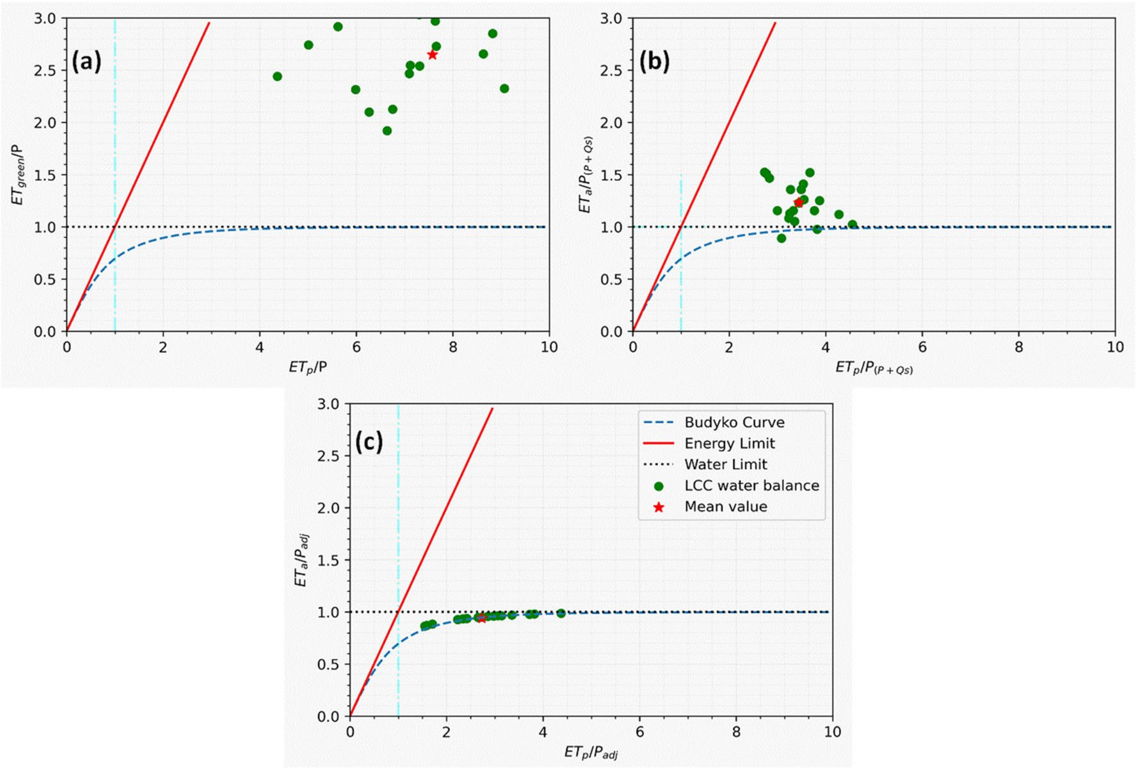

Fig. 5 Fitting of empirical model based on the Budyko theory. **a** For partitioning ET_a into ET_g and ET_b. **b** Verifying if there is additional water in the water balance in addition to precipitation and diverted canal water. **c** Using adjusted precipitation (P_{adj}) to calculate groundwater contributions. The light blue line represents the ideal balance point where the energy and water supply are in equilibrium

3.2 Future variations of WSP

The estimation of ET_p is the primary factor in predicting WSP shifts. The temperature data from selected GCMs are used to calculate the ET_p using Hargreeve's method. The ET_p values were used to calculate the ET_a based on the polynomial relationship developed during the historical period. We separated ET_b and ET_g from ET_a using our calibrated empirical model. Then, we estimated the variations in Q_{gw}, Q_T, and WSP compared to the historical period in LCC. The projected ET_p values were almost similar for SSP245 and SSP585 under all GCMs until 2060, except for the cold-wet future projection (CNRM), where SSP245 showed significantly higher ET_p. After 2060, all future projections show higher ET_p for the SSP585 scenario (Fig. 7a). The projected ET_p for SSP245 and SSP585 were 2873 ± 104 mm/year and 3197 ± 44 mm/year, respectively (Fig. 7b).

ET_b, Q_T, Q_{gw}, and CF are expected to increase remarkably in response to all future climate projections (Table 3). It is important to note that these results are achieved without any changes in the groundwater recharge (i.e., *S*3). ET_b is projected to increase by 72 ± 9% and 102 ± 9% under SSP245 and SSP585 by the late twenty-first century, respectively. The projected ET_b is higher for SSP245 compared to the high-emission scenario in LCC. The projected ET_b is the highest for warm-dry future projections (Table 3 and Fig. 8). ET_a is projected as 1178 ± 101 mm/year and 1491 ± 43 mm/year under SSP245 and SSP585 by the end of the twenty-first century.

The spatial distribution of the projected ET_b highlighted higher values over upper command areas of the Sagar and Upper Gugera and lower parts of the Lower Gugera and Burala branch canals. The differences between cold-dry to warm-wet scenarios are significant (Fig. 8a). The future climate scenarios projected similar spatial patterns for Q_T (Fig. 8b). There are significant differences in spatial distribution of Q_T for the cold-wet and warm-wet scenarios compared to other climate change scenarios, especially in the command areas of the Mian Ali, Rakh, Jhang, and upper parts of Lower Gugera branch canals (Fig. 8b).

The CF is also projected to increase (~ 50%) under all scenarios of all future projections. The lowest increase with higher uncertainty (44 ± 9%) is projected for SSP585 for the cold-wet scenario. In contrast, the highest increase (54 ± 2%) is projected for SSP245 of the cold-dry future projection (Table 3 and Fig. 8c).

The Q_{gw} is also projected to increase under all scenarios except SSP245 warm-dry future projection (Table 3). The

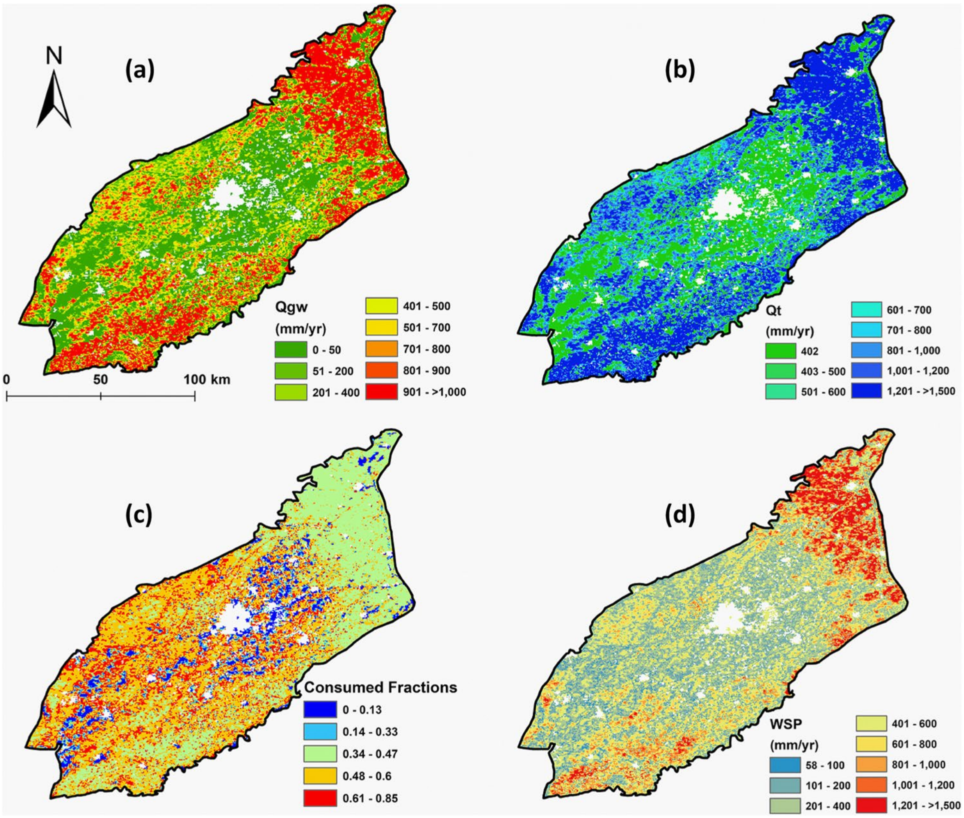

Fig. 6 Spatial distribution of (**a**) annual average groundwater contributions (Q_{gw}), (**b**) total diverted water (Q_T), (**c**) consumed fractions (CF), and (**d**) water-saving potential (WSP) in LCC during 2001–2020

higher uncertainty in Q_T and Q_{gw} projections is noted. The spatial distributions of projected Q_{gw} projected the highest in the head distributary (Sagar, Upper Gugera, and upper parts of Main Ali branch canal) command areas and also in the southern tail (lower parts of Burala branch canal) command areas (Fig. 9a).

The WSP in LCC is projected to decrease significantly under future climate changes during the ending period of the twenty-first century (Fig. 9b). However, the negative changes in the WSP are predicted to be the highest in the cold-dry future projection (− 68 ± 3%) under SSP245 and lowest (− 48 ± 13%) in the cold-wet projection under the high-emission scenario (SSP585) (Table 3).

3.3 Impacts of artificial groundwater recharge on WSP

The water management scenarios explored a substantial effect of the future WSP variations in LCC. The negative recharge (− 20% and − 10% groundwater recharge, i.e., groundwater abstraction is increased by 20% and 10% compared to business-as-usual scenario) scenarios showed a reduction in WSP up to 151% (Fig. 10a). In contrast, the positive groundwater recharge scenarios (i.e., 10% and 20% reduced groundwater abstraction) highlighted a significant increase of up to 14% and 79% in the WSP for SSP585 of future projections. For the + 20% groundwater recharge scenario, the average (SSP245 and SSP585) increase in the WSP was 70 ± 9% (Fig. 10a).

For SSP245, the main effect of the scenario is statistically significant and large (F (4, 45) = 132.39, $p < 0.001$; $\eta^2 = 0.92$, 95% CI [0.88, 1.00]). For SSP585, the main effect of groundwater recharge is statistically significant and large (F (4, 45) = 75.27, $p < 0.001$; $\eta^2 = 0.87$, 95% CI [0.81, 1.00]). Pairwise comparisons among groundwater recharge scenarios suggested that all the scenarios were significantly different except $S1$ and $S2$ for both SSPs (Fig. 10b).

4 Discussion

4.1 Role of groundwater in WSP

Groundwater is a vital component of the true water-energy balance and plays a crucial role in correctly quantifying WSP in the Indus River Basin. In this study, we used the true water-energy balance to successfully quantify the total water supply in the LCC command area (Fig. 5). The true water-energy balance demonstrates a considerable WSP of 466 ± 48 mm/year in the study area (Fig. 6d).

The main source of additional water in the LCC command area is groundwater, with an average recharge of

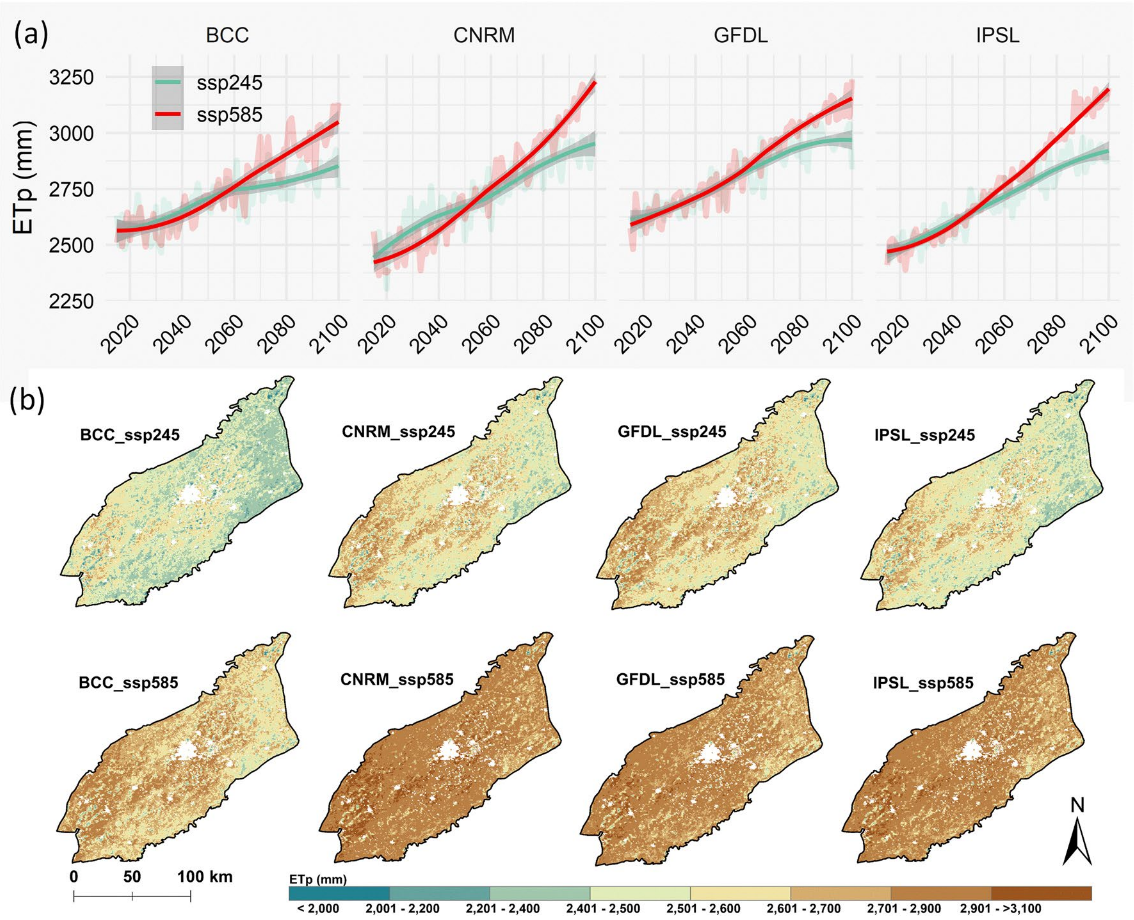

Fig. 7 Temporal (**a**) and spatial (**b**) distribution of projected ET$_p$ based on selected GCMs in LCC for 2015–2100

Table 3 Projected changes (%) in ET$_b$, Q_T, CF, Q_{gw}, and WSP in LCC based on CMIP6 climate data for the business as usual (*S*3, i.e., without any changes in groundwater recharge values). The changes were the average values for the first and last decades of the twenty-first century

	Cold-dry		Cold-wet		Warm-dry		Warm-wet	
Variable	BCC ssp245	BCC ssp585	CNRM ssp245	CNRM ssp585	GFDL ssp245	GFDL ssp585	IPSL ssp245	IPSL ssp585
ET$_b$	64 ± 5	93 ± 21	74 ± 21	90 ± 28	85 ± 30	117 ± 30	64 ± 13	107 ± 24
Q_T	3 ± 4	23 ± 13	10 ± 14	26 ± 15	17 ± 19	39 ± 19	4 ± 9	33 ± 15
CF	54 ± 2	51 ± 2	52 ± 3	44 ± 9	52 ± 2	50 ± 2	52 ± 1	49 ± 2
Q_{gw}	13 ± 12	43 ± 40	15 ± 49	8 ± 61	35 ± 61	75 ± 59	− 1 ± 27	50 ± 50
WSP	− 68 ± 3	− 60 ± 4	− 64 ± 3	− 48 ± 13	− 62 ± 3	− 54 ± 4	− 65 ± 2	− 53 ± 3

648 ± 192 mm/year over the period 2001–2020 (Fig. 6a). To compensate for these high withdrawals, artificial groundwater recharge is crucial for the sustainability of water resources in the region, as it helps to balance the aquifer system's discharge and withdrawal components. This claim agrees with previous studies (Jabeen et al. 2020; Lytton Lucy et al. 2021; Malakar 2021). However, unsustainable groundwater pumping and water reuse can impact the aquifer system's balance and reduce WSP (Q_{gw} term in water-energy balance).

The Budyko-based empirical model used in this study helps to describe the system in which the differences between canal water supply and crop water demands are compensated by pumping groundwater, particularly during the irrigation season. However, irrigation in the LCC is characterized by the pumping of significant non-consumed flows that are generated within the command area (Fig. 6a). This trait of the non-consumed network of water has been supported by previous studies (Awan and Ismaeel 2014; Hafeez and Awan 2022; Simons et al. 2020). It has also

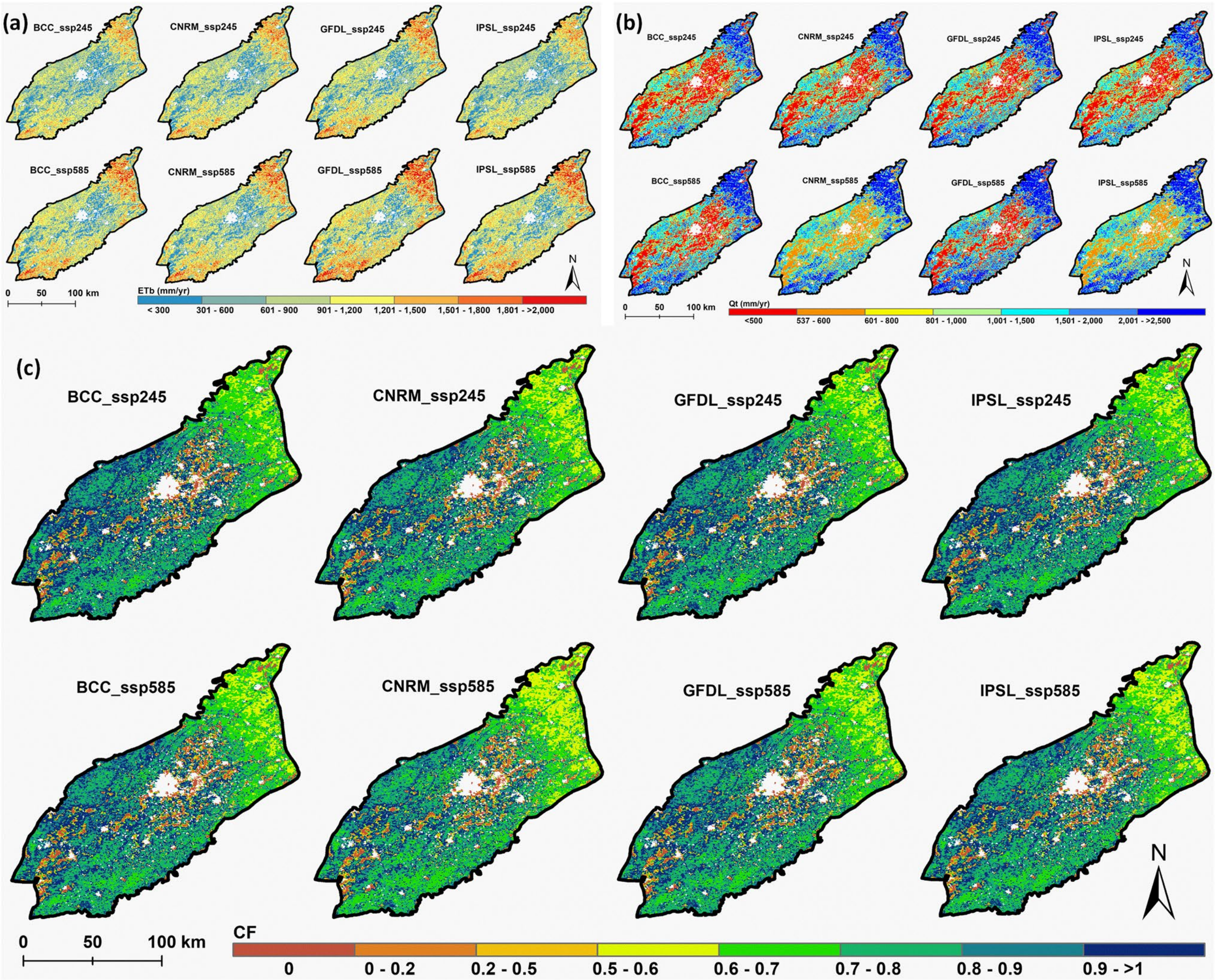

Fig. 8 Calculated **a** ET$_b$, **b** Q_T, and **c** CF for selected GCMs. The values are average for the last decade (2091–2100)

been well documented that the abstraction and recharge of groundwater are not in balance in the region due in part to the significant increase in the number of tube wells and the lack of metering and tariff systems for groundwater abstraction (Cheema et al. 2014; Laghari et al. 2012). In addition to unjust pumping, poor storage and conveyance infrastructure also contribute to losses in the system and negatively influence the WSP.

4.2 The efficiency of LCC irrigation system and WSP

In this study, we used the concept of CF to measure the efficiency of the LCC irrigation system. Previous studies have used a variety of definitions of irrigation efficiency, including measures of "losses" associated with water diverted through canals and applied to fields (Baoqing et al. 2020; Berbel et al. 2018; Grafton et al. 2018; Linstead 2018; Pérez-Blanco et al. 2020). Others have defined irrigation efficiency as the reuse of return flows or water-saving potential as the reuse of return flows (Ha et al. 2017; Wu et al. 2019). The Budyko-based empirical model used in this study yields higher values of CF (0.55 ± 0.05) compared to irrigation efficiencies that have been reported in previous studies for Pakistan, which range between 0.3 and 0.49 (Shafeeque et al. 2016; Simons et al. 2020; Watto and Mugera 2019). This suggests that irrigation in the LCC is more "efficient" than previously thought, at least in terms of the consumed fraction.

Evaluating CF at various spatial scales can provide insight into the reuse of non-consumed flows at a system scale (Cao et al. 2020; Chiara and Marco 2022; Pérez-Blanco et al. 2020; Wu et al. 2019). Here, we define "improving efficiency" in two ways: (1) increasing water abstraction for use, which can lead to the potential for unintended consequences, and 2) reducing waste, which ideally should lead to improved water balance without significant

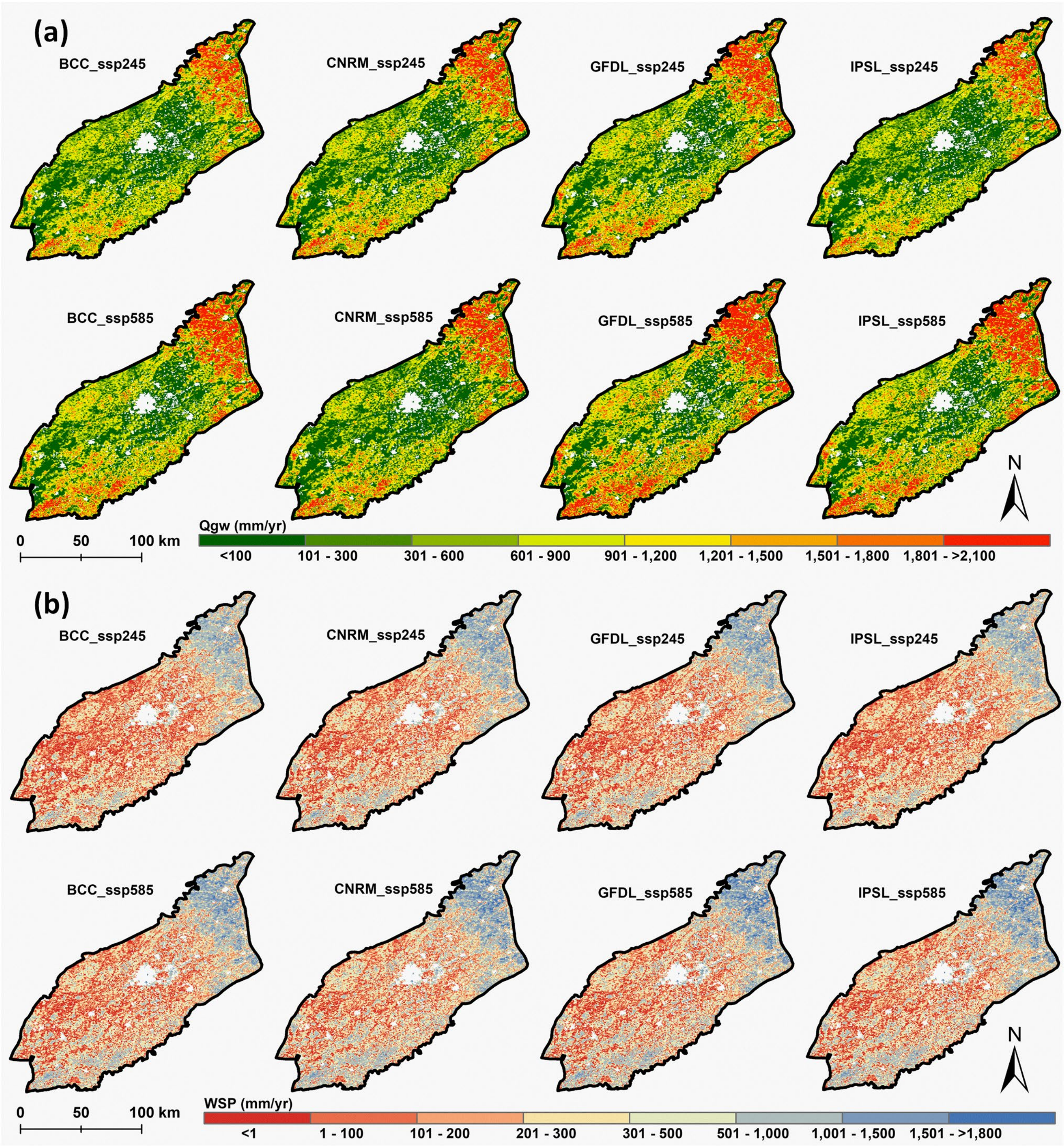

Fig. 9 Projected **a** Q_{gw} and **b** WSP in LCC based on CMIP6 climate change data for selected GCMs

negative effects. The findings of this study highlight the importance of considering the system scale when implementing efficiency improvement measures in a command area. According to the irrigation efficiency paradox (Grafton et al. 2018; Zhang et al. 2020), increasing water abstraction (the first definition of improving efficiency) in command areas can sometimes have unintended consequences, such as reducing groundwater recharge, reducing water availability to downstream users, and causing the groundwater table to decline (Ahmad et al. 2021; Scott et al. 2014). These consequences can ultimately reduce the WSP and undermine sustainable water resource management in the long term (Avellà-Reus et al. 2017; Shoukat et al. 2021). However, efficiency improvements in the sense of reducing waste

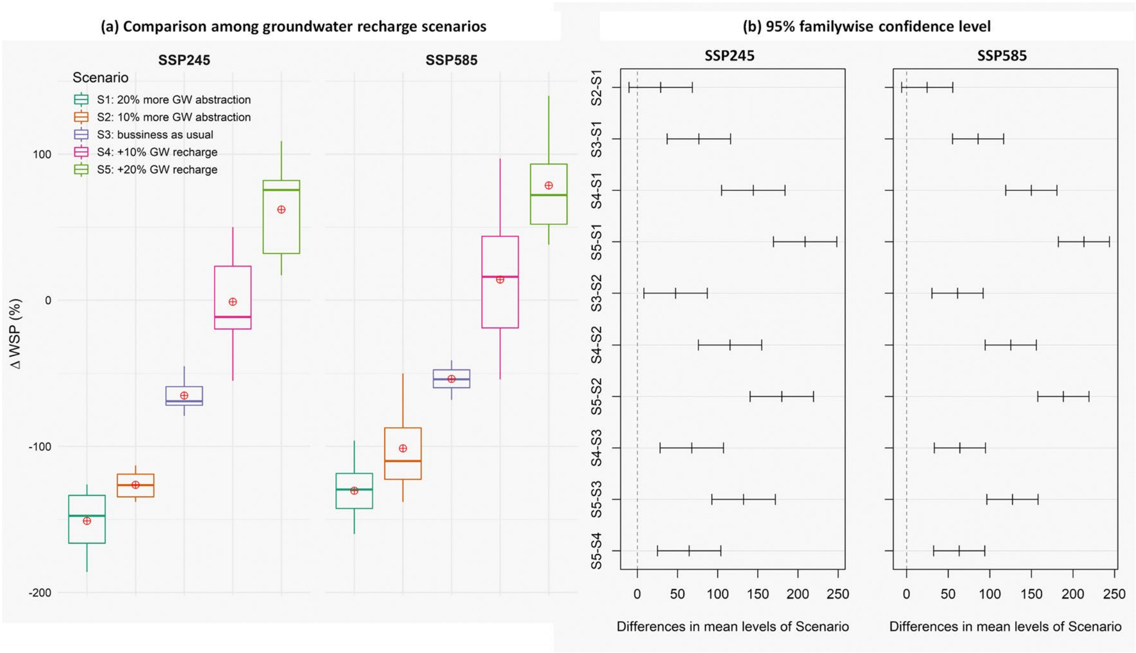

Fig. 10 **a** Water-saving potential (WSP) under different groundwater recharge (GWR) scenarios (10% and 20% higher groundwater abstraction and + 10% and + 20% increased recharge compared to business-as-usual scenario) toward the end of the twenty-first century in LCC. **b** Graphical representation of Tukey's honestly significant difference (Tukey's HSD) post hoc test for pairwise comparisons among groundwater recharge scenarios

(the second definition) should not have these large negative effects, assuming abstractions remain constant. Therefore, it is important to consider the potential impacts of both types of irrigation efficiency improvements on the overall water balance in a given area and to adopt a holistic approach to water resource management that considers the interconnectedness of surface and groundwater resources.

4.3 Projected WSP under climate change and artificial groundwater recharge

The results of this study show that WSP in the LCC command area is projected to decrease by – 68 ± 3% under the ensemble (SSP245 and SSP585) warm-dry scenario and – 48 ± 13% under the ensemble cold-wet scenario by 2100 (Fig. 7 and Table 3). These projections are in line with previous studies that have predicted a decline in water availability in the Indus River Basin under future climate change scenarios (Huss and Hock 2018; Immerzeel et al. 2020; Nepal and Shrestha 2015; Shrestha et al. 2015; Yang et al. 2016). A reduced WSP in LCC would also affect the water availability in other canal command areas of the Indus Basin, especially the downstream canal command areas.

One potential way to mitigate the negative impacts of climate change on WSP in the LCC command area is through artificial groundwater recharge. Our results show that WSP could be increased by up to 70 ± 9% by artificially recharging 20% of the abstracted groundwater per year in the LCC command area by the late twenty-first century (Fig. 10). Artificial groundwater recharge is an effective way to increase water availability and improve water security in other regions (Dillon et al. 2018; Moharir et al. 2019). Several studies have demonstrated the effectiveness of artificial groundwater recharge in increasing water availability and improving WSP (Fathi et al. 2021). Several researchers found that artificial recharge can be a potential solution for water shortages (Ahirwar et al. 2020; Aju et al. 2021; Hughes 2021; Kim et al. 2021; Zammouri and Brini 2020). However, more research is needed to examine the economic and social impacts of water resource management strategies, including the costs and benefits of artificially recharging groundwater (Fathi et al. 2021; Mukherjee 2016). Policymakers in the Indus River Basin should consider the potential benefits of artificial groundwater recharge to enhance WSP and sustainably manage water resources in the LCC command area.

4.4 Implications for water resource management

The findings of this study have important implications for water resource management in the Indus River Basin, notably, groundwater's role in the water-energy balance, particularly for WSP assessments in irrigated areas. The high values of CF (Fig. 6) observed in this study suggest that the LCC irrigation system is more efficient than previously thought. However, the "efficiency" interpretation varies: increased water withdrawals versus improved water use with less waste (Grafton et al. 2018). These distinctions can affect the quantified WSP and downstream water availability because of the interlinkage nature of the canal commands in the Indus Basin (Simons et al. 2020). The framework developed in this study (Fig. 3) for quantifying the efficiency (Fig. 8c) and WSP (Figs. 9 and 10) is applicable to assessing water management practices' impacts in a canal command area. The framework can be applied to any other canal command area. The quantified impacts of climate change (Fig. 9 and Table 3) and artificial groundwater recharge on WSP (Fig. 10) are transferable and describe the future water availability in the downstream areas. However, it is important to note the potential influences of underestimated evaporation or overestimated precipitation on quantified values. Although our methodology minimizes these risks, inherent uncertainties remain. An uncertainty or sensitivity analysis was not included in the scope of this study but could provide further robustness to the results and is recommended for future research.

Our findings underscore the urgency for adaptive measures considering the projected WSP decline under climate change (Table 3). The potential for increasing WSP through artificial groundwater recharge (Fig. 10) offers a promising option for enhancing water availability and improving water security in the LCC command area. Higher WSP and efficient artificial groundwater recharge would enhance the overall efficiency in the Indus Basin by ensuring more water availability for downstream canal command areas. However, implementing and managing artificial groundwater recharge greatly impact its success in enhancing the WSP. The choice of technique, availability of suitable water sources, and feasibility of water transportation are indeed critical (El Mansouri and El Mezouary 2015; Fathi et al. 2021; Pande and Moharir 2021; Velis et al. 2017). Moreover, the economic feasibility, institutional and legal frameworks, stakeholder engagement, and community support significantly influence these projects' outcomes. The economics, legality, and effective involvement of stakeholders in implementing artificial groundwater recharge would be the most influential constraints in LCC. The potential risks, such as groundwater contamination and long-term impacts on hydrological systems (Hartmann et al. 2021), further underline the complexity of artificial groundwater recharge projects. In the LCC command area, such contamination risks might arise due to industrial waste and excessive use of fertilizers. A thorough evaluation process, including multi-criteria decision analysis to identify suitable recharge sites (Pande and Moharir 2021) and inclusive decision-making processes involving stakeholders (Fuentes and Vervoort 2020), is recommended for successful and sustainable water resource management in the LCC command area. Future research should focus on these aspects to address the challenges of implementing artificial groundwater recharge in the LCC command area.

This study discovered that artificial groundwater recharge practices significantly influence the WSP in the LCC, situated within the interconnected Indus Basin. Increased groundwater abstraction led to a decrease in WSP, while reducing it resulted in a WSP increase, highlighting the "irrigation efficiency paradox" where conservation measures can inadvertently increase total water use (Contor and Taylor 2013; Dagnino and Ward 2012; Grafton et al. 2018). These changes in the LCC's WSP could substantially impact water availability in the upstream and downstream canal command areas due to the strong linkages within the basin (Simons et al. 2020), necessitating improved water management coordination (Cheema et al. 2014; Watto and Mugera 2019). The research underscores the need to consider broader basin impacts when implementing water conservation measures, especially in the face of varying climate scenarios.

4.5 Limitations and future work

There are several limitations to this study that should be considered when interpreting the results. One limitation is the reliance on CMIP6 future climate change, remote sensing, and model-based data to quantify the water balance components, which may introduce uncertainty into the estimates. In our Budyko-based empirical model, we assumed that some fractions of canal water and groundwater would be lost due to conveyance, application, and infiltration losses to estimate WSP. These assumptions are based on literature (Ahmad and Majeed 2001; Khan et al. 2021; Mujtaba et al. 2022; Rizwan et al. 2018), which may vary for different cases. We also recognize that our projections relied on a constant canal discharge, a simplification due to our study's scope and data limitations. Several modeling studies suggested that river discharges in the upper reaches of the Indus River will increase until the 2060s before starting to decline (Lutz et al. 2016; Shafeeque et al. 2022a), affecting water availability at the Khanki Headworks and eventually discharge in the LCC. Future research could refine our findings by incorporating these transient canal discharges, more detailed and ground-based observations for a more nuanced picture of potential future scenarios. Nonetheless, our current results offer valuable insights into the impacts of climate change and groundwater recharge scenarios.

Another potential area for future work is examining the role of irrigation system infrastructure and management practices on WSP. Improving irrigation infrastructures, such as canal lining and metering, and adopting more efficient irrigation techniques, such as drip irrigation, could potentially lead to increased WSP (Bhatti 2020; Cheema et al. 2014; Janjua et al. 2021). Further research could also explore the trade-offs between increasing WSP and other water resource management objectives, such as water quality and environmental impacts.

Artificial groundwater recharge, with the potential to improve WSP and water security, particularly in arid regions, is not without challenges, such as cost, feasibility, and risk of contamination (Fathi et al. 2021; Hartmann et al. 2021). Depending on recharge techniques and geographical context, the full economic and social implications remain under-studied (Ahirwar et al. 2020; Hughes 2021; Janjua et al. 2021; Mukherjee 2016). Moreover, successful implementation extends beyond technical feasibility, requiring careful consideration of institutional and legal frameworks, stakeholder involvement, and community support (Dillon et al. 2018; Fathi et al. 2021; Fuentes and Vervoort 2020; Velis et al. 2017). Future research must therefore explore these aspects in greater detail to pave the way for sustainable groundwater management in the LCC command area.

5 Conclusions

This study is aimed at quantifying water-saving potential (WSP) in the Lower Chenab Canal (LCC) command area of the Indus River Basin in Pakistan. We modified and forced an empirical model based on the Budyko theory to assess WSP and its potential future variations under different climate and groundwater recharge scenarios.

Based on the findings of this study, the WSP in the LCC command area was found to be 466 mm/year from 2001 to 2020. The WSP is expected to decrease significantly under future climate change projections, with a potential reduction of up to 68% under the warm-dry scenario by the late twenty-first century. However, the implementation of artificial groundwater recharge practices has the potential to significantly increase WSP, with an estimated increase of 70% under certain scenarios. These findings highlight the importance of considering the role of groundwater recharge in enhancing WSP and sustainably managing water resources in the LCC command area. Policymakers in the Indus River Basin should consider these findings when developing water resource management strategies to ensure the long-term sustainability of water resources in the region.

Future research should focus on using detailed data on future climate conditions to predict WSP variations better, exploring different approaches to artificially recharging groundwater, examining the economic and social impacts of water resource management strategies, including the costs and benefits of artificially recharging groundwater, studying the potential effects of these strategies on other sectors and stakeholders, and evaluating the use of water-saving technologies to improve WSP.

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Author contribution M.S. and M.H. contributed to the conception and design of the study. M.S. was responsible for developing and forcing the model, collecting and analyzing the data, and writing the first draft of the manuscript. M.H. provided supervision and funding for the research. A.S., A.A., T.K., M.I.A., S.A., and A.D. contributed to analyzing the data and editing the final draft. All authors have reviewed and approved the final manuscript.

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Data availability The datasets used in the study are available from the relevant departments and links, listed in Table 1.

Declarations

Competing interests The authors declare no competing interests.

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