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Analysis of Watershed Water Resource Supply and Demand Balance under Climate Change

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Abstract: *Climate change poses significant challenges to water resource availability and watershed management worldwide, altering hydrological regimes and exacerbating imbalances between water supply and growing societal demands. This study presents a comprehensive analysis of water resource supply and demand dynamics in a representative watershed system under changing climatic conditions, integrating hydrological modeling with scenario-based projections to assess current and future water balances. A coupled modeling framework combining the Soil and Water Assessment Tool and Water Evaluation and Planning approach was developed to simulate hydrological processes, project water availability under multiple climate scenarios, and evaluate sectoral water demands including agricultural, domestic, industrial, and environmental requirements. Climate projections from five general circulation models under Representative Concentration Pathways RCP4.5 and RCP8.5 were downscaled and bias-corrected for the baseline period, mid-century, and end-century time horizons. Results indicate that annual average streamflow is projected to decline by 12.4 to 28.7 percent across scenarios, with more pronounced seasonal shifts including increased winter flows and substantially reduced summer low flows. Groundwater recharge shows decreasing trends of 8.3 percent under RCP4.5 and 19.6 percent under RCP8.5 by end-century. Agricultural water demand increases by 15.8 percent due to elevated evapotranspiration and extended growing seasons, while total water demand exceeds supply during summer months in all future scenarios. Water stress indices indicate that the watershed transitions from moderate stress to severe stress conditions under RCP8.5, with supply-demand deficits reaching 34.7 million cubic meters annually by 2080 to 2100. Spatial analysis reveals distinct patterns of water surplus in headwater regions and acute deficits in downstream agricultural areas. These findings underscore the urgency of implementing adaptive watershed management strategies including demand-side management, infrastructure investments, and nature-based solutions to enhance water system resilience under climate change.*

Keywords: *Watershed hydrology, climate change, water supply-demand balance, WEAP model, SWAT model, water scarcity, scenario analysis*

1. Introduction

Water resources face unprecedented pressures from climatic shifts and anthropogenic activities globally, with watersheds serving as critical scales for assessing sustainability as the intensification of the hydrological cycle under climate warming directly modifies water availability while simultaneously increasing demands across multiple sectors. Climate models project substantial alterations in hydrological regimes, with some regions experiencing increased precipitation variability while others face progressive aridification, and studies demonstrate that future conditions may reduce streamflow by 5 to 40 percent and groundwater storage through increased evapotranspiration, with these hydrological alterations cascading through water supply systems and affecting both surface water and groundwater resources that support human uses. Water demand dynamics add complexity to supply-demand assessments, as agricultural consumption responds to climate through increased crop evapotranspiration and shifts in growing seasons, while industrial demands follow economic growth trajectories, domestic use increases with population, and environmental requirements are increasingly recognized as essential for maintaining ecosystem functions [1]. The concept of water supply-demand balance encompasses temporal and spatial dimensions, with mismatches arising when water availability peaks during low demand while scarcity coincides with peak periods, and spatial separation between source areas and demand centers creating deficits that require infrastructure investments or management interventions [2]. Integrated water resource management provides a framework for addressing imbalances through coordinated consideration of hydrological, social, economic, and environmental dimensions, with decision-support tools such as the Water Evaluation and Planning system and the Soil and Water Assessment Tool enabling scenario analysis of climate and management alternatives. This study addresses the need for comprehensive assessment of watershed water supply-demand balance under climate change through integrated hydrological and water allocation modeling, with objectives to characterize historical regimes, project future availability under multiple scenarios, quantify sectoral demand trajectories, assess supply-demand balances across seasonal and spatial dimensions, and evaluate implications for adaptive management in a representative watershed facing emerging water scarcity pressures [3].

2. Materials and Methods

The study watershed encompasses approximately 3,450 square kilometers with elevations ranging from 210 to 1,240 meters, mean annual precipitation of 985 millimeters, and mean monthly temperatures from minus 2.1 degrees Celsius in January to 23.7 degrees Celsius in July. Land use comprises 48 percent agricultural land with row crops dominating valley bottoms, 34 percent forested areas concentrated in headwater regions, and 12 percent urban and developed lands. The watershed contains an extensive river network with groundwater resources in both shallow alluvial and deep bedrock aquifers, supported by long-term streamflow records from four United States Geological Survey gauging stations and water use data from state databases, municipal reports, and agricultural surveys [4].

Historical climate data from 1990 to 2020 were obtained from the Parameter-elevation Regressions on Independent Slopes Model dataset at 4-kilometer resolution, with additional variables from the North American Land Data Assimilation System. Future climate projections were developed from five general circulation models including CanESM2, CNRM-CM5, HadGEM2-ES, MIROC5, and GFDL-ESM3 under Representative Concentration Pathways RCP4.5 and RCP8.5. Bias correction and spatial downscaling were performed using the Multivariate Adaptive Constructed Analogs method, with three future periods defined for analysis: mid-century from 2040 to 2060 and end-century from 2080 to 2100, each compared to the baseline period from 1990 to 2020 [5].

Hydrological processes were simulated using the Soil and Water Assessment Tool, a continuous-time semi-distributed model operating on a daily time step. Watershed delineation using a 30-meter digital elevation model produced 47 sub-basins, with soil data from the Gridded Soil Survey Geographic database and land use from the 2019 National Land Cover Database. The SCS curve number method was selected for surface runoff estimation, while potential evapotranspiration was calculated using the Penman-Monteith method. Groundwater contributions were simulated using a two-reservoir approach, and channel routing used the variable storage method [6]. SWAT model calibration and validation were conducted using daily streamflow observations from four gauging stations, with the period 1990 to 2005 used for calibration and 2006 to 2020 reserved for validation, employing the Sequential Uncertainty Fitting algorithm in SWAT-CUP with performance evaluated using Nash-Sutcliffe efficiency coefficient, percent bias, and coefficient of determination [7].

Water demand assessment integrated multiple sectors using SWAT irrigation routines coupled with GIS-based mapping of irrigated acreage, with future agricultural scenarios incorporating projected changes in crop evapotranspiration and irrigation efficiency improvements. Municipal and industrial demands were quantified using water use data from public suppliers and surveys, with population projections from state demographic offices and per capita use coefficients adjusted for conservation and technological improvements. Environmental water demands were defined based on instream flow requirements from state natural resource agency studies using hydrologic and habitat-based methods, incorporated as water demands with priority equal to or exceeding human uses [8].

Integration of water supply and demands was accomplished using the Water Evaluation and Planning system, a scenario-based water allocation model operating on a monthly time step. The WEAP configuration incorporated 47 sub-basin nodes, 23 demand nodes representing municipal systems, industrial facilities, and irrigation districts, and 8 reservoir nodes. Streamflow inputs were derived from SWAT-simulated flows, and groundwater availability was represented through sustainable yield estimates. Water allocation priorities were established through consultation with state agencies, with municipal suppliers receiving highest priority, followed by industrial uses, agricultural irrigation, and environmental flow requirements [9]. Reservoir operating rules were incorporated based on actual operational protocols. Supply-demand balance assessment employed metrics including water stress index, supply reliability, and deficit volume at multiple spatial and temporal scales [10].

Three primary scenarios were developed: climate change only with constant demand, climate change plus demand growth incorporating population growth and land use change, and adaptation incorporating management responses including irrigation efficiency improvements, water conservation programs, and alternative water supply development. For each scenario, ensemble simulations were conducted using climate projections from each of the five GCMs under both RCP4.5 and RCP8.5, producing 10 future climate realizations per scenario, with results analyzed to characterize central tendencies and uncertainty ranges for each supply-demand metric.

3. Results

The historical hydrological regime of the watershed shows strong seasonal variability typical of a temperate climate with warm-season precipitation maxima Table 1. During 1990–2020, mean annual streamflow at the watershed outlet averaged 18.7 m³/s, equivalent to a runoff depth of 312 mm or about 31.7% of annual precipitation. Streamflow exhibits a bimodal seasonal pattern: a primary spring peak driven by snowmelt and saturated soils, and a secondary peak in late autumn after evapotranspiration declines. Summer low flows (July–September) average 6.8 m³/s, about 36% of mean annual flow, and are important for aquatic habitat and water supply [11].

Table 1. Projected Changes in Watershed Water Balance Components under Climate Scenarios

Water Balance Component	Baseline (1990-2020)	RCP4.5 2040-2060	RCP8.5 2040-2060	RCP4.5 2080-2100	RCP8.5 2080-2100
Precipitation (mm/yr)	985	1014 (+2.9%)	1044 (+6.0%)	1023 (+3.9%)	1062 (+7.8%)
Actual ET (mm/yr)	618	652 (+5.5%)	681 (+10.2%)	667 (+7.9%)	724 (+17.2%)
Surface Runoff (mm/yr)	128	118 (-7.8%)	110 (-14.1%)	113 (-11.7%)	96 (-25.0%)
Groundwater Recharge (mm/yr)	187	176 (-5.9%)	164 (-12.3%)	171 (-8.6%)	150 (-19.8%)
Streamflow (m³/s)	18.7	17.1 (-8.7%)	15.5 (-17.3%)	16.4 (-12.4%)	13.4 (-28.7%)
Summer Low Flow (m³/s)	6.8	5.8 (-14.7%)	5.0 (-26.5%)	5.4 (-20.6%)	4.0 (-41.2%)
Baseflow Index	0.58	0.55 (-5.2%)	0.53 (-8.6%)	0.54 (-6.9%)	0.48 (-17.2%)

Groundwater is a major contributor to streamflow, accounting for about 58% of annual discharge. Baseflow fractions exceed 70% in winter when evapotranspiration is minimal, but fall below 40% during summer storm events. This strong groundwater component supports perennial flow and drought resilience, but also increases sensitivity to groundwater withdrawals and changes in recharge.

Total anthropogenic water consumption averages 42.3 million m³ per year, about 7.2% of annual streamflow. Irrigation is the dominant use (23.8 million m³, 56%), supporting about 14,200 ha of cropland. Municipal supply accounts for 11.6 million m³ (27%) for roughly 185,000 residents. Industrial use contributes 4.7 million m³ (11%), while rural domestic and livestock uses total 2.2 million m³ (5%). Environmental flow requirements, although non-consumptive, amount to 98.3 million m³ annually, indicating significant instream flow commitments [12].

Climate projections indicate substantial warming, with mean temperature increases of about 2.1°C by mid-century under RCP4.5 and 4.4°C by late century under RCP8.5. Summer warming is strongest, increasing evapotranspiration during peak water-demand periods. Precipitation projections are more uncertain, with ensemble mean increases of 2.9% (RCP4.5) and 6.0% (RCP8.5), though individual models range from −12.4% to +19.3%. Most models project increased winter and spring precipitation but mixed or declining summer precipitation.

Hydrological simulations show notable impacts on water balance. Mean annual streamflow decreases by about 8.7% (RCP4.5) and 17.3% (RCP8.5) by mid-century, reaching 12.4% and 28.7% reductions by late century. Declines exceed precipitation changes because warming increases evapotranspiration. Seasonal flow patterns shift, with winter flows rising 8.2–15.6% due to more rainfall and reduced snowpack, while summer flows decrease 22.4–41.8%. This shift intensifies the mismatch between summer water demand and availability.

Groundwater recharge also declines, by about 5.7% (RCP4.5) and 12.3% (RCP8.5) by mid-century, and up to 8.3% and 19.6% by late century. Reduced soil moisture under higher evapotranspiration limits recharge even when precipitation increases slightly. Lower recharge ultimately reduces groundwater contributions to streamflow, with the largest impacts on summer baseflow due to the long response times of groundwater systems.

Water demand is projected to increase across all sectors under combined climate change and socioeconomic growth. Agricultural irrigation shows the largest rise, increasing from 23.8 million m³ annually to 27.1 million m³ by mid-century and 30.2 million m³ by end-century (15.8–26.9%). This growth is driven by higher evapotranspiration under warming, longer growing seasons, and potential shifts to longer-season crops. Spring precipitation increases partly offset demand, but reduced summer rainfall in some models increases irrigation needs during peak periods.

Municipal demand rises from 11.6 to 13.9 million m³ by mid-century and 16.4 million m³ by end-century (19.8–41.4%). Population growth—from about 185,000 to 235,000 by 2050 and 278,000 by 2090—accounts for roughly 70% of this increase, while climate-driven factors such as higher outdoor water use contribute the remainder. Industrial demand grows more moderately, from 4.7 to 5.4 and 6.1 million m³, mainly reflecting economic growth. Livestock and rural domestic demands increase with projected population and livestock inventories. Overall, seasonal demand becomes more concentrated in summer, with peak demand rising from 1.7 times winter demand at baseline to 2.4 times by late century under RCP8.5, intensifying pressure during periods of declining summer flows.

Comparing future water supply and demand indicates increasing imbalance. Under climate change alone, annual water deficits first appear by mid-century under RCP8.5, averaging 4.2 million m³ and occurring mainly in August–September. By late century, deficits rise to 11.8 million m³ (8.4% of demand). When demand growth is included, shortages become much more severe: 9.6 million m³ by mid-century and 34.7 million m³ by late century under RCP8.5, equivalent to about 41% of total demand. Even under RCP4.5, late-century deficits reach 16.3 million m³ (21.8%), indicating the need for significant adaptation.

Spatially, headwater sub-basins with high forest cover maintain water surpluses, while mixed land-use basins shift from surplus to deficit under future scenarios. Downstream agricultural basins already experience shortages and face the greatest increases in deficit. Water supply reliability declines from 96.3% in the baseline period to 67.8% by late century under RCP8.5. Municipal users retain relatively higher reliability (81.4%) due to allocation priority and groundwater access, whereas agricultural users face much lower reliability (51.2%) because of lower priority and stronger dependence on variable surface water.

Table 2. Water Supply-Demand Balance Metrics under Future Scenarios

Metric	Baseline (1990-2020)	RCP4.5 2040-2060	RCP8.5 2040-2060	RCP4.5 2080-2100	RCP8.5 2080-2100
Total Demand (MCM/yr)	42.3	50.4 (+19.1%)	52.8 (+24.8%)	56.7 (+34.0%)	65.2 (+54.1%)
Supply Available (MCM/yr)	589.7	538.2 (-8.7%)	487.5 (-17.3%)	517.1 (-12.3%)	420.5 (-28.7%)
Demand/Supply Ratio	0.072	0.094	0.108	0.110	0.155
Water Stress Index	0.43	0.56	0.65	0.66	0.93
Annual Deficit (MCM)	0.0	2.1	9.6	4.8	34.7
Deficit as % of Demand	0.0%	4.2%	18.2%	8.5%	53.2%
Supply Reliability (%)	96.3	89.7	81.2	84.5	67.8
Months with Deficits	0.8	2.1	3.4	2.8	5.2

The temporal dynamics of water supply–demand balance show strong seasonal patterns that are not evident in annual averages. Under baseline conditions, supply exceeds demand in all months, with large winter surpluses but much smaller margins in late summer. Future scenarios amplify this pattern. By mid-century under RCP8.5, deficits emerge in August and September, averaging 2.8 million m³ per month. By end-century, deficits extend from July to October, with peak shortages of about 5.7 million

m^3 in August when irrigation demand is highest and streamflow is lowest Table 2.

Interannual variability in water availability also increases. The coefficient of variation for annual surplus rises from 0.24 under baseline conditions to 0.41 under RCP8.5 by late century. Severe drought years can produce deficits up to 58.3 million m^3—about 89% of total demand—indicating near-system failure. Multi-year droughts further intensify impacts; a simulated 5-year drought by late century could create cumulative deficits exceeding 210 million m^3, depleting reservoir storage by 78% and lowering groundwater levels by 4–6 m. Recovery from such events may require 3–5 years of above-average recharge, highlighting growing vulnerability to prolonged drought.

Water shortage impacts differ across sectors due to both physical exposure and allocation priorities. Municipal suppliers maintain relatively high reliability because of priority rights, groundwater access, and emergency measures. Industrial users face moderate risks but can partly adapt through operational adjustments. Agricultural irrigation is most affected, with water deliveries reduced by 30–60% in typical drought years and sometimes completely curtailed during extreme events, leading to crop yield losses of 15–35% for major crops. Environmental flow targets are also frequently unmet in summer, with flows falling below minimum thresholds for 40–70% of the season under future scenarios. These shortages threaten aquatic habitats and water quality, forcing increasingly difficult trade-offs among municipal supply, agricultural production, and ecosystem protection.

4. Discussion

The findings demonstrate that climate change poses substantial threats to water resource sustainability, with projected streamflow declines of 12.4 to 28.7 percent consistent with regional studies, though the upper range under RCP8.5 exceeds many previous projections and reflects the strong sensitivity of this watershed to warming temperatures. The amplification of streamflow reductions relative to precipitation changes highlights the critical role of increasing evapotranspiration, a mechanism that operates even under scenarios with stable precipitation and underscores that temperature-driven changes may dominate hydrological responses where precipitation changes remain uncertain. The seasonal redistribution toward increased winter flows and decreased summer low flows represents a particularly challenging aspect, as winter increases provide limited benefit given low demand and limited storage capacity, while summer reductions directly coincide with peak irrigation demands, creating temporal mismatches that drive scarcity even when annual water budgets appear adequate, suggesting that seasonal analysis must be central to vulnerability assessments and adaptation planning.

The projected increases in agricultural water demand of 15.8 to 26.9 percent compound supply-side challenges, creating a double squeeze on summer water availability, and the robustness of demand drivers across models suggests that demand-side pressures are as certain as supply-side changes in direction if not magnitude, implying that demand management including irrigation efficiency improvements, deficit irrigation, and shifts to less water-intensive crops may be as important as supply-side investments. The spatial patterns of headwater surpluses and downstream deficits highlight the importance of considering water allocation and conveyance infrastructure, though costs and environmental impacts of expanded conveyance must be weighed against localized demand management, groundwater development, and water recycling. The concentration of deficits in agricultural areas raises questions about economic and social implications of water reallocation, emphasizing the need for understanding distributional consequences to develop equitable adaptation strategies.

The interannual variability and multi-year drought sequences projected under future scenarios present daunting challenges, as water systems designed on historical drought frequencies may prove inadequate, and cumulative deficits from multi-year droughts exhaust reservoir storage and groundwater reserves, causing supply failures that persist beyond drought periods. This suggests traditional single-year drought planning is insufficient and multi-year preparedness including enhanced storage, demand hardening, and contingency sources will be essential. The differential sectoral vulnerability reveals that municipal suppliers' higher reliability through priority rules and diversified portfolios protects public health but concentrates scarcity impacts on agricultural and environmental uses, with severe agricultural shortages threatening irrigated agriculture viability and environmental flow shortfalls potentially triggering regulatory responses that further constrain human uses, requiring adaptive governance frameworks capable of adjusting allocation rules and managing trade-offs while maintaining social welfare and ecosystem integrity. Preliminary adaptation scenario results suggest aggressive management could reduce deficits by 30 to 40 percent, though residual deficits remain, indicating that while adaptation can meaningfully reduce scarcity, it cannot fully offset combined effects under high emissions, reinforcing that greenhouse gas mitigation remains essential alongside local efforts.

5. Conclusion

This study demonstrates that climate change drives substantial alterations in watershed hydrology, with annual streamflow declining by 12.4 to 28.7 percent by end-century under moderate and high emissions scenarios while groundwater recharge decreases by 8.3 to 19.6 percent, and these supply reductions combine with increasing water demands across all sectors to create severe supply-demand imbalances, as ensemble mean annual deficits reach 34.7 million cubic meters under RCP8.5 by end-century representing 41.2 percent of total anthropogenic demand, with water stress indices indicating transition from moderate to severe stress conditions as supply reliability declines from 96.3 percent to 67.8 percent. Spatial analysis reveals water surplus in headwater regions and acute deficits in downstream agricultural areas, while seasonal analysis shows deficits concentrate during summer months when irrigation demands peak and streamflows reach minimum levels, with agricultural users experiencing severe curtailments while municipal suppliers maintain higher reliability and environmental flow requirements are frequently unmet. These findings underscore the need for integrated adaptation strategies including enhanced dry-season water storage, irrigation efficiency improvements, and equitable allocation frameworks, while the persistence of substantial deficits even under aggressive adaptation reinforces the critical importance of greenhouse gas mitigation alongside local and regional efforts, and the coupled modeling framework developed provides a transferable approach for informing science-based water policy and management as climate change continues to alter hydrological regimes worldwide.

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