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Coupled Climate-Land Use Change Impacts on Hydrology and Crop Productivity in Condamine–Balonne River Basin of Australia: A SWAT+ Assessment.

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Declarations Statements

1. Ethics approval and consent to participate

Not applicable.

2. Consent for publication

Not applicable.

3. Competing interests

The authors declare that they have no competing interests.

4. Author contributions

Suresh Prasain: Conceptualization, methodology, software, data curation, formal analysis, writing—original draft.

Tek Maraseni: Supervision, validation, writing—review and editing.

Thong Nguyen-Huy: Supervision, validation, writing—review and editing.

Manish Shrivastab: Supervision, validation, writing—review and editing.

Rajesh Khatakho: Methodology support, data interpretation, writing—review and editing, and preparation of the declaration section.

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Coupled Climate-Land Use Change Impacts on Hydrology and Crop Productivity in Condamine–Balonne River Basin of Australia: A SWAT+ Assessment.

Abstract

Climate and land use change (CLUC) pose significant challenges to water resources and agricultural productivity in arid and semi-arid regions globally. This study provides a comprehensive and integrated assessment of the combined impacts of CLUC on hydrological process and crop productivity in the Condamine–Balonne River Basin (CBRB), Australia, using the Soil and Water Assessment Tool Plus (SWAT+). Spatially explicit climate projections from the CanESM2 model under the RCP4.5 scenario, together with land use projections derived from the LUTO framework and CA–Markov modelling, were integrated to simulate baseline (2000–2025) and future conditions (2030–2100).

Results indicate that climate change is the dominant driver of hydrological alteration, with projected temperatures increases up to ~3.5 °C (from 2000-2100), increased rainfall variability, and elevated evapotranspiration. These changes substantially lead to reduced soil moisture, groundwater recharge, and baseflow, intensifying water scarcity across the basin. Consecutively, crop yields are projected to decline consistently, ranging from approximately −12% in the near terms soon (2030s) to −33% by the end of the century, primarily due to heat stress and reduced water availability. Land use change further exacerbates these impacts by driving a transition from irrigated cropping systems to toward pasture-dominated systems, reducing overall agricultural productivity. Importantly, the study reveals considerable spatial heterogeneity in hydrological responses, underscoring the critical need for sub-basin-scale assessment water resource planning. This study advances current understanding by explicitly linking climate–land use interactions with surface water–groundwater processes and agricultural productivity within a unified modelling framework. The findings provide robust, policy-relevant insights to support adaptive water–land management, climate-resilient agricultural planning, and sustainable water–food security strategies in Australia and comparable semi-arid regions worldwide.

Keywords: *Climate Change; Land Use Change; SWAT+; Modelling; Water Balance; Crop Yield; Condamine–Balonne River Basin; Murray-Darling River Basin; Great Artesian Basin; Surat Groundwater Basin.*

1. Introduction

Climate change (CC) in Australia has intensified in recent decades, with mean air temperature rising by >1.44 °C above pre-industrial levels, increased rainfall variability, and accelerating sea-level rise (Prasain, 2025; Boulaire et al., 2025), consistent with global CC trends (Yin et al., 2025; Prasain, 2018, 2017). Since the 1970s, annual rainfall has declined by ~16% in southwestern/southern Australia and ~12% in southeastern regions, alongside rising interannual variability (CCA, 2023; DCCEEW, 2023) . These shifts have strengthened the influence of large-scale climate drivers— El Niño–Southern Oscillation (ENSO), Indian Ocean Dipole (IOD), Madden–Julian Oscillation (MJO), and Southern Annular Mode (SAM)—leading to more frequent and intense hydroclimatic extremes (Prasain et al., 2026; Taschetto et al., 2025). El Niño events, positive IOD phases, MJO-driven extremes, and positive SAM trends have collectively reshaped Australia's hydroclimate since the 1980s, increasing floods in the north and east and intensifying drought and aridity in the west and south (Taschetto et al., 2025; Singh et al., 2025). These changes alter basin water balance components (precipitation, evapotranspiration, runoff, recharge, and baseflow), with direct consequences for agriculture through disrupted surface water–groundwater interactions and reduced productivity (Boulaire et al., 2025; Maheshwari, 2021).

In parallel, CC drives land-use change that further modifies hydrological processes (Lukas et al., 2025; Oo and Humphries, 2025). Shifts in cropping systems, urban expansion, and ecosystem disturbances (e.g., deforestation and fires) have altered soil moisture, evapotranspiration, infiltration, and runoff, often reducing land productivity and increasing degradation (Sankarrao and Rathinasamy, 2025; Mondal et al., 2025). Given the tight coupling between climate, land use, and hydrology, integrated CLUC assessments provide a more robust understanding than single-factor analyses (Khatakho et al., 2026; Loukika et al., 2025). Across major Australian basins—including the Murray–Darling Basin (MDB), Lake Eyre Basin (LEB), Perth Groundwater Basin (PPGB), Daly River Basin (DRB), and the Surat and Eromanga sub-basins of the Great Artesian Basin (GAB)—CLUC has led to declining surface water availability and groundwater depletion, with some regions showing groundwater declines >1 m yr^{-1} (Wasko et al., 2024; Prosser et al., 2021). These trends reflect reduced rainfall effectiveness, higher evapotranspiration, and altered recharge–baseflow dynamics, ultimately reducing agricultural productivity and increasing drought vulnerability, farm losses, and rural migration (Khatakho et al., 2024; Fan et al., 2023). Water thus acts as the central link in coupled water–land–food systems, where changes in hydrology directly constrain food production (Khatakho et al., 2026; Salim et al., 2024). Despite advanced water governance, Australia faces growing challenges due to the spatially heterogeneous and nonlinear nature of CLUC impacts (Mewett et al., 2013; White et al., 2007).

Globally, distributed hydrological models integrated with remote sensing and GIS (Birks et al., 2025; Khatakho et al., 2021)—particularly Soil and Water Balance Models (SWBMs) and integrated its' into Numerical Hydrological Models (NHMs) (refer to Table 1, Supplementary file) are widely applied to quantify CLUC impacts on water balance components (Anıl Tezel et al., 2025; Khatakho et al., 2024). Among these, the Soil and Water Assessment Tool (SWAT) (Choudhary et al., 2026; Ahmadi et al., 2026) are well suited to representing spatial heterogeneity, land-use dynamics, and climate variability (Prasain et al., 2026; Zhang et

al., 2025). However, fine-scale integrated water–food assessments remain limited in Australia, particularly in key agricultural basins like the MDB and GAB (Dzvene et al., 2025; Mewett et al., 2013). As a result, understanding of how CLUC jointly affects hydrological partitioning and crop productivity at management scales remains incomplete (Nazari et al., 2025; Page et al., 2023).

Within this context, the Condamine–Balonne River Basin (CBRB), hydraulically connected to both the MDB and GAB, provides a representative case of strongly coupled surface water–groundwater–agriculture systems (Clark et al., 2025; Ayele, 2024). Here, changes in precipitation, evapotranspiration, runoff, and recharge directly influence streamflow, aquifer storage, irrigation supply, and crop productivity (Davamani et al., 2024; Cook et al., 2022). However, spatially explicit assessments of combined CLUC impacts on water–food systems remain limited (Saha et al., 2019; CSIRO, 2014).

Although previous studies (Clark et al., 2025; Nazari et al., 2025; Ayele, 2024; Fu et al., 2020) in the CBRB have examined individual aspects of climate variability, water dynamics, or land-use change; and leaving four key gaps: (i) lack of integrated spatially distributed CLUC assessments across all water balance components and crop yield; (ii) limited understanding of CLUC impacts on surface water–groundwater interactions; (iii) reliance on basin-averaged results with poor resolution of local variability; and (iv) insufficient evaluation of long-term water–food security implications within a unified framework.

To address these gaps, this study applies the SWAT+ model to the Condamine River Basin to quantify the combined impacts of CLUC on water balance components and crop yield under baseline and projected scenarios. The specific objectives are to: (i) analyse the climate and land-use change scenarios within CBRB ; (ii) create the model setup of SWAT+ for baseline study and calibration and validation with observed stream flow and crop yield data within CBRB (iii) disentangle and compare the effects of climate change alone and combined CLUC on key water balance components, including evapotranspiration, surface runoff, percolation (groundwater recharge), lateral flow, and groundwater flow, and their linkages to crop yield variability; (iv) evaluate how combined CLUC alters surface water–groundwater interactions, with particular emphasis on recharge and baseflow contributions to agricultural productivity for analysis of long-term water–food security within CBRB.

This study advances understanding of coupled climate–land use impacts through a high-resolution, integrated assessment of water balance and crop yield in a tightly linked surface water–groundwater system. Using a unified SWAT+ framework, it connects hydrological partitioning, recharge–baseflow dynamics, and agricultural productivity to reveal spatial heterogeneity and micro-watershed vulnerabilities beyond basin-scale analyses. The results show how future CLUC may reshape water availability and food production in the CBRB and similar Australian basins, while providing a transferable framework for adaptive water planning, improved water–food system resilience, and evidence-based policy under climate uncertainty.

2. Methodology

To achieve above stated objectives, the following methodological framework was utilized as shown in Figure 2. Based on this framework, this heading is subdivided into following sub-heading:

2.1 Description of Study Area

The Condamine–Balonne River Basin (CBRB) consists of four sub-basins—Condamine River (CRB), Balonne River (BRB), Maranoa River (MRB), and Wallam Creek (WCB)—each with distinct climate, hydrology, and land use (Harding et al., 2024; BOM, 2025).

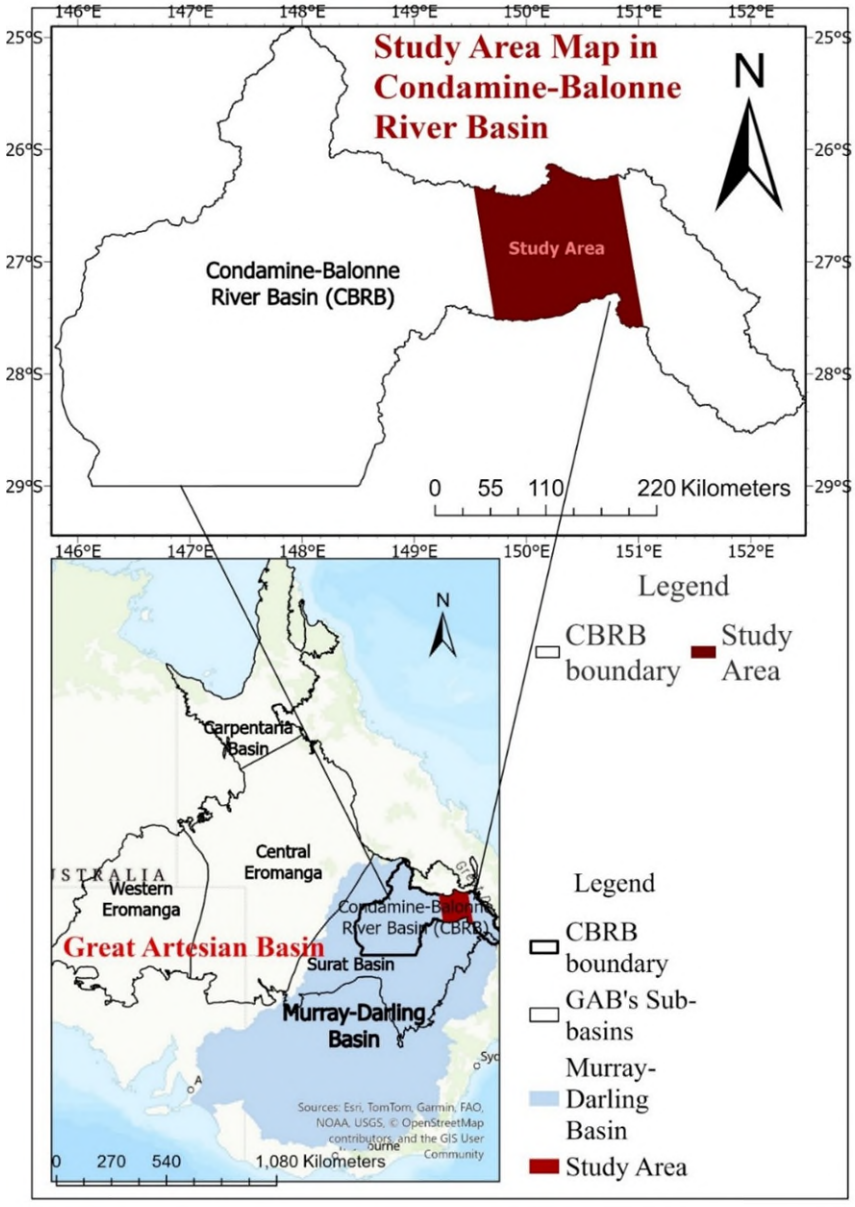


Figure 1: Location of the Study Area within Condamine-Balonne River Basin in the Great Artesian Basin and the Murray-Darling River Basin.

The CRB (≈35% of basin area) forms the upper catchment, receives higher rainfall (600–800 mm), and supports intensive irrigated agriculture with strong surface–groundwater interaction and significant baseflow contribution. The BRB (≈30%) is downstream, drier (400–600 mm), dominated by grazing (>80%), and exhibits highly variable flows influenced by floodplains and regulation, with mean annual discharge of ~500–1500 GL/year (CEWO, 2021; Cassel et al., 2015). The MRB (≈25%) is semi-arid (400–600 mm), with

intermittent streamflow and predominantly grazing land use (70–80%). The WCB (≈10%) is the driest sub-basin (350–500 mm), characterised by ephemeral streams, high infiltration, and groundwater recharge (CEWH, 2025; CEWO, 2021).

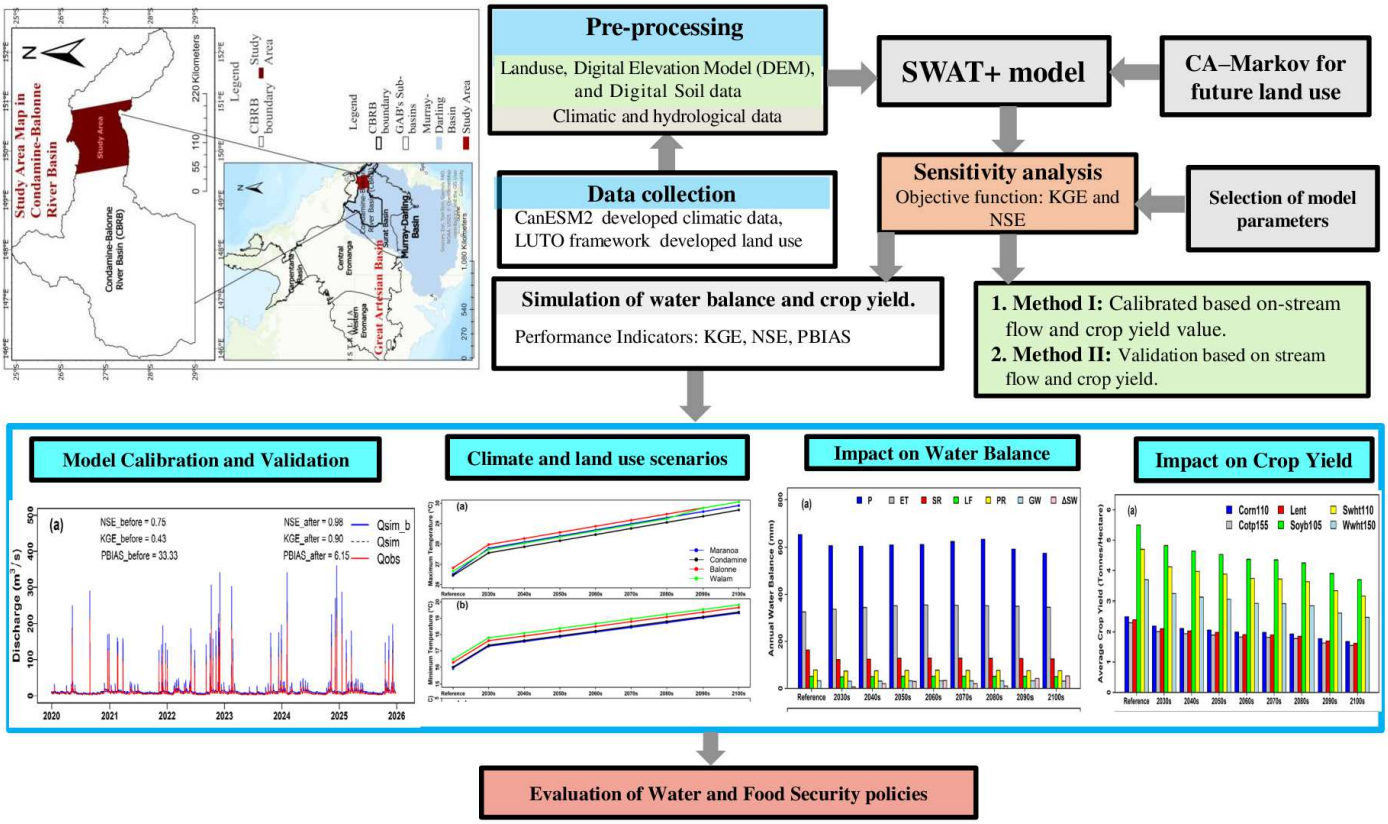


Figure 2: Methodological framework for evaluating the impact of CLUC in water balance components and crop yield of CBRB by using SWAT+ model.

The study focuses on an ~17,000 km² area (Figure 1) in central CBRB, spanning the lower CRB and upper BRB within the Surat Groundwater Basin (SGB) of the Great Artesian Basin (GAB). Overall, the CBRB drains ~143,900 km² (27.1–29.8°S, 152.4–146.0°E) and contributes ~14% of the Murray–Darling Basin (MDB) (MDBA, 2025; CSIRO, 2014). Therefore, the study area functions as an integrated surface–groundwater system, acting both as the uppermost catchment of the Condamine–Balonne river system and as a major groundwater sub-basin of the GAB (Harding et al., 2024; MDBA, 2016). Hydro-geologically, the system includes the Upper Condamine Alluvium (UCA), a shallow unconfined aquifer directly connected to river flows and overlying confined aquifers of SGB (Winton–Mackunda, Cadna-owie–Hooray, Precipice), separated by aquitards of the Rolling Downs Group (CSIRO, 2014; Maheshwari, 2021). The UCA is a key groundwater-dependent system sustaining baseflow, irrigation, and ecosystems under MDBA and Queensland water plans (Harding et al., 2024; MDBA, 2016). The region has a subtropical to semi-arid climate with highly variable summer rainfall and high evapotranspiration, driving strong interannual variability in water availability and crop demand. Dominant land uses include irrigated and dryland agriculture and grazing, making the system highly sensitive to climate variability, land-use change, and groundwater extraction (CEWO, 2021; CSIRO, 2014). These coupled hydroclimatic, topographic, hydrogeological, and land-use characteristics provide the basis for SWAT+ modelling, where the basin is discretised into sub-basins and

HRUs to simulate runoff, soil moisture, evapotranspiration, groundwater recharge, baseflow, and crop yield responses under changing climate and land-use conditions.

2.2 Data Type and Source

SWAT+ requires spatial and statistical datasets to simulate watershed processes and crop production, along with observed streamflow and crop yield data for calibration and validation (Tarkegn et al., 2025b; Kardhana et al., 2024). In this study, a 90 m SRTM DEM, SLGA soil data, LULC, and daily climate datasets were compiled from multiple sources (Table 2, Supplementary file). The DEM, widely used in hydrological modelling, was obtained via Open Topography in QGIS and validated using the Geoscience Australia GAB 3-arcsecond DEM (Tumsa et al., 2022; Nelson et al., 2013). Soil inputs were derived from the CSIRO SLGA dataset (90 m resolution), which provides depth-resolved, Australia-calibrated properties, reducing uncertainty compared to HWSD-based approaches (Viscarra Rossel et al., 2024; Malone and Searle, 2021). These datasets provide physical, chemical, and hydrological soil properties estimated at the centre of each 3-arcsecond grid cell (~90 × 90 m) across Australia (Searle et al., 2021; Grundy et al., 2015). The spatial soil layers and SWAT+ soil tables were generated using ArcGIS Pro and ArcPy. Daily climate data were obtained from the Bureau of Meteorology and CSIRO Climate Change in Australia datasets (5 km resolution), including CMIP5/CMIP6 downscaled projections using the QDC method (Heady and Clarke, 2025; Irving and Macadam, 2024). CanESM2 under RCP4.5 was selected due to strong historical performance in Australia and its consistency with national mid-range emissions pathways (Webb et al., 2024; CSIRO, 2024). The CanESM2 has demonstrated superior performance (having high value of correlation of coefficient (CoC), standard deviation (SD), and low value of root-mean-square error (RMSE)) relative to other global climate models (CNRM-CM5, GFDL-ESM2M, MIROC5, NorESM1-M, and ACCESS1-0) in reproducing historical precipitation and temperature extremes across Australia, supporting its suitability for impact-based applications (DCCEEW, 2023; Moise et al., 2015). In this study, the CanESM2 under the CMIP5 RCP4.5 (mid-way) scenario (mid-way) was selected to represent future climate conditions which is aligned with Australia's Nationally Determined Contribution (43 % emissions reduction by 2030) and the Net Zero by 2050 target (Cook et al., 2022; Crosbie et al., 2010). CMIP5 was preferred over CMIP6 due to longer continuous 40-year time slices, better suited for hydrological analysis.

Similarly, The land-use change data were obtained from Australian Collaborative Land Use and Management Program (ACLUMP) in Land-Use Trade-Offs (LUTO) framework (developed 654 scenarios) (ACLUMP, 2024; Gao and Bryan, 2017) and filtered for consistency with RCP4.5, medium-impact assumptions, and balanced policy settings; and scenario S266_M2_CanESM2_M_Bal_2x_U was selected and processed in ArcGIS Pro for making input file in land use data. The crop management inputs data for each spatial land-use classes were developed using SWAT+ Editor (v3.0.12) from Australian Collaborative Land Use and Management Program (ACLUMP), Australian Bureau of Agricultural and Resource Economics and Sciences (ABARES), Monthly Irrigated and Rainfed Crop Areas around the year 2000 (MIRCA2000), and Digital Earth Australia (DEA) and Normalized Difference Vegetation Index (NDVI) phenology datasets (ABARES, 2025a;

Portmann et al., 2013), defining planting, harvesting, irrigation, and fertiliser schedules for plant communities. These processed crop management datasets enabled accurate definition of plant communities (plant.ini) and management schedules (management.sch) in SWAT+, ensuring realistic simulation of crop growth, yield, and water use within the study area (Table 3, Supplementary file).

Model calibration and validation used streamflow data (2012–2025) from Queensland Water Monitoring Information Portal (WMIP) across six gauging stations (DLGWV, 2025; Ayele, 2024) in the study area, while crop yields (2012–2015) were sourced from ABARES (ABARES, 2025b, 2025a) and Australian Bureau of Statistics (ABS) data frame (ABS, 2024, 2020) which provide annual crop production and yield estimates at national and regional scales.

2.3 Model Setup and Processing

The watershed was delineated using channel and stream threshold areas of 7,500 and 7,900 km², respectively, generating 114 sub-basins and 120 channels. Landscape Units (LSUs) and Hydrologic Response Units (HRUs) were defined using 5% thresholds for land use and soil, and 10% for slope, resulting in 120 LSUs and 15,000 HRUs (reduced from 17,108), consistent with previous studies worldwide (Kishore et al., 2025; Kardhana et al., 2024). The SWAT+ (Leone et al., 2025; L. Villani et al., 2024) model, which extends SWAT (Abbas et al., 2022; Zhang et al., 2025) with enhanced structural flexibility and explicit representation of upland–wetland processes, was applied to simulate watershed hydrology based on the water balance framework. Surface runoff was estimated using the Soil Conservation Service (SCS Curve) Number method, soil water retention followed standard formulations, potential evapotranspiration was computed using the Penman–Monteith method, and channel routing was simulated using the variable-storage approach (L. Villani et al., 2024; Singh et al., 2023). Crop growth was modelled using the Environmental Policy Integrated Climate (EPIC)-based framework (Tarkegn et al., 2025b; Madasamy et al., 2025) embedded in SWAT+, integrating plant parameters, land use, and management practices. Crop phenology was represented using heat units combined with fixed planting dates to better capture irrigated and rainfall-driven systems (Kumari et al., 2024; Tan et al., 2022). Biomass accumulation was simulated from intercepted radiation and converted to yield at harvest. Crop management inputs (e.g., planting, irrigation, fertilisation, refers to supplementary file-final, Table 2) were parameterised using Australian agronomic guidelines (Grains Research and Development Corporation (GRDC) and state Departments of Primary Industries (DPI)), representing dominant practices across Queensland and the Murray–Darling Basin (GRDC, 2026; Darbas and Lawrence, 2011).

Sensitivity analysis was conducted using the Sobol method with 1,900 samples and Kling–Gupta Efficiency (KGE) as the objective function based on previous SWAT and SWAT+ applications across diverse hydroclimatic regions. A total of 18 parameters (14 hydrological and 4 crop-related refer to supplementary file-final, Table 3), including key SWAT+ parameters (e.g., perco, cn3-swf) in SWAT+ Toolbox v3.0.7, were evaluated. Sensitivity indices were used to prioritise influential parameters, constrain calibration ranges, and reduce equifinality. Afterward, model calibration and validation were performed using a combined manual–automatic approach within SWAT+ Toolbox, applying the Dynamically Dimensioned Search (DDS) algorithm

(Tezel et al., 2025; N'Guessan et al., 2023) over 500 iterations. A multisite calibration strategy was implemented using streamflow data (DLGWV, 2025; CEWO, 2021) from seven gauging stations (Yuleba Creek at Forestry, Condamine River at Cotswold, Condamine River at Chinchilla, Dogwood Creek at Gilweir, Condamine River at Bedarra, Charleys Creek at Chinchilla and Condamine River at Brigalow). Calibration was conducted for 2020–2025 and validation for 2012–2019 based on previous studies (Anil Tezel et al., 2025; Tarkegn et al., 2025a; Tapas et al., 2025; Kardhana et al., 2024; R. L. Oliver et al., 2024; G. Villani et al., 2024a; Singh et al., 2023; Tumsa et al., 2022) in different hydro-climatic regions. Crop yield calibration and validation used aggregated Queensland-level data (GRDC, 2026; ABARES, 2025b) for major crops (winter wheat, summer wheat, soybean, lentil, corn, and cotton, corresponding to dominant crop communities represented in the land-use management scheme), aligned with the same periods.

Model performance was evaluated using multiple metrics, including Kling–Gupta Efficiency (KGE refers to Eq1), Percent Bias (PBIAS refers to Eq2), Nash–Sutcliffe Efficiency (NSE refers to Eq3), Mean Squared Error (MSE refers to Eq4), Root Mean Squared Error (RMSE refers to Eq5), and Mean Absolute Relative Error (MARE refers to Eq6), providing a comprehensive assessment of accuracy, bias, and variability (Tarkegn et al., 2025b; Abitew et al., 2023). Collectively, these metrics enable a robust assessment of model accuracy, bias, variability, and error structure during the calibration and validation processes.

If, O_i = observed value at time i.

S_i = simulated value at time i.

$\bar{O}$ = mean of observed values.

$\bar{S}$ = mean of simulated values.

n= number of observations.

σ_O, σ_S = standard deviation of observed and simulated values.

$$KGE = 1 - \sqrt{(r-1)^2 + (\beta-1)^2 + (\gamma-1)^2} \quad \ldots Eq1$$

Where,

linear correlation (r) = $\frac{Cov(O,S)}{\sigma_O \, \sigma_S}$

bias ratio (β) = $\frac{\bar{S}}{\bar{O}}$

variability ratio (γ) = $\frac{\sigma_S/\bar{S}}{\sigma_O/\bar{O}}$

$$PBIAS = 100 \times \frac{\sum_{i=1}^{n}(O_i - S_i)}{\sum_{i=1}^{n} O_i} \quad \ldots Eq2$$

$$NSE = 1 - \frac{\sum_{i=1}^{n}(O_i - S_i)^2}{\sum_{i=1}^{n}(O_i - \bar{O})^2} \quad \ldots Eq3$$

$$MSE = \frac{1}{n}\sum_{i=1}^{n}(O_i - S_i)^2 \quad \ldots Eq4$$

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(O_i - S_i)^2} \quad \ldots\ldots Eq5$$

$$MARE = \frac{1}{n}\sum_{i=1}^{n}\left|\frac{O_i - S_i}{O_i}\right| \quad \ldots\ldots Eq6$$

2.4 Process for Climate and Land Use Change Scenarios.

Spatial climate change (CC) and land use change (LUC) datasets for Australia were processed in ArcGIS Pro and Python (Visual Studio Code) to derive inputs for the CBRB (Figure 1, Supplementary file). A baseline period (2000–2025) representing recent conditions was defined for both climate-only (CC) and combined climate–land use (CLUC) scenarios. Daily observed climate data, aligned with available streamflow and crop yield records, were used for model calibration and validation and served as the reference for future projections. Maximum temperature (TMAX), minimum temperature (TMIN), and precipitation (PCP) were selected as primary variables following IPCC guidance. Future climate projections were derived from downscaled CanESM2 outputs under CMIP5 RCP 4.5. Simulations were conducted for consecutive decadal periods from the 2030s (2026–2035) to the 2100s (2096–2105) across all sub-basins, using continuous daily inputs. Changes in TMAX, TMIN, and PCP were quantified relative to the baseline and incorporated into SWAT+ to evaluate CC and CLUC impacts.

LUC scenarios were initially based on LUTO model projections using ACLUMP data, aligned with the same climate forcing (CanESM2, RCP 4.5) based on previous studies (Gao and Bryan, 2017; Bryan et al., 2015; Millar and Roots, 2012). As LUTO outputs extend only to the 2050s, a hybrid approach was applied by integrating a Cellular Automata–Markov (CA–Markov) model to project LUC from the 2060s to 2100s, ensuring temporal continuity. The CA–Markov model was implemented in ArcGIS Pro through: (i) harmonisation of historical (2000–2025) and LUTO-derived (2030s–2050s) land use maps; (ii) derivation of transition probability matrices; (iii) generation of suitability maps based on elevation, slope, river proximity, and existing land use; (iv) application of neighbourhood rules to simulate spatial dynamics; and (v) validation against 2050s LUTO outputs using Kappa statistics. The validated model was then used to generate future LUC maps (2060s–2100s) (Figure 1, Supplementary file).

All projected LUC maps were reclassified into SWAT+ categories and integrated with consistent soil, slope, and management parameters. Changes in land use extent were quantified relative to the baseline. Combined climate and land use scenarios were subsequently used to assess impacts on hydrological processes and agricultural productivity, including evapotranspiration, surface runoff, groundwater recharge, lateral flow, baseflow, soil moisture, and crop yield.

2.5 Impact on Water Balance Components and Crop Productivity.

The impacts of CC and combined CLUC scenarios on hydrological processes and crop yield were assessed by comparing decadal simulations (2030s–2100s) against a baseline period (2000–2025). To isolate the effects of

CC and CLUC, soil properties and crop management practices (e.g., planting dates, fertilisation, irrigation) were held constant across all simulations, and baseline-calibrated model parameters were retained. Two scenario types were evaluated: (i) climate change only (CC) and (ii) combined climate and land-use change (CLUC). Key water balance components analysed included precipitation, actual evapotranspiration, surface runoff, groundwater flow below the root zone, groundwater recharge (percolation), and lateral flow (baseflow). These variables collectively represent surface water–groundwater interactions and basin-scale water availability.

Crop yield responses were evaluated for major rainfed and irrigated crops simulated within SWAT+ model. Crop growth and yield were modelled using the EPIC-based module, linking biomass accumulation to soil moisture, evapotranspiration demand, and irrigation. Annual yields were aggregated at HRU, sub-basin, and basin scales to capture spatial variability and long-term trends. Absolute and percentage changes in hydrological variables and crop yield were calculated relative to the baseline. Seasonal and annual averages were used to minimise short-term variability. Spatial analyses at HRU and sub-basin levels identified areas sensitive to CC, CLUC, and their interactions. Comparative assessment between CC and CLUC scenarios enabled quantification of the relative and non-linear effects of climate and land-use change on water resources and agricultural productivity. This decadal framework provides a consistent basis for evaluating long-term system responses in the CBRB.

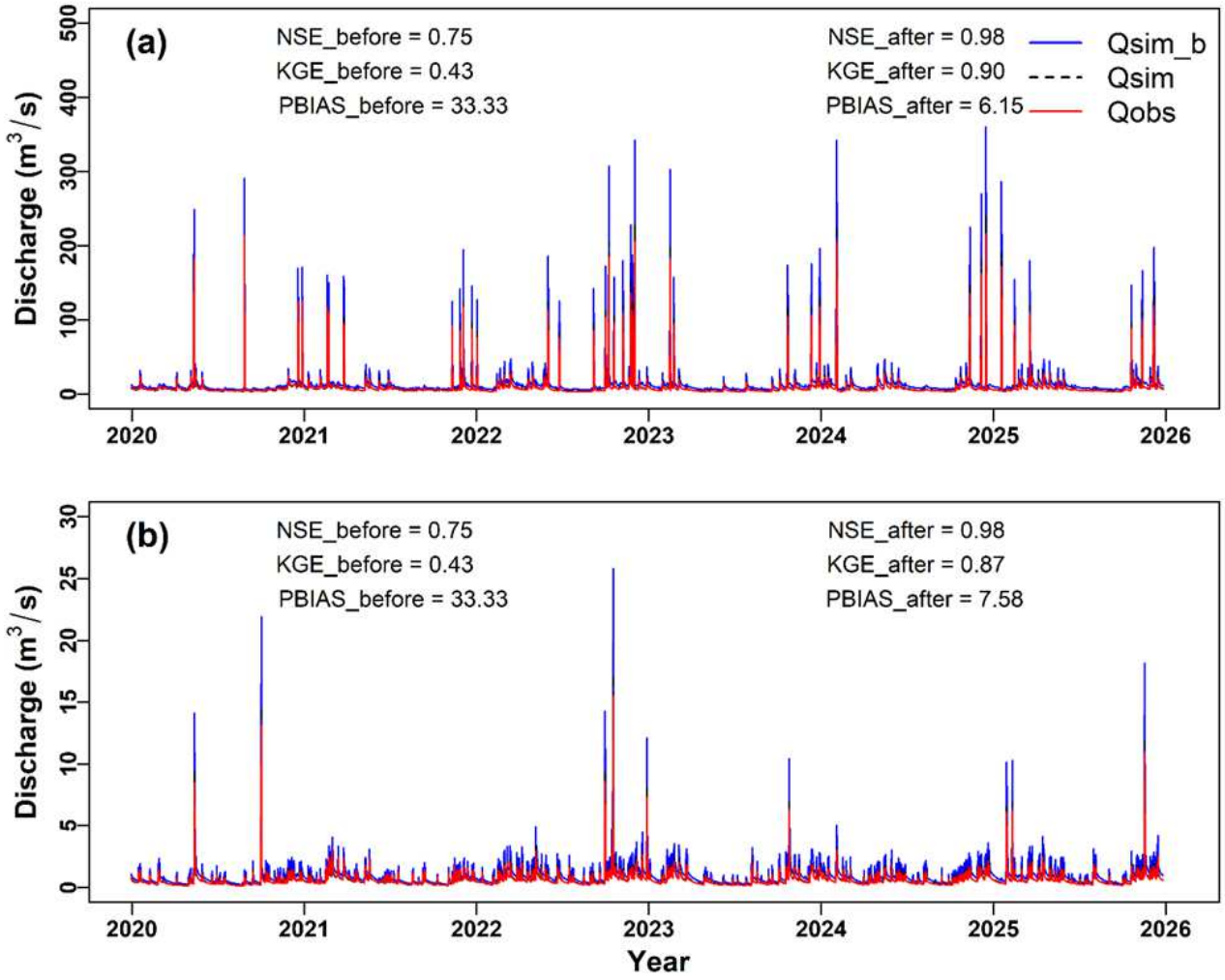
3. Results and Discussion

3.1 Evaluation of Sensitivity Analysis

Sensitivity analysis identified 11 of 18 parameters as significant for streamflow simulation. The most influential were cn2.hru, canmax.hru, cn3_swf.hru, alpha.aqu, biomix.hru, revap_co.aqua, and alb.sol, ranked from highest to lowest, while the remaining sensitive parameters ranked 8^{th}–18^{th}, (Table 4, supplementary file-final). For crop yield, 10 of 18 parameters were significant, with esco.hru, canmax.hru, biomix.hru, lai_pot.hru, epco.hru, harv_idx.hru, perco.hru, alb.sol, ovn.hru, and revap_min.aqua ranked highest to lowest. Other parameters ranked 11^{th}–18^{th} (Table 4, supplementary file-final). C These findings are consistent with previous studies (Tapas et al., 2025; Tarkegn et al., 2025b, 2025a; Anil Tezel et al., 2025; Anıl Tezel et al., 2025; Kardhana et al., 2024; A. Oliver et al., 2024; R. L. Oliver et al., 2024; L. Villani et al., 2024; G. Villani et al., 2024a; Singh et al., 2023; Tumsa et al., 2022) across different regions.

Notably, newly introduced SWAT+ parameters (cn3_swf.hru and perco.hru) showed high sensitivity for streamflow and crop yield, respectively. Cross-sensitivity was also observed: biomix.hru influenced streamflow, while esco.hru, canmax.hru, and perco.hru affected crop yield (Table 5, Supplementary file). Given that streamflow and crop yield are the primary outputs, all eight cross-sensitive parameters were included in calibration, consistent with earlier studies (Tarkegn et al., 2025b; Tapas et al., 2025) that incorporate both sensitive and less-sensitive parameters for simulating hydrological processes and crop

311 productivity.



312

313 Figure 3: The graphical comparison of observed and simulated streamflow during the calibration period for
314 main channel (a) at Cotwood river station (b) at Doog Gill creek station.

315 **3.2 Model performance during calibration and validation**

316 The model was calibrated and validated against observed streamflow at multiple channel sites (main channels:
317 72, 75; branches: 31, 38, 39, and 34) and basin-scale crop yield. Calibration covered 2020–2025 and validation
318 2012–2019. Observed streamflow data were obtained from six gauging stations representing these channels.
319 Pre-calibration results (Table 6, Supplementary file) showed acceptable NSE (0.60–0.76) but high bias
320 (PBIAS: 16.28–38.76%), leading to the selection of Kling–Gupta Efficiency (KGE: 0.42–0.47) as the primary
321 objective function, with NSE and PBIAS as complementary metrics. Post-calibration performance (Figure 3)
322 improved substantially, with KGE (0.87–0.96), NSE (0.86–0.99), and PBIAS (0.46–8.15%). Validation results
323 (Figure 4) remained strong (KGE: 0.84–0.98; NSE: 0.86–0.99; PBIAS: 1.61–6.28%), indicating excellent
324 predictive capability (Moriasi et al., 2023); and supporting the model's suitability for further hydrological
325 applications. Similarly, crop yield simulation also showed strong agreement, with calibration statistics of KGE
326 = 0.88, NSE = 0.86, and PBIAS = 8.15%, and validation values of KGE = 0.86, NSE = 0.87, and PBIAS =
327 6.28%. Simulated yields closely matched (Table 6, Supplementary file) observed averages yield (2012–2025)
328 across major crops (rngb_sum (45% of land cover), rngb_suhf (3%), swht110 (3%), wwht150 (6%), clvr (2%),

corn110 (1.5%), cotp155 (1%), lent (0.5%), and soyb105 (0.5%)), and variability was well captured (standard deviation: observed 1.62 vs simulated 1.51 t/ha).

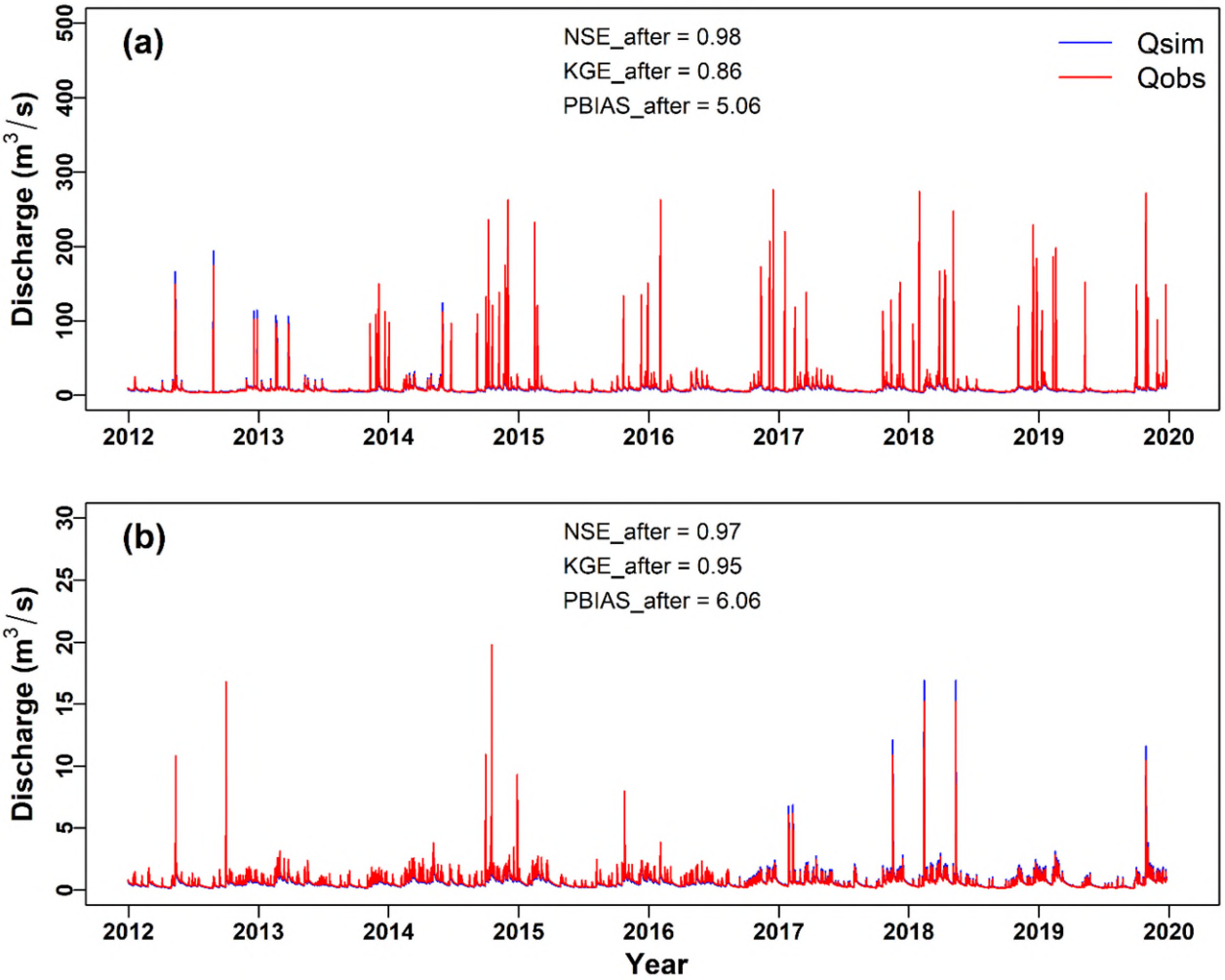


Figure 4: The graphical comparison of observed and simulated streamflow during the validation period for main channel (a) at Cotwood river station (b) at Doog Gill creek station.

Overall, the model reliably reproduces long-term basin-scale crop yield (ABARES, 2025b, 2025a; GRDC, 2026; ABS, 2024, 2020) and streamflow in basin (BOM, 2025; CEWH, 2025; CEWO, 2021; MDBA, 2016; Cassel et al., 2015; CSIRO, 2014), consistent with regional datasets and previous studies (Anil Tezel et al., 2025; Anıl Tezel et al., 2025; G. Villani et al., 2024b, 2024a; Singh et al., 2023), supporting its suitability for further hydrological applications.

3.3 Evaluation of Climate Change Scenarios.

Baseline (2000–2025) annual maximum temperature (Tmax) in the CBRB ranges from 25.5–26.8°C, with minimal spatial variation across sub-basins. Future annual and seasonal projections (Table 7 and Table 8 Supplementary file) show a consistent warming trend, with Tmax increasing by +1.1 to +1.4°C by the 2030s and +3.2 to +3.5°C by the 2100s (~0.3°C per decade). All sub-regions follow similar patterns (Figure 2, Supplementary file), though slightly higher increases occur in MRB and BRB. By century's end, Tmax approaches 30°C. Seasonal analysis (Table 8, Supplementary file) indicates strongest warming in summer and spring, with increases up to ~+3.7–3.9°C, extending high-temperature conditions beyond summer, while

winter warming (~+3.0°C) reduces cold intensity. Similarly, baseline Tmin (15.95–16.47°C) increases uniformly, reaching +1.3°C in the 2030s and +3.3–3.4°C by the 2100s, with limited spatial variability (Figure 2, Supplementary file). By late century, Tmin rises to ~19.3–19.8°C, indicating substantial nighttime warming. Seasonal Tmin (Table 9, Supplementary file) increases are consistent (~+3.3–3.5°C by 2100s), with notable winter warming reducing cold extremes and summer Tmin reaching ~24–25°C, implying warmer nights. These trends align with previous studies (Prasain et al., 2026; Taschetto et al., 2025; CCA, 2023; DCCEEW, 2023; Heady et al., 2021; Prosser et al., 2021; Crosbie et al., 2013), and reflect stronger inland warming and land amplification effects. These combined Tmax and Tmin increases indicate systematic warming, likely intensifying evapotranspiration, irrigation demand, and heat stress, while reducing soil moisture and diurnal temperature range. Stronger summer–spring warming suggests a longer hot season, with implications for water resources and agriculture. These level of impacts have been quantified further in sub-headings 3.5 and 3.6.

Beside these, the rainfall projections (Figure 3 and Table 10, Supplementary file) show an overall decline, with reductions of −4% to −11% in the 2030s, intensifying mid-century, and reaching −18% to −26% by the 2100s despite temporary increases in the late century. Seasonal patterns (Figure 3 and Table 11, Supplementary file) indicate redistribution rather than uniform decline: increased summer rainfall (up to +50%) contrasts with substantial autumn decreases (−24% to −50%), variable winter rainfall, and spring increases followed by sharp late-century declines. This shift toward wetter summers and drier transitional seasons reflects increasing variability and extremes, consistent with regional (Taschetto et al., 2025; CCA, 2023; DCCEEW, 2023; Prosser et al., 2021; Saha et al., 2019) and global projections (Pekárová et al., 2026; Prasain et al., 2026; Bai et al., 2025; Zamaria and Arhonditsis, 2025) of precipitation.

Overall, the CBRB is expected to experience significant warming, declining annual rainfall, and pronounced seasonal shifts, leading to a more variable hydrological regime with increased climatic extremities, reduced soil moisture, groundwater recharge, and agricultural reliability.

3.4 Evaluation of Land Use Change Scenarios.

Spatially explicit land-use projections (Figure 5 and Table 12, Supplementary file) for the CBRB indicate major climate-driven shifts in agriculture from 2030 to 2100. Using LUTO projections (2030s–2050s), a CA–Markov model (2040s–2100s), and decadal climate inputs (TMAX, TMIN, PCP) from CanESM2 under RCP 4.5, results show substantial changes in crop and pasture distribution. Model validation was strong (Kappa = 0.93), and all maps were harmonized into SWAT+ land-use classes.

Irrigated crops decline consistently: cereals drop ~35% by the 2060s and ~48% by 2100; cotton remains ~50% below baseline; legumes decline >85–88%; horticulture falls 58–73%; and oilseeds decrease ~79% after a brief rise. These trends reflect increasing evapotranspiration and reduced rainfall, leading to contraction of water-intensive systems. In contrast, rain-fed systems expand markedly. Forage increases >300% by 2100, while pasture rises from ~12% in the 2030s to >15% by 2100. This indicates a structural shift from irrigated cropping to more climate-resilient grazing systems. Non-agricultural land uses remain largely stable (<1% change), suggesting transitions occur mainly within agricultural categories (Figure 5, Supplementary file).

These findings align with previous studies (Prasain, 2025; ACLUMP, 2024; Bryan et al., 2015; Mewett et al., 2013, 2013; Millar and Roots, 2012), indicating warmer, drier conditions across inland Australia. Overall, climate and land-use changes are likely to reduce crop productivity, increase irrigation demand, and intensify water stress, while favouring grazing. Adaptation through efficient irrigation, resilient crops, and improved grazing management will be essential.

3.5 Evaluation of Impact on Water Balance Components.

The evaluation of water balance components under future climate scenarios (Figure 6 and Table 13, Supplementary file) indicates significant hydrological changes driven by declining rainfall and rising temperatures. Compared to the baseline precipitation (651.36 mm), rainfall decreases consistently by −6.79% in the 2030s to −11.77% by the 2100s, reflecting a clear drying trend consistent with inland Australia studies (Nazari et al., 2025; Prasain, 2025; Saha et al., 2019; Smerdon et al., 2012).

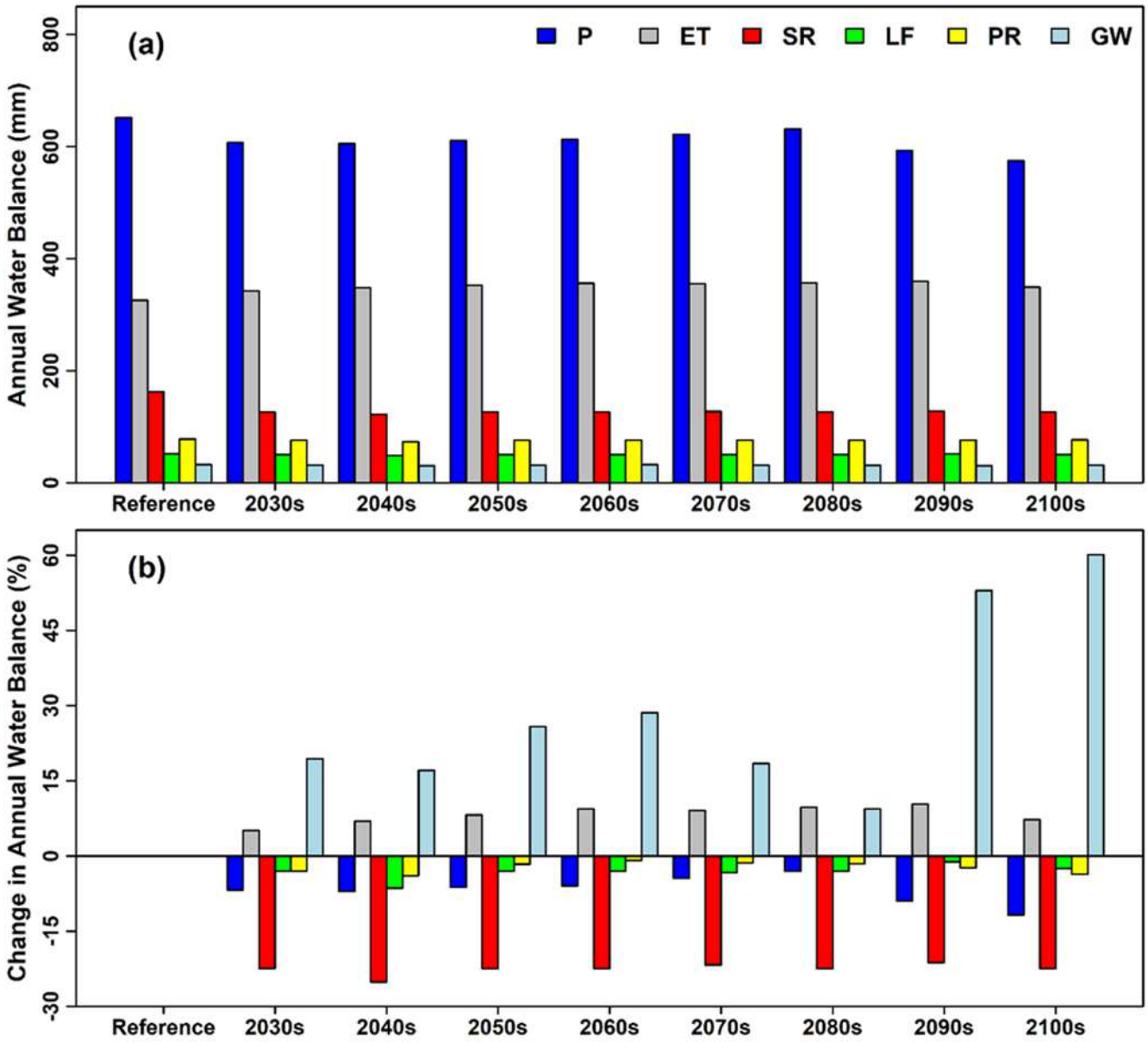


Figure 5: : Graphical diagram of impact of CLUC on a) annual water balance and b) % of change in annual water balance for future periods based on reference (baseline) period (*Note: P = Rainfall, ET = Evapotranspiration, SR = Surface Runoff, LF = Lateral Flow, PR = Percolation, GW = Baseline Flow, ΔS = Water Deficit).*

Despite reduced precipitation, evapotranspiration (ET) increases due to higher temperatures, rising from 325.68 mm to a peak of 355.14 mm (+9.04%) in the 2060s, and remaining above baseline thereafter. Surface runoff declines substantially (−20% to −25%), dropping from 162.84 mm to 122.63 mm, indicating reduced streamflow generation. Similarly, lateral flow and groundwater recharge decrease (−0.87% to −5.87%), reflecting reduced infiltration and soil water movement. Groundwater contribution to streamflow also declines slightly, indicating reduced baseflow under drier conditions. Consequently, soil water deficit increases significantly, reaching over 53 mm by the 2100s, highlighting growing moisture stress. In proportional terms, evapotranspiration increases from ~50% to 56–60% of precipitation, while surface runoff declines from ~25% to 20–22% (Figure 6, Supplementary file). Other components remain relatively stable in proportion but decrease in absolute terms. Overall, climate change reduces water availability, increases atmospheric demand, and intensifies soil moisture deficits.

When land use change is included, hydrological responses become more complex (Table 14, Supplementary file and Figure 5). Evapotranspiration increases further (up to +10.32%) due to expanded pasture systems, while runoff continues to decline similarly to the climate-only scenario. Lateral flow and percolation decrease slightly more, indicating reduced subsurface movement. In contrast, groundwater flow shows notable increases in some periods, likely due to redistribution and delayed recharge influenced by land use changes (Figure 5).

Overall, the combined effects amplify evapotranspiration, reduce surface water availability, and alter subsurface hydrology, leading to a more water-limited system. This reflects a shift from blue water (runoff and baseflow) to increased reliance on green water (evapotranspiration). These findings align with projections of rising temperatures (~3.5°C) and declining rainfall in Australia (Nazari et al., 2025; Prasain, 2025; Saha et al., 2019; Smerdon et al., 2012). While land use change modifies hydrological processes, climate change remains the dominant driver, ultimately intensifying water scarcity and challenging long-term agricultural sustainability.

3.6 Evaluation of Impact on Crop Yield.

The results indicate a consistent decline in crop yields across all major crops under future climate scenarios. Compared to the baseline, yields decrease by about 12% in the 2030s, worsening to approximately 33% by the 2100s. This pattern is uniform across corn, cotton, soybean, lentil, and wheat, suggesting a strong climate-driven effect rather than crop-specific variability (Table 15 and Figure 7, Supplementary file). Yield reductions are primarily driven by rising temperatures and declining rainfall. Maximum temperature is projected to increase by up to ~3.5°C by the end of the century, intensifying evapotranspiration and crop water demand. Meanwhile, rainfall decreases and becomes more variable, particularly during key growing periods. These changes reduce soil moisture, shorten crop growth duration, and increase heat stress, leading to lower productivity. Even relatively resilient crops such as soybean and wheat show similar proportional declines, highlighting their vulnerability under sustained warming and drying (Figure 7, Supplementary file).

When land use change is considered alongside climate change, production losses become more severe. Although yield declines (t/ha) remain similar, reductions in cultivated area amplify total output losses. Harvested area declines across all crops, ranging from ~3% in the 2030s to over 14% by the 2090s. Soybean shows the largest contraction (>40%), followed by wheat, cotton, and corn, indicating a shift away from water-intensive cropping systems. As a result, weighted average yields decline further, reflecting both reduced productivity and shrinking agricultural area (Table 16, Supplementary file and Figure 6).

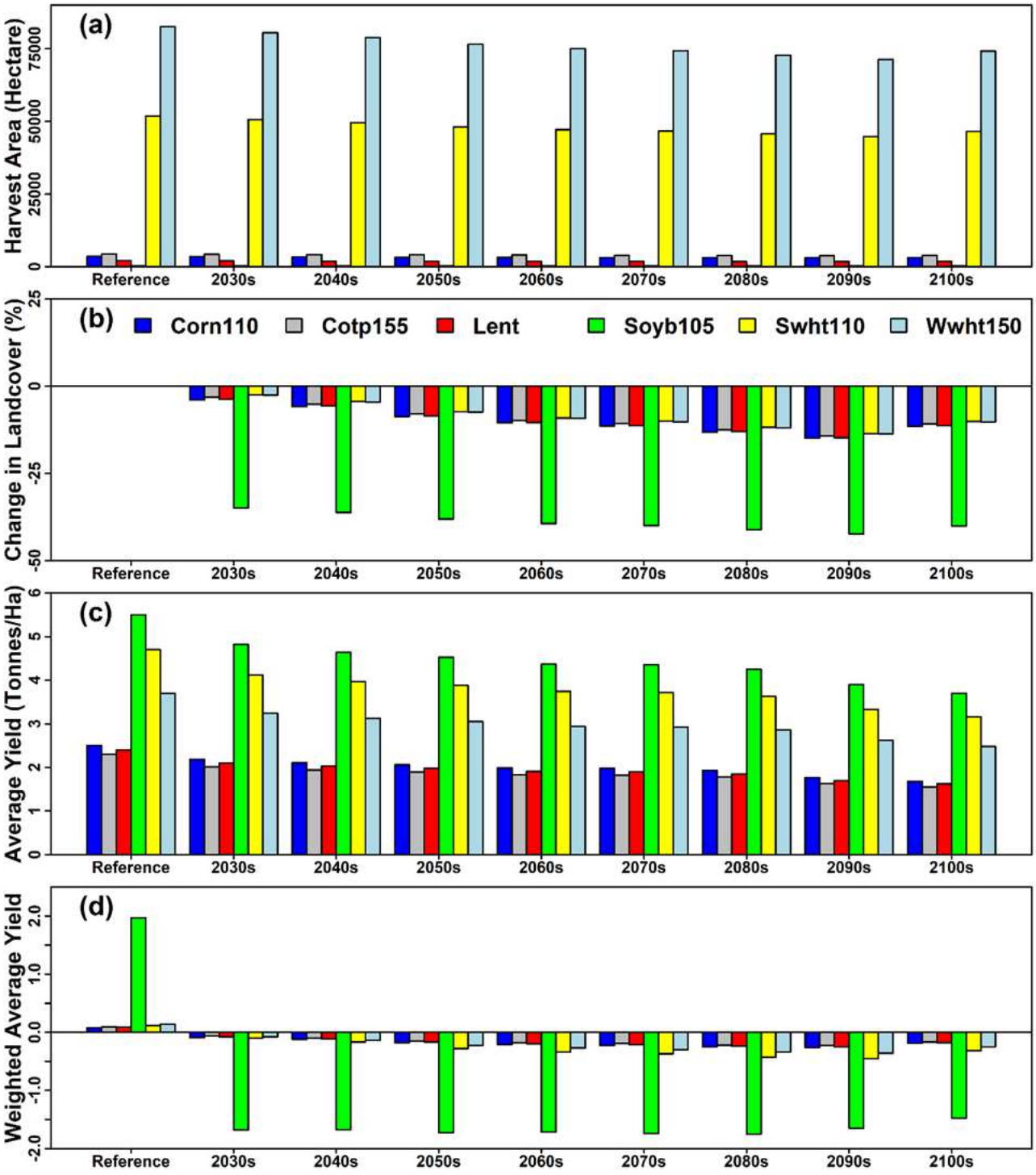


Figure 6:Graphical diagram of impact of CLUC on a) irrigated cropping land b) % of change in LUC c) average crop yield of irrigated crops and b) % of change in average crop yield for future periods based on reference (baseline) period.

When land use change is considered alongside climate change, the decline in agricultural productivity becomes more pronounced at the system level. While individual crop yields (t/ha) follow similar decreasing trends as in the climate-only scenario, significant reductions in harvested area and land use share amplify the overall production losses. Harvested area decreases steadily across all crops, with reductions ranging from about −3% in the 2030s to more than −14% by the 2090s. The most substantial decline is observed in soybean, where land use decreases by over −40%, reflecting its high sensitivity to water stress and climatic variability. Similarly, wheat, cotton, and corn show consistent contraction in cultivated area, indicating a gradual withdrawal from water-intensive cropping systems. The combined effect is captured in the weighted average yield, which shows a strong and continuous decline across all crops (Figure 13 and refers to supplementary file_final: Table 15). These trends indicate a structural shift in the agricultural system, with movement from irrigated cropping toward pasture-based systems. While this may provide some adaptive benefits, increased evapotranspiration from pasture further raises water demand, reinforcing negative impacts on crop production.

Overall, the decline in crop yield is closely linked to hydro-climatic changes, including rising temperatures, reduced and variable rainfall, increased evapotranspiration, and declining soil moisture and groundwater recharge. Land use change acts as both an adaptation and a constraint, reducing cropping intensity and total production. These findings are consistent with previous studies (Prasain, 2025; Penny et al., 2023; Fu et al., 2020; Mewett et al., 2013; Millar and Roots, 2012; Dawes et al., 2012) and broader global evidence from semi-arid regions.

In summary, climate change is the primary driver of yield decline, while land use change amplifies reductions in total production. By the end of the century, these combined impacts are likely to significantly reduce agricultural productivity and reshape the basin's agricultural systems. This highlights the need for climate-resilient crop varieties, improved irrigation efficiency, adaptive land use planning, and integrated water–agriculture management strategies.

3.7 Evaluation of Water–Food Security Policies.

The assessment of water–food security under future CLUC scenarios indicates a transition toward a more water-limited and productivity-constrained system. CC is the dominant driver, while land use change modifies and often amplifies these impacts. These findings align with national and global frameworks such as the National Climate Resilience and Adaptation Strategy and the Paris Agreement (Prasain et al., 2026; Dzvene et al., 2025; Prasain, 2025; Salim et al., 2024; Mitra et al., 2021; Zaveri et al., 2016), which emphasise climate-resilient water–food systems. Declining precipitation (−6.8% to −11.8%) and rising temperatures increase evapotranspiration (~9–10%) and reduce surface runoff (−20% to −25%), limiting water availability for irrigation and ecosystems. Reductions in lateral flow, percolation, and groundwater recharge further constrain resources. A growing share of precipitation (56–60%) is lost as evapotranspiration, increasing reliance on green water and intensifying soil moisture deficits (>53 mm by the 2100s). These trends challenge the sustainability goals of the Murray–Darling Basin Plan (Clark et al., 2025; Doble et al., 2024; Maheshwari, 2021; Prosser et al., 2021; Saha et al., 2019) by reducing allocation reliability and environmental flows. LUC

further increases evapotranspiration (up to +10.3%) and reduces subsurface flows, indicating that adaptation through land use shifts redistributes water but does not offset climate-driven scarcity. Declining groundwater recharge raises concerns for long-term aquifer sustainability, consistent with priorities under the National Water Initiative and the Great Artesian Basin Strategic Management Plan (Dzvene et al., 2025; Fu et al., 2020; Saha et al., 2019; Smerdon et al., 2012). Crop yields decline across all systems (−12% by the 2030s to ~−33% by the 2100s) due to higher temperatures, increased evapotranspiration, and reduced rainfall. LUC exacerbates these losses through reduced harvested area (−3% to >−14%), particularly for water-intensive crops such as soybean (up to −40%). Although shifts toward pasture represent adaptive responses, they reduce overall food production, highlighting trade-offs between water conservation and productivity.

These outcomes are directly relevant to policies such as the National Agricultural Innovation Policy Statement and the National Drought Agreement (Clark et al., 2025; Prasain, 2025; Page et al., 2023; Maheshwari, 2021; Millar and Roots, 2012), suggesting that existing frameworks may require strengthening to address long-term declines. The combined impacts point to increasing water scarcity, reduced agricultural output, and a shift from blue to green water dependence, consistent with global priorities under the Sustainable Development Goals (Makhlouf et al., 2024; Mundetia et al., 2024; Rossi et al., 2022), particularly SDG 2 (Zero Hunger), SDG 6 (Clean Water and Sanitation), and SDG 13 (Climate Action) with reinforcing the interconnected nature of water, food, and climate systems. From a sustainability perspective, declining recharge and increasing extraction pressures may intensify streamflow reduction, salinisation, ecosystem degradation, and socio-economic risks. Addressing these challenges will require integrated and adaptive water management, including managed aquifer recharge, improved irrigation efficiency, and enhanced soil moisture conservation.

In summary, climate change is the primary driver of declining water and food security, while land use change provides limited adaptation and may further reduce productivity. Strengthening and integrating existing policy frameworks within a climate-informed decision-making context will be essential to ensure long-term sustainability in Australia and other water-limited regions.

4. Limitations and Future Pathways

Despite providing an integrated assessment of CLUC impacts on hydrology and crop yield in the CBRB, several limitations remain. Future climate was represented using a single model (CanESM2) under RCP4.5, which does not capture projection uncertainty. The SWAT+ model simulates surface processes well but has limited representation of groundwater dynamics, introducing uncertainty in recharge and baseflow estimates. Land-use projections from LUTO and CA–Markov depend on assumptions that may not reflect future conditions. Modelling was restricted to selected sub-basins, limiting basin-scale generalisation, while calibration relied on sparse data. Static crop management assumptions further constrain realism.

Future research should adopt more integrated approaches. Coupling SWAT+ with MODFLOW would improve representation of surface–groundwater interactions, while integrating WEAP would enable inclusion of water allocation policies and socio-economic dynamics. Expanding to full basin-scale modelling using high-

performance computing, along with multi-model climate ensembles and dynamic land-use scenarios, would enhance reliability. Improved calibration through remote sensing and high-resolution field data is also needed. Finally, evaluating adaptation strategies—such as deficit irrigation, climate-resilient crops, soil moisture conservation, and managed aquifer recharge—would provide practical insights for sustainable water and food security under climate change.

5. Conclusion

This study provides a comprehensive and spatially explicit assessment of the combined impacts CLUC on water balance components and crop yield in the CBRB using the SWAT+ modelling framework. The results demonstrate that climate change is the dominant driver of hydrological and agricultural change in the basin, characterised by increasing temperatures (up to ~3.5 °C), declining and more variable rainfall, and intensified evapotranspiration. These changes significantly alter water balance partitioning, leading to reduced soil moisture, declining groundwater recharge, and decreased baseflow, ultimately intensifying water scarcity across the basin. Crop yield analysis reveals a consistent and substantial decline across all major crops, with reductions ranging from approximately −12% soon to −33% by the end of the century. These declines are driven by increased heat stress, reduced water availability, and shortened growing periods. When land use change is incorporated, agricultural production losses are further amplified due to reductions in cultivated area and a structural shift from irrigated cropping to pasture-based systems. While this transition may represent an adaptive response to water scarcity, it results in lower overall food production. The combined CLUC impacts highlight a critical shift in the basin's hydrological and agricultural systems—from relatively stable water availability and crop production toward increased variability, water stress, and reduced productivity. The findings also reveal strong spatial heterogeneity, emphasizing the importance of micro-watershed-scale analysis for targeted water and land management interventions. From a policy perspective, the results suggest that existing water–food security frameworks may be insufficient to address long-term climate risks without significant adaptation. Strengthening integrated water resource management, improving irrigation efficiency, enhancing soil moisture conservation, and promoting climate-resilient agricultural practices are essential to sustaining productivity and water availability.

Beyond these findings, this study establishes a robust foundation for scenario-based decision-making under uncertainty, enabling evaluation of trade-offs across water, land and agricultural systems. The integrated modelling framework offers a scalable tool for basin-level planning and supports a transition from reactive responses to proactive, climate-resilient adaptation pathways. Incorporating socio-economic dynamics and policy-driven scenarios in future applications can further strengthen its relevance for long-term resource management.

Overall, this study underscores the urgent need for integrated and adaptive management strategies that link climate projections, land use planning, and hydrological processes. The modelling framework developed in this research provides a transferable approach for assessing climate–land–water interactions and supports

565 evidence-based decision-making for sustainable water and food security in the CBRB and similar semi-arid
566 regions globally.
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References

ABARES, Australian Bureau of Agricultural and Resource Economics and Sciences, 2025a. Australian Agricultural Census 2020–21 visualisations (data). Australian Bureau of Statistics (ABS), Australia. https://www.agriculture.gov.au/abares/aclump/land-use/agriculture-census-dashboards-sa2.

ABARES, Australian Bureau of Agricultural and Resource Economics and Science, 2025b. Australian Crop Report December 2025 (No. 216). Australian Bureau of Agricultural and Resource Economics and Sciences, Australia. https://daff.ent.sirsidynix.net.au/client/en_AU/search/asset/1037661/0/_AustCropRrt20251202_v1.0.0.pdf.

Abbas, S.A., Bailey, R.T., White, J.T., Arnold, J.G., White, M.J., 2025. Estimation of groundwater storage loss using surface-subsurface hydrologic modelling in an irrigated agricultural region. SCIENTIFIC REPORTS 15. https://doi.org/10.1038/s41598-025-92987-6.

Abitew, T.A., Borga, M., Hrachowitz, M., 2023. Hydrological model performance evaluation using multiple objective functions under climate change conditions. Journal of Hydrology: Regional Studies 47, 101414. https://doi.org/10.1016/j.ejrh.2023.101414.

ABS, Australian Bureau of Statistics, 2024. Release of historic agricultural data and an update on future agricultural data. Australia. https://www.abs.gov.au/articles/release-historic-agricultural-data-and-update-future-agricultural-data.

ABS, Australian Bureau of Statistics, 2020. Improving agricultural crop statistics using satellite data (data No. 1). Australian Bureau of Statistics (ABS), Australia. https://www.abs.gov.au/statistics/research/improving-agricultural-crop-statistics-using-satellite-data.

ACLUMP, Australian Bureau of Agricultural and Resource Economics and Sciences, 2024. Catchment scale land use of Australia and commodities – Update December 2023 (map No. 1). Australian Bureau of Agricultural and Resource Economics and Sciences (ABARES), Australia. https://www.agriculture.gov.au/abares/aclump/land-use/catchment-scale-land-use-and-commodities-update-2023. Ahmadi, H., Scott, D., Sample, D.J., Saksena, S., 2026. Evaluating the combined effects of climate and land use change on hydrological response in a mixed land use watershed. Journal of Environmental Management 397, 128277. https://doi.org/10.1016/j.jenvman.2025.128277.

Alexandra, J., 2022. Climate adaptation options for the 2026 Basin Plan: opportunities for managing climate risk. Australasian Journal of Water Resources 27, 18–30. https://doi.org/10.1080/13241583.2022.2157107

Arnold, J.G., Moriasi, D.N., Srinivasan, R., 2022. SWAT+ model use, calibration, and validation for hydrologic and agricultural systems. Journal of Hydrology 604, 127242. https://doi.org/10.1016/j.jhydrol.2021.127242.

Ayele, G.T., 2024. Review of Climate Change Impacts on Water Quantity and Quality in the Murray–Darling Basin, Australia. Water 16, 3506. https://doi.org/10.3390/w16233506.

Ayieko, A., Moses, G., Godfrey, M., Kimwatu, D., Mwangi, A., 2024. Spatial modeling of groundwater across land use land cover and climate change gradient using SWAT and Logan's method: a case study of Mbagathi sub-catchment. MODELING EARTH SYSTEMS AND ENVIRONMENT 10, 285–301. https://doi.org/10.1007/s40808-023-01769-4.

Bai, H., Zhong, Y., Ma, N., Kong, D., Mao, Y., Feng, W., Wu, Y., Zhong, M., 2025. Changes and drivers of long-term land evapotranspiration in the Yangtze River Basin: A water balance perspective. Journal of Hydrology 653, 132763. https://doi.org/10.1016/j.jhydrol.2025.132763.

Bieger, K., Neitsch, S., Arnold, J.G., 2023. Introduction to SWAT+—A completely restructured version of the Soil and Water Assessment Tool. Environmental Modelling & Software 162, 105684. https://doi.org/10.1016/j.envsoft.2023.105684.

Birks, S.J., Gibson, J.J., Fennell, J.W., Mcclain, C.N., Sayanda, D., Bickerton, G., Yi, Y., Castrillon-Munoz, F., 2025. Groundwater vulnerability in the Athabasca and Cold Lake oil sands regions: gaps, opportunities, and challenges. ENVIRONMENTAL REVIEWS 33. https://doi.org/10.1139/er-2024-0002.

BOM, Bureau of Meteorology, 2025. Coal resource development and water resources in the Maranoa-Balonne-Condamine subregion (No. 1). Department of the Environment and Energy, Bureau of Meteorology. https://www.bioregionalassessments.gov.au/factsheets/coal-resource-development-and-water-resources-maranoa-balonne-condamine-subregion.

Boulaire, F.A., Cook, S., Fleming, A., Romanach, L., Capon, T., Po, M., Darbyshire, R., Barnett, G., Bluhm, S., Lin, B.B., 2025. Insights on the process to develop Australia's first national climate risk assessment. iScience 28. https://doi.org/10.1016/j.isci.2025.112068.

Bryan, B., Nolan, M., Brennan, L., Connor, J., Newth, D., Harwood, T., King, D., Navarro, G.J., Cai, Y., Gao, L., Grundy, M., Graham, P., Ernst, A., Dunstall, S., Stock, F., Brinsmead, T., Harman, I., Grigg, N., Battaglia, M., Hatfield-Dodds, S., Keating, B., Wonhas, A., 2015. Australian land-use and sustainability data: 2013 to 2050. (No. 4). CSIRO, Australia, Australia. https://doi.org/10.4225/08/5756169E381CC.

Cassel, R., Ransley, T., Shi, X., Janardhanan, S., 2015. Current water accounts and water quality for the Maranoa-Balonne-Condamine subregion, product 1.5 for the Maranoa-Balonne-Condamine subregion from the Northern Inland Catchments Bioregional Assessment. (Annual Report No. 1.5). Department of the Environment, Bureau of Meteorology, CSIRO and Geoscience Australia, Australia, https://eprints.gla.ac.uk/174811/1/174811.pdf.

CCA, Climate Change Authority, 2023. ANNUAL PROGRESS REPORT (Annual Report No. 1). Climate Change Authority, Commonwealth of Australia, Australia. https://www.climatechangeauthority.gov.au/sites/default/files/documents/2023-11/2023%20AnnualProgressReport_0.pdf.

CEWH, Commonwealth Environmental Water Holder, 2025. Water Management Plan 2024–25: Chapter 3 – Condamine–Balonne Valley Water Plan. (No. 3), 1. Commonwealth of Australia, Australia. https://www.dcceew.gov.au/cewh/manage-water/planning/water-management-plan.

CEWO, Commonwealth Environmental Water Office, 2021. Water Management Plan Chapter 3.2 – Condamine-Balonne (No. 3.2). Commonwealth Environmental Water Office, Australia. https://www.dcceew.gov.au/sites/default/files/documents/water-mgt-plan-2020-21-chapter-3-2-condamine-balonne.pdf.

Choudhary, P., Devatha, C.P., Azhoni, A., 2026. Simulating Streamflow Scenarios Using Hydrological Modeling Integrated with Future Land Use and CMIP6 Climate Projections. Water Resources Management 40, 103. https://doi.org/10.1007/s11269-025-04406-0.

Clark, S.R., Gonzalez, D., Fu, G., Janardhanan, S., 2025. Machine learning insights into groundwater demand under changing surface water availability: Murray-Darling Basin, Australia. JOURNAL OF HYDROLOGY-REGIONAL STUDIES 62. https://doi.org/10.1016/j.ejrh.2025.102772.

Cook, P., Black, E.C.L., Verhoef, A., Macdonald, D.M.J., Sorensen, J.P.R., 2022. Projected increases in potential groundwater recharge and reduced evapotranspiration under future climate conditions in West Africa. Journal of Hydrology: Regional Studies 41. https://doi.org/10.1016/j.ejrh.2022.101076.

Crosbie, R., Pickett, T., Mpelasoka, F., Hodgson, G., Charles, S., Barron, O., 2013. An assessment of the climate change impacts on groundwater recharge at a continental scale using a probabilistic approach with an ensemble of GCMs. CLIMATIC CHANGE 117, 41–53. https://doi.org/10.1007/s10584-012-0558-6.

Crosbie, R.S., McCallum, J.L., Walker, G.R., Chiew, F.H.S., 2010. Modelling climate-change impacts on groundwater recharge in the Murray-Darling Basin, Australia. Hydrogeology Journal 18, 1639–1656. https://doi.org/10.1007/s10040-010-0625-x.

CSIRO, Commonwealth Scientific and Industrial Research Organization, 2024. Key points on Australia's climate, global climate and projected future changes: State of the Climate 2024. Commonwealth Scientific and Industrial Research Organization, Australian Government (CSIRO), Australia. https://www.csiro.au/en/research/environmental-impacts/climate-change/State-of-the-Climate.

CSIRO, Commonwealth Scientific and Industrial Research Organization, 2014. Bioregional Assessment in Context statement for the Maranoa-Balonne-Condamine subregion. (No. 1.1). https://www.bioregionalassessments.gov.au/assessments/11-context-statement-maranoa-balonne-condamine-subregion. https://www.csiro.au/en/research/environmental-impacts/climate-change/State-of-the-Climate. Darbas, T., Lawrence, D., 2011. The influence of agronomic advice upon soil water thresholds used for planting decisions in Southern Queensland's grains region. Agricultural Systems 104, 20–29. https://doi.org/10.1016/j.agsy.2010.08.008.

Davamani, V., John, J., Poornachandhra, C., Gopalakrishnan, B., Arulmani, S., Parameswari, E., Santhosh, A., Srinivasulu, A., Lal, A., Naidu, R., 2024. A Critical Review of Climate Change Impacts on Groundwater Resources: A Focus on the Current Status, Future Possibilities, and Role of Simulation Models. ATMOSPHERE 15. https://doi.org/10.3390/atmos15010122.

Dawes, W., Ali, R., Varma, S., Emelyanova, I., Hodgson, G., McFarlane, D., 2012. Modelling the effects of climate and land cover change on groundwater recharge in south-west Western Australia. HYDROLOGY AND EARTH SYSTEM SCIENCES 16, 2709–2722. https://doi.org/10.5194/hess-16-2709-2012.

DLGWV, Department of Local Government, Water and Volunteers, Water and Volunteers, 2025. Water Monitoring Information Portal API and Web Services (No. FS 605172). Department of Local Government, Water and Volunteers, Queensland Government, Australia. https://www.dcceew.gov.au/sites/default/files/documents/annual-climate-change-statement-2023.pdf.

DLGWV, D. of L.G., Water and Volunteers, 2025. Water Monitoring Information Portal API and Web Services (No. FS 605172). Department of Local Government, Water and Volunteers, Queensland Government, Australia.

Doble, R., Walker, G., Crosbie, R., Guillaume, J., Doody, T., 2024. An overview of groundwater response to a changing climate in the Murray-Darling Basin, Australia: potential implications for the basin system and opportunities for management. HYDROGEOLOGY JOURNAL 32, 59–80. https://doi.org/10.1007/s10040-023-02723-5.

Dolgorsuren, S.-E., Ishgaldan, B., Purevtseren, P., Kumar, P., Meraj, G., Singh, S.K., Kanga, S., Almazroui, M., 2024. Hydrological Responses to Climate Change and Land-Use Dynamics in Central Asia's Semi-arid Regions: An SWAT Model Analysis of the Tuul River Basin. Earth Sys. Environ. 8, 297–323. https://doi.org/10.1007/s41748-023-00367-9.

Dzvene, A.R., Zhou, L., Slayi, M., Dirwai, T.L., 2025. A scoping review on challenges and measures for climate change in arid and semi-arid agri-food systems. Discover Sustainability, SPRINGER 6, 151. https://doi.org/10.1007/s43621-025-00945-z.

Fan, X., Peterson, T., Henley, B., Arora, M., 2023. Groundwater Sensitivity to Climate Variations Across Australia. WATER RESOURCES RESEARCH 59. https://doi.org/10.1029/2023WR035036.

Feng, G., Jin, W., Ouyang, Y., Huang, Y., 2024. The role of changing land use and irrigation scheduling in groundwater depletion mitigation in a humid region. Agricultural Water Management 291. https://doi.org/10.1016/j.agwat.2023.108606.

Fu, G., Zou, Y., Crosbie, R., Barron, O., 2020. Climate changes and variability in the Great Artesian Basin (Australia), future projections, and implications for groundwater management. HYDROGEOLOGY JOURNAL 28, 375–391. https://doi.org/10.1007/s10040-019-02059-z.

Gao, L., Bryan, B.A., 2017. Finding pathways to national-scale land-sector sustainability. Nature 544, 217–222. https://doi.org/10.1038/nature21694.

GRDC, Grains Research and Development Corporation, 2026. The National Variety Trials (NVT) Crop Sowing Guides (No. 123). Grains Research & Development Corporation, Australia. https://nvt.grdc.com.au/nvt-supplements/crop-sowing-guides.Grundy, M.J., Rossel, R.A.V., Searle, R.D., Wilson, P.L., Chen, C., Gregory, L.J., 2015. Soil and Landscape Grid of Australia. Soil Research 53, 835–844. https://doi.org/10.1071/SR15191.

Harding, D.J., Burke, C.L., Carpenter-Bundhoo, L., Fawcett, J.H., Sternberg, D., Kennard, M.J., Kerr, J.L., Mullins, T.M., Prior, A.E., 2024. Movement patterns of Murray cod (Maccullochella peelii) and golden perch (Macquaria ambigua) in a northern Murray–Darling Basin dryland river. Marine & Freshwater Research 75, MF24043. https://doi.org/10.1071/MF24043.

Heady, C., Clarke, J., 2025. CCiA/CSA application ready daily data interpolated across Australia from 8 selected CMIP5 GCMs (No. 393871). CSIRO, Australia, Australia. http://hdl.handle.net/102.100.100/393871?index=1.

Heady, C., Clarke, J., Erwin, T., Bedin, T., 2021. CCiA/CSA application ready thresholds data interpolated across Australia from 8 selected CMIP5 GCMs (EP2024-0338 No. 394328). CSIRO, Australia, Australia. http://hdl.handle.net/102.100.100/394328?index=1.

IPCC, Intergovernmental Panel on Climate Change, 2022. Climate Change 2021 – The Physical Science Basis: Working Group I Contribution to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge. https://doi.org/10.1017/9781009157896.

Irving, D., Macadam, I., 2024. Application-ready climate projections from CMIP6 using the Quantile Delta Change method (Climate change impacts and adaptation No. csiro:EP2024-6112). CSIRO, Australia. https://doi.org/10.25919/03by-9y62.

Kardhana, H., Lihawa, A.W., Rohmat, F.I., Wulandari, S., Harjupa, W., Adiprawita, W., Kardena, E., Kusuma, M.S., 2024. Water Balance Analysis in the Majalaya Watershed: Two-Step Calibration and Application of the SWAT+ Model for Low-Flow Conditions. Water 16, 3498. https://doi.org/10.3390/w16233498.

Khatakho, R., Firoz, A., Elagib, N.A., Fink, M., 2024. Hydrological Modelling Using Gridded and Ground-Based Precipitation Datasets in Data-Scarce Mountainous Regions. HYDROLOGICAL PROCESSES 38, e70024. https://doi.org/10.1002/hyp.70024.

Khatakho, R., Suwal, N., Ankon, S.B., Jha, A.N., 2026. Improving hydrological model performance and parameter transferability for data-scarce Himalayan basins to inform water resource decisions. Hydrological Sciences Journal 1–20. https://doi.org/10.1080/02626667.2026.2621067.

Khatakho, R., Talchabhadel, R., Thapa, B.R., 2021. Evaluation of different precipitation inputs on streamflow simulation in Himalayan River basin. Journal of Hydrology 599, 126390. https://doi.org/10.1016/j.jhydrol.2021.126390.

Kishore, N., Pandey, A., Reddy, C.R.G., Sahu, R.T., 2025. Evaluation of the SWAT model for water balance components under changing climatic conditions in the Mahanadi River Catchment, Chhattisgarh. Water Practice and Technology 20, 1220–1236. https://doi.org/10.2166/wpt.2025.072.

Kling, H., Gupta, H.V., Yilmaz, K.K., 2021. Improving the interpretability of the Kling–Gupta Efficiency. Water Resources Research 57, e2020WR027690. https://doi.org/10.1029/2020WR027690.

Kumari, P., Singh, A., Parhi, P.K., 2024. Assessment of the Effect of Land Use and Climate Change on Natural Resources and Agriculture in the Subarnarekha Basin, India, Using the SWAT. Nat. Resourc. Res. 33, 1893–1911. https://doi.org/10.1007/s11053-024-10356-y.

Leone, M., Attar, O., Brouziyne, Y., El Khalki, E.M., Bouchaou, L., de Girolamo, A.M., 2025. Assessing the long-term water footprint of olive grove under changing climate (Apulia, Italy). Agric. Water Manage. 320. https://doi.org/10.1016/j.agwat.2025.109875.

Loukika, K.N., Keesara, V.R., Buri, E.S., Sridhar, V., Dzwairo, B., Montenegro, S., 2025. Integrated impacts of land use changes and climate dynamics on hydrological components in the Munneru River basin, India. JOURNAL OF ENVIRONMENTAL MANAGEMENT 380. https://doi.org/10.1016/j.jenvman.2025.125096.

Lukas, P., Melesse, A.M., Kenea, T.T., 2025. Integrating Land Use/Land Cover and Climate Change Projections to Assess Future Hydrological Responses: A CMIP6-Based Multi-Scenario Approach in the Omo–Gibe River Basin, Ethiopia. CLIMATE 13, 51. https://doi.org/10.3390/cli13030051.

Madasamy, N., Meiyappan, V., Muthiah, M., Elango, S., 2025. Hydrological Simulation Model on Climate Change Impact of a Lower Bhavani Basin Using GIS and SWAT. J. Ind. Soc. Remote Sens. 53, 3669–3689. https://doi.org/10.1007/s12524-025-02150-x.

Maheshwari, B., 2021. Chapter 28 - Groundwater in Australia—understanding the challenges of its sustainable use. Global Groundwater (Source, Scarcity, Sustainability, Security, and Solution), ELSEVIER 28, 383–392. https://doi.org/10.1016/B978-0-12-818172-0.00028-1.

Majola, K., Xu, Y., Kanyerere, T., 2022. Review: Assessment of climate change impacts on groundwater-dependent ecosystems in transboundary aquifer settings with reference to the Tuli-Karoo transboundary aquifer. Ecohydrology and Hydrobiology 22, 126–140. https://doi.org/10.1016/j.ecohyd.2021.08.013.

Makhlouf, A., El-Rawy, M., Kanae, S., Ibrahim, M., Sharaan, M., 2024. Integrating MODFLOW and machine learning for detecting optimum groundwater abstraction considering sustainable drawdown and climate changes. JOURNAL OF HYDROLOGY 637. https://doi.org/10.1016/j.jhydrol.2024.131428

Malone, B., Searle, R., 2021. Updating the Australian digital soil texture mapping (Part 2*): spatial modelling of merged field and lab measurements. Soil Research 59, 435–451. https://doi.org/10.1071/SR20284.

MDBA, Murray–Darling Basin Authority, 2025. Basin Plan Review The future of climate and water availability in the Murray–Darling Basin Sustainable yields report (1). Murray–Darling Basin Authority, Australia. https://www.mdba.gov.au/publications-and-data/publications/summary-sustainable-yields.

MDBA, Murray–Darling Basin Authority, 2016. Assessment of environmental water requirements: Condamine–Balonne river system (1). Murray–Darling Basin Authority, Australia. https://www.mdba.gov.au/sites/default/files/publications/nbr-environmental-water-requirements-condamine-balonne.pdf.

Mewett, J., Paplinska, J., Kelley, G., Lesslie, R., Pritchard, P., Atyeo, C., 2013. Towards national reporting on agricultural land use change in Australia (No. 13.06). Australian Bureau of Agricultural and Resource

Economics and Science (ABARES), Australia. https://apo.org.au/sites/default/files/resource-files/2013-10/apo-nid35974.pdf.
Millar, J., Roots, J., 2012. Changes in Australian agriculture and land use: implications for future food security. International Journal of Agricultural Sustainability, Taylor and Francise 12, 25–39. https://doi.org/10.1080/14735903.2012.646731.
Mitra, S., Mehta, P., Mishra, S., 2021. Farmers' Perception, Adaptation to Groundwater Salinity, and Climate Change Vulnerability: Insights from North India. WEATHER CLIMATE AND SOCIETY 13, 797–811. https://doi.org/10.1175/WCAS-D-20-0135.1.
Moise, A., Bhend, J., Watterson, I., Wilson, L., 2015. CHAPTER FIVE EVALUATION OF CLIMATE MODELS in Climate Change in Australia: Regional Report. Climate Change Authority, Commonwealth of Australia and CSIRO, Australia. https://www.climatechangeinaustralia.gov.au/media/ccia/2.2/cms_page_media/168/CCIA_2015_NRM_TR_Chapter%205.pdf.
Mondal, K., Gupta, V., Chatterjee, C., Singh, R., 2025. Analysing the Impact of Climate Change on Crop Yield and Its Consequences for the Water-Energy-Food Nexus in an Indian River Basin, in: Nanda, A., Gupta, P.K., Gupta, Vivek, Jha, P.K., Dubey, S.K. (Eds.), Navigating the Nexus: Hydrology, Agriculture, Pollution and Climate Change, Volume 1. Springer Nature Switzerland, Cham, pp. 173–194. https://doi.org/10.1007/978-3-031-76532-2_8.
Moriasi, D.N., Sahoo, D., Van Liew, M.W., 2023. Model evaluation guidelines for systematic quantification of accuracy in watershed simulations. Transactions of the ASABE 66, 439–458. https://doi.org/10.13031/trans.14901.
Mummed, B.A., Seleshi, Y., 2024. Assessment of the effects of climate change on water balance components in the upper Erer subbasin, Ethiopia. Heliyon 10. https://doi.org/10.1016/j.heliyon.2024.e30297.
Mundetia, N., Sharma, D., Sharma, A., 2024. Groundwater sustainability assessment under climate change scenarios using integrated modelling approach and multi-criteria decision method. Ecological Modelling, ELSEVIER 487, 110544. https://doi.org/10.1016/j.ecolmodel.2023.110544.
Nazari, S., Kruse, I.L., Moosdorf, N., 2025. Spatiotemporal dynamics of global rain-fed groundwater recharge from 2001 to 2020. JOURNAL OF HYDROLOGY 650. https://doi.org/10.1016/j.jhydrol.2024.132490.
Nelson, G., Carey, H., Radke, B., Ransley, T., 2013. Layer 01 Great Artesian Basin 3-second Digital Elevation Model surface: A report to the Australian Government from the CSIRO Great Artesian Basin Water Resource Assessment. (No. ANZCW0703014182). Geoscience Australia, Australia. http://pid.geoscience.gov.au/dataset/ga/75990.
N'Guessan, B.K., Smith, J., Johnson, P., 2023. Automatic calibration of SWAT+ using the Dynamically Dimensioned Search algorithm. Environmental Modelling & Software 160, 105637. https://doi.org/10.1016/j.envsoft.2022.105637.
Oliver, R.L., Carter, T., McDonald, S., 2024. Hydrological model calibration strategies under data scarcity conditions. Hydrological Processes 38, e15122. https://doi.org/10.1002/hyp.15122.
Oo, T.Z., Humphries, U.W., 2025. Hydrological Modeling of Flood Impacts under Land Use and Land Cover Change: A Systematic Review of Tools, Trends, and Challenges. MethodsX 1, 103724. https://doi.org/10.1016/j.mex.2025.103724.
Page, D., Vanderzalm, J., Gonzalez, D., Bennett, J., Castellazzi, 2023. Managed aquifer recharge for agriculture in Australia – History, success factors and future implementation. Agricultural Water Management, ELSEVIER 285, 108382. https://doi.org/10.1016/j.agwat.2023.108382.
Palmate, S.S., Pandey, A., Tigabu, T.B., Mercado-Bettín, D., Fohrer, N., Wagner, P.D., 2025. A conceptual framework to disentangle land use and climate change impacts on water balance components and sediment yield. Environ. Dev. Sustainability 27, 7033–7061. https://doi.org/10.1007/s10668-023-04179-9.
Pekárová, P., Leščešen, I., Pekár, J., Bajtek, Z., Bačová Mitková, V., Halmová, D., 2026. Assessment of Water Balance and Future Runoff in the Nitra River Basin, Slovakia. Water 18, 208. https://doi.org/10.3390/w18020208.
Penny, J., Ordens, C.M., Barnett, S., Djordjevi?, S., Chen, A.S., 2023. Small-scale land use change modelling using transient groundwater levels and salinities as driving factors Â– An example from a sub-catchment of Australia's Murray-Darling Basin. Agricultural Water Management 278. https://doi.org/10.1016/j.agwat.2023.108174.

Pianosi, F., Beven, K., Freer, J., 2020. Sensitivity analysis of environmental models: A systematic review. Environmental Modelling & Software 134, 104851. https://doi.org/10.1016/j.envsoft.2020.104851.
Portmann, F., DÃ¶ll, P., Eisner, S., FlÃ¶rke, M., 2013. Impact of climate change on renewable groundwater resources: assessing the benefits of avoided greenhouse gas emissions using selected CMIP5 climate projections. ENVIRONMENTAL RESEARCH LETTERS 8. https://doi.org/10.1088/1748-9326/8/2/024023.
Prasain, S., 2025. Developing of Integrated Modelling Framework to Evaluate Sustainability of Climate Smart and Drought-Resilience Agricultural Technologies by Concerning Water, Land and Food Security Network. https://doi.org/10.5281/zenodo.18025744.
Prasain, S., 2018. Climate change adaptation measure on agricultural communities of Dhye in Upper Mustang, Nepal. Climatic Change, SPRINGER 148, 279–291. https://doi.org/10.1007/s10584-018-2187-1.
Prasain, S., 2017. Community based adaptation measures of agriculture system in Himalayan Region of Nepal: a case study of Dhye village, Upper Mustang. Sustainable Water Resources Management, SPRINGER 4, 823–832. https://doi.org/10.1007/s40899-017-0174-8.
Prasain, S., Maraseni, T., Liu, X., Zhang, Z., Scobie, M., Shrivastav, M., Bhandari, A., 2026. A comprehensive review on impact of climate change and land use change on groundwater. Journal of Hydrology: Regional Studies 64, 103213. https://doi.org/10.1016/j.ejrh.2026.103213.
Prosser, I.P., Chiew, F.H.S., Stafford Smith, M., 2021. Adapting Water Management to Climate Change in the Murray–Darling Basin, Australia. Water 13, 2504. https://doi.org/10.3390/w13182504.
Rossi, M., Donnini, M., Beddini, G., 2022. Nationwide groundwater recharge evaluation for a sustainable water withdrawal over Italy. JOURNAL OF HYDROLOGY-REGIONAL STUDIES 43. https://doi.org/10.1016/j.ejrh.2022.101172.
Saha, P.P., Zeleke, K., Hafeez, M., 2019. Chapter 15 - Impacts of land use and climate change on streamflow and water balance of two sub-catchments of the Murrumbidgee River in Southeastern Australia, in: Melesse, A.M., Abtew, W., Senay, G. (Eds.), Extreme Hydrology and Climate Variability. Elsevier, pp. 175–190. https://doi.org/10.1016/B978-0-12-815998-9.00015-4.
Sahoo, S., Dey, S., Dhar, A., Debsarkar, A., Pradhan, B., 2019. On projected hydrological scenarios under the influence of bias-corrected climatic variables and LULC. ECOLOGICAL INDICATORS 106. https://doi.org/10.1016/j.ecolind.2019.105440.
Salim, M., Choudhari, N., Abdulla-Al Kafy, Nath, H., Alsulamy, S., Rahaman, Z., Aldosary, A., Rahmand, M., Al-Ramadan, B., 2024. A comprehensive review of navigating urbanization induced climate change complexities for sustainable groundwater resources management in the Indian subcontinent. GROUNDWATER FOR SUSTAINABLE DEVELOPMENT 25. https://doi.org/10.1016/j.gsd.2024.101115.
Sankarrao, L., Rathinasamy, M., 2025. Impacts of agricultural intensification on the hydrologic components for a coastal river basin using coupled hydrological model. GROUNDWATER FOR SUSTAINABLE DEVELOPMENT 29. https://doi.org/10.1016/j.gsd.2025.101440.
Searle, R., McBratney, A., Grundy, M., Kidd, D., Malone, B., Arrouays, D., Stockman, U., Zund, P., Wilson, P., Wilford, J., Van Gool, D., Triantafilis, J., Thomas, M., Stower, L., Slater, B., Robinson, N., Ringrose-Voase, A., Padarian, J., Payne, J., Orton, T., Odgers, N., O'Brien, L., Minasny, B., Bennett, J.M., Liddicoat, C., Jones, E., Holmes, K., Harms, B., Gray, J., Bui, E., Andrews, K., 2021. Digital soil mapping and assessment for Australia and beyond: A propitious future. Geoderma Regional 24, e00359. https://doi.org/10.1016/j.geodrs.2021.e00359.
Shrestha, S., Neupane, S., Mohanasundaram, S., Pandey, V.P., 2020. Mapping groundwater resiliency under climate change scenarios: a case study of Kathmandu Valley, Nepal. Environmental research 183, 109149. https://doi.org/10.1016/j.envres.2020.109149.
Singh, S., Hwang, S., Arnold, J.G., Bhattarai, R., 2023. Evaluation of Agricultural BMPs' Impact on Water Quality and Crop Production Using SWAT+ Model. Agriculture 13, 1484. https://doi.org/10.3390/agriculture13081484.
Singh, S., Saju, C., Athira, K., 2025. Chapter 7 - Impacts of ocean atmospheric phenomena on hydroclimate extremes, in: Behera, M.D., Behera, S.K., Barik, S.K., Mohapatra, M., Mohapatra, T. (Eds.), Sustainable Development Perspectives in Earth Observation. Elsevier, pp. 119–133. https://doi.org/10.1016/B978-0-443-14072-3.00003-4.
Smerdon, B., Ransley, T., Radke, B., Kellett, J., 2012. Water resource assessment for the Great Artesian Basin. A report to the Australian Government from the CSIRO Great Artesian Basin Water Resource Assessment,

CSIRO: Water for a Healthy Country Flagship. CSIRO, Australia, Australia. https://doi.org/10.4225/08/584c45a39e1b5.
Tan, L., Feng, P., Li, B., Huang, F., Liu, D.L., Ren, P., Liu, H., Srinivasan, R., Chen, Y., 2022. Climate change impacts on crop water productivity and net groundwater use under a double-cropping system with intensive irrigation in the Haihe River Basin, China. Agricultural Water Management 266. https://doi.org/10.1016/j.agwat.2022.107560.
Tapas, M.R., Etheridge, R., Tran, T.-N.-D., Le, M.-H., Hinckley, B., Nguyen, V.T., Lakshmi, V., 2025. Evaluating combinations of rainfall datasets and optimization techniques for improved hydrological predictions using the SWAT+ model. Journal of Hydrology: Regional Studies 57, 102134. https://doi.org/10.1016/j.ejrh.2024.102134.
Tarkegn, T.G., Tefera, A., Gebremichael, M., 2025a. Global sensitivity and uncertainty analysis of SWAT+ streamflow simulations under climate and land-use change. Journal of Hydrology 634, 130237. https://doi.org/10.1016/j.jhydrol.2024.130237.
Tarkegn, T.G., van Oel, P.R., Chukalla, A.D., Ray, R.L., Tefera, G.W., Worqlul, A.W., Dile, Y.T., Haileslassie, A., Adgo, E., Bantider, A., Taye, M.T., 2025b. Modeling impacts of climate change on blue and green water, and crop yield using SWAT + in Lake Tana sub-basin (Ethiopia). Modeling Earth Systems and Environment 12, 7. https://doi.org/10.1007/s40808-025-02641-3.
Taschetto, A.S., McGregor, S., Dommenget, D., Gillett, Z.E., Nicholls, N., Sharmila, S., van Rensch, P., Verdon-Kidd, D., Boschat, G., Chung, C., Lieber, R., Abram, N., Allan, R., Allen, K., Ashcroft, L., Brown, J.R., Cai, W., Chand, S., Cowan, T., Dao, T.L., de Burgh-Day, C., Freund, M.B., Gallant, A., Gergis, J., Holbrook, N.J., Heidemann, H., Holgate, C., Hope, P., King, A., Lim, E.-P., McBride, J.L., McKay, R.C., Nguyen, H., Pepler, A., Perkins-Kirkpatrick, S., Power, S., Risbey, J.S., Santoso, A., Ummenhofer, C.C., Wang, G., Zhang, X., 2025. Climate impacts of the El Niño–Southern Oscillation on Australia. Nature Reviews Earth & Environment. https://doi.org/10.1038/s43017-025-00747-x.
Tezel, Anıl, Akpınar, A., Bor, A., Alfredsen, K.T., 2025. Exploring Hydrological Response to Land Use/Land Cover Change Using the SWAT+ Model in the İznik Lake Watershed, Türkiye. Water 17, 1924. https://doi.org/10.3390/w17131924.
Tezel, Anil, Demir, A., Yilmaz, K., 2025. Assessing SWAT+ performance for streamflow and crop yield using multi-objective calibration. Environmental Modelling & Software 170, 105946. https://doi.org/10.1016/j.envsoft.2025.105946.
Tumsa, B.C., Kenea, G., Tola, B., 2022. The application of SWAT plus model to quantify the impacts of sensitive LULC changes on water balance in Guder catchment, Oromia, Ethiopia. HELIYON 8. https://doi.org/10.1016/j.heliyon.2022.e12569.
Villani, G., Rossi, F., Bianchi, A., 2024. Evaluation of SWAT+ crop yield simulations under climate variability. Agricultural Water Management 293, 108742. https://doi.org/10.1016/j.agwat.2024.108742.
Villani, L., Castelli, G., Yimer, E.A., Nkwasa, A., Penna, D., van Griensven, A., Bresci, E., 2024. Exploring adaptive capacities in Mediterranean agriculture: Insights from Central Italy's Ombrone catchment. Agric. Syst. 216. https://doi.org/10.1016/j.agsy.2024.103903.
Viscarra Rossel, R., Chen, C., Grundy, M., Searle, R., Clifford, D., Odgers, N., Holmes, K., Griffin, T., Liddicoat, C., Kidd, D., 2024. Soil and Landscape Grid National Soil Attribute Maps - Available Water Capacity (3" resolution) - Release 1. https://doi.org/10.4225/08/546ED604ADD8A.
Wasko, C., Stephens, C., Peterson, T.J., Nathan, R., Pepler, A., Hettiarachchi, S., Vogel, E., Johnson, F., Westra, S., 2024. Understanding the implications of climate change for Australia's surface water resources: Challenges and future directions. Journal of Hydrology 645, 132221. https://doi.org/10.1016/j.jhydrol.2024.132221.
Webb, L., Macadam, I., Nguyen, K., Irving, D., Bodman, R., 2024. Climate Innovation Hub Technical Note 1. Quantile-quantile scaled projections. (No. EP2024- 0338). CSIRO, Australia, Australia. https://doi.org/10.25919/88wm-mw53.
White, I., Falkland, T., Metutera, T., Metai, E., Overmars, M., Perez, P., Dray, A., 2007. Climatic and human influences on groundwater in low atolls. Vadose Zone Journal 6, 581–590. https://doi.org/10.2136/vzj2006.0092.
Yin, W., Yang, X., Liu, W., 2025. Sustainable Management and Regulation of Agricultural Water Resources in the Context of Global Climate Change. SUSTAINABILITY 17, 2760. https://doi.org/10.3390/su17062760.

Zamaria, S.A., Arhonditsis, G.B., 2025. A Framework for Evaluating Irrigation Impact on Water Balance and Crop Yield Under Different Soil Moisture Conditions. Hydrol. Processes 39. https://doi.org/10.1002/hyp.70232.

Zaveri, E., Grogan, D.S., Fisher-Vanden, K., Frolking, S., Lammers, R.B., Wrenn, D.H., Prusevich, A., Nicholas, R.E., 2016. Invisible water, visible impact: groundwater use and Indian agriculture under climate change. Environmental Research Letters 11, 84005. https://doi.org/10.1088/1748-9326/11/8/084005.

Zhang, L., Deng, C., Wei, J., Zou, J., 2025. Assessing the impacts of climate change and land use/land cover data characteristics on streamflow using the SWAT model in the Upper Han River Basin. Journal of Hydrology: Regional Studies 61, 102764. https://doi.org/10.1016/j.ejrh.2025.102764.

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