

Water Stress Analysis Considering Climate Change Scenarios in Semi-Arid Regions Using WEAP Model

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Abstract

Water stress is defined as the condition in which the demand for freshwater in a given region persistently exceeds the water available to meet it, a challenge increasingly intensified by climate change, population growth, and land use change. Semi-arid regions such as Multan District in southern Punjab, Pakistan, are particularly vulnerable, already facing a documented baseline supply-demand deficit of 848.7 Mm³ (26%) even before future climate-driven pressures are applied, compounded by rapid urbanization, expanding water-intensive cropping patterns, and groundwater tables declining at 0.5–1 m per year. Prior studies applying the Water Evaluation and Planning (WEAP) model across Pakistan, South Asia, and comparable semi-arid basins worldwide have demonstrated its effectiveness in simulating sector-wise water demand and supply under socioeconomic and climate scenarios, while CMIP6-based assessments confirm that South Asia faces substantial additional warming under SSP pathways with direct implications for evapotranspiration and irrigation requirements; however, district-scale quantification of water stress for Multan integrating CMIP6 projections with land use change remains limited. This study addressed that gap by developing a WEAP model for Multan District, calibrated and validated using PEST against observed canal discharge and meteorological data (1990–2020), and driven by CMIP6 MRI-ESM2-0 projections under SSPs 1-2.6, SSPs 2-4.5, and SSPs 5-8.5 to simulate agricultural, domestic, and industrial water stress from 2015 to 2055. Results show total demand rising from 1,449.24 MCM in 2015 to 4,944.02 MCM by 2055, with total annual water stress reaching 38.2, 22.8, and 27.2 Mm³ under SSPs 1-2.6, SSPs 2-4.5, and SSPs 5-8.5 respectively by 2055. Agriculture drives water stress under moderate scenarios, while domestic water stress overtakes it under high-warming SSPs 5-8.5. The study concludes that Multan District's water stress is structurally pre-existing and will intensify under every climate pathway, requiring urgent, integrated, multi-sector water management interventions before 2035.

Keywords: Water stress; WEAP model; Climate change scenarios; Semi-arid regions; CMIP6; SSP pathways; Water demand-supply gap; Multan District; PEST calibration; Groundwater depletion

1 Introduction

Fresh water is the most important natural resource for human life, but it is under growing pressure from the population growth, farming, city growth, and climate change. Water stress happens when demand for clean, usable water is higher than what is available [1], [2]. In 2022, about half of the world's people faced severe water shortages for part of the year, and one quarter faced “extremely high” water stress, using more than 80% of their renewable water

[3]. The global water gap is now 457.9 km³ per year and could grow by 14.7 %under 3°C of warming [4]. Between 2002 and 2021, droughts affected more than 1.4billion people, costing over USD 307 billion a year [5]. Water use grew four times over the 20th century, and the number of people facing water shortage rose from 0.24 billion (14%) in the 1900s to 3.8 billion (58%) by the 2000s [6]. World water demand may grow 20-25% by 2050 [7], while water availability per person has dropped 7% over the last decade [8]. Farming uses about 72% of all

freshwater withdrawn worldwide, industry uses 19% and home use 11% (including drinking water) [2]. In Pakistan, water demand is rising by about 10% every year, and by 2025 the country may need 338 Km³ but have only 240-258 km³ available creating a serious gap [9]. Without strong action, dry regions like Multan District will likely face worse shortages. Population growth and urban growth are the main reasons water demand is rising in Multan and across Pakistan's population passed 240 million in 2023 and may reach about 350 million by 2050, needing far more water for food, sanitation and industry [10]. In Multan, urban areas grew by 49% between 2010 and 2020, which reduced farmland, changes the crops grown, and added pressure on water infrastructure [11]. Rice farming which needs 1500 mm of water per season, grew by 92% between 2010 and 2020, and sugarcane, which needs 2,100 mm, grew by 63% over same period [11]. These crop changes are a major reason the demand-supply gap is widening in this area. Semi-arid areas get less than 250-500 mm of rain a year and lose much water to evaporation, so they depend heavily on irrigation, water transfers and groundwater [12]. In dry and semi-dry areas, water shortage is now one of the biggest barriers to socials and economic development, especially in farming-based developing countries [13]. Pakistan is one of the most severely affected countries: water available per person fell from 5260 m³ in 1951 to about 800 m³ by 2025 [9]; [14]. Pakistan's water shortage caused by climate change, fast population growth, urban growth, industrial growth, unequal water sharing, and poor management [10]. The Indus Basin Irrigation System, which manages about 180 billion cubic meters of water across 16 billion hectares, is heavily affected. The number of tubewells grown 1,500% between 1975 and 2021, and groundwater now supplies 60% of farming, 90%

of household, and 100% of industrial needs far faster than it can be refilled [15]. Studies of similar Pakistani areas, such as the Hub River Basin, show climate change directly alters water resources by changing rainfall and weather patterns, with dry areas most at risk because of their reliance on rain and limited storage. Agriculture covers 81% (3721 km²) of Multan [16];[11] growing wheat, rice, cotton, sugarcane, other crops, and orchards, each with distinct seasonal water needs (480-2,100 mm) [17];[11]. In 2020, irrigation demand was 3,280.7 Mm³ against a supply of only 2,432 Mm³ a 848.7 Mm³ (26%) shortfall [11], already present before future climate driven demand is added. Groundwater fills the gap unsustainably: Multan's water table drops 0.5-1 m/year [18]. Punjab's Indus Basin aquifer is depleted 94 MCM/season beyond recharge [19] with agriculture responsible for 97% of Punjab's 60 million m³ annual groundwater use [11]; [15] and also causing salinity and contamination in shallow water table areas [15]. Multan semi-arid climate brings extreme seasonal stress. May averages 42°C (up to 47 °C) [16], summer humidity falls below 18%, and rainfall averages only 170 mm/years, 75% concentrated in the August-September monsoon. A 1.1°C rise (1990-2020) [20] is consistent with CMIP6 projections of 1.2°C to 4.3 °C further warming for South Asia by century's end [21]. Multan is supplied by the Sudhnai Canal which is sourced from Ravi River via four branch canals [11]. Total 2020 canal supply was 1,866.9 Mm³ and rainfall supply 565.1 Mm³ [11]; seasonal canals provide no winter water, limiting Rabi crops. Multan's soils mostly sandy loam and sandy clay loam are shallow with low organic matter, increasing irrigation dependency [22]. The Sidhnai Canal and the broader Punjab canal network were established under British colonial administration from the late 19th century, transforming semi-arid land into productive

farmland. The 1947 partition splits Punjab canal system; the 1960 Indus Water Treaty gave Pakistan the Chenab River as Multan's main source. The Green Revolution (1960s-70s) raised both output and water demand through water-intensive crops and tubewells expansion, and per capita availability began its long decline from 5,260 m³ (1951) as tubewells grew 1500% (1975-2021) [15]. Population grew from 85 million 1981 to 132 million 1998. Water body area fell 7.5% in 1990-2020 from urban growth [11], while canal efficiency declined through seepage losses (30-40%), unequal head-tail distribution and water logging/salinity from over extraction compounding a national demand growth rate of 10%/year [9]. In 1999-2002 drought accelerated groundwater over-extraction, and by 2010 Pakistan's per person availability fell below the 1,000 m³ scarcity threshold [9]. Between 2010 and 2020, Multan rice grew 92%, sugarcane 63%, while cotton fell 24%, orchards 47% [11], sharply raising water use per unit of land; 788 m³ of water losses occurred as land use shifted toward urban areas [25]. Today Multan's documented irrigation gap stands at 848.7 Mm³ of 26% [11], with groundwater still declining 0.5 to 1 m/year [18]. Addressing this requires stronger institutions, better regulation, participatory irrigation management, and improved farm-level water productivity practices. Both surface and ground water are necessary and have created a difficult network of dependency and interdependencies, where extraction and infrastructure deficiencies have led to current water shortages. In addition, these issues are exacerbated by the increasing effects of climate change that continue to influence water demand and supply in these areas. The study area is situated in a semi-arid area with much less rain than other areas, and therefore limited natural water resources. Meanwhile, the rapid urbanization and population growth have significantly raised

water demand, especially in dense urban areas. The overall water unbalance between limited water resources and growing demands has serious physical water stress, resulting in water scarcity that is impacting the local population and putting more pressure on sustainable water resource management.

2 Literature Review

The water stress and water scarcity thresholds are based on previous studies by Falkenmark (1989). [6] reported that population went up by 3.8 billion at 58% and the number of people who are "severely scarce" rose from 0.24 billion at 14% to 2 billion of 54%. By 2025, almost one in three of the world's population could be at risk of scarcity [27][13]. According to [1] 25 countries a quarter of the world's population experience very high stress; [7] predicts demand growth of 20-35% by 2055. Semi-arid areas having less than <250 mm rainfall, high evapotranspiration, monsoon concentrated rain, irrigation dependent [12] have severe development constraints [13] as is evident in the Bundelkhand region of India low yields, low rain water efficiency, limited water [13]; [28]. Three common drivers are identified: Population growth is the primary structural driver. [29] documented that population-driven growth in water allocation must balance equity, efficiency, and sustainability across sectors; their optimal allocation study for China's Heihe River Basin confirmed that population-driven demand increases create structural imbalances without integrated management. [30] and [31] confirmed that water stress in Bundelkhand is directly linked to population growth and poor infrastructure, themes directly applicable to Multan District. In Pakistan, water demand grows at 10% per year and is projected to reach 338 km³ against availability of 240–258 km³ by 2025 [9], creating a structural supply deficit that mirrors the Dhasan River Basin's trajectory of accelerating water stress which can cause of unmet demand. Agricultural water demand and

cropping pattern shifts are the dominant mechanisms in semi-arid agrarian economies. [32] studied sustainable exploitation of groundwater resources under climate change and land use change, finding that irrigation demands are the primary driver of aquifer depletion in semi-arid regions. [33] projected agricultural water stress for climate change scenarios in Iraq, a comparable semi-arid context, finding that changing crop water requirements under warming scenarios significantly widen the demand-supply gap. In Multan District, the planting area for rice 1,500 mm/season increased by 92% and sugarcane 2,100 mm/season by 63% from 2010 to 2020, producing a documented annual irrigation demand-supply gap of 848.7 Mm³ of 26% shortfall [11]. [34] confirmed that crop water requirements across Pakistan's semi-arid zones are projected to rise 8–14% under SSP5-8.5, with arid zones exhibiting the largest absolute gaps. Climate change amplifies both demand and reduces supply reliability. [27] documented that land use and land cover changes in Ghana's Pra River Basin from 1986 to 2025 significantly affected water balance components, confirming the dual role of LULC change and climate variability in reducing water availability. [35] quantified uncertainty of climate change impacts on crop characteristics in Iran, finding that higher emission scenarios produce substantially greater increases in crop water requirements a finding directly applicable to the present study's SSP scenario analysis for Multan. In Multan, temperatures have already increased by 1.1°C over 30 years 1990–2020, increasing evapotranspiration and driving irrigation demand upward [20]. [36] confirmed that conventional surface irrigation in Southern Punjab wastes water, and that drip irrigation is urgently needed to reduce climate-driven ET losses.

The development of integrated water resource modelling tools has proceeded alongside the recognition of water scarcity as a global challenge. Early river basin models focused on

supply-side management and optimal allocation under steady-state conditions. The Soil and Water Assessment Tool (SWAT), developed by Arnold at 1998, enabled watershed-scale modelling of water quality and quantity and was widely applied across South Asia and Africa [41]. [42] demonstrated comparative SWAT performance assessment across two distinct catchments under various DEM scenarios, validating its capability for regional-scale water balance analysis. [43] applied SWAT to a semi-arid basin in Morocco M'dez watershed, providing a directly comparable application context to the present study. [44] applied SWAT to the Dehbar River Basin in Iran to quantify climate change impact uncertainty on discharge and sediment yield. The MODSIM decision support system Labadie, 1995 addressed long-term river basin planning and management. System Dynamics (SD) models captured non-linear demand-supply performances [45]; [46]. DUWSiM enabled long-term urban water demand and supply analysis [47], and [48] applied artificial intelligence techniques for urban water resource management for sustainable environment planning, confirming the growing role of AI in augmenting hydrological models. Despite these diverse tools, the spatial multi-sector water balance requirements of the present study covering agricultural, industrial, and domestic demand across an entire district under multiple climate pathways are most effectively addressed by the WEAP model. [49] confirmed that river basin management plans integrated with models like WEAP provide the most effective tool for sustainable transboundary water management, combining equity, efficiency, and sustainability in water allocation. [33] confirmed WEAP's effectiveness for projecting agricultural water stress under climate change scenarios in a comparable developing-country semi-arid context. A recent review of machine learning and WEAP models for water allocation under climate change confirmed WEAP remains the most scalable and reliable tool for scenario-

based water planning, with ML integration offering potential accuracy improvements. Both surface and ground water are necessary and have created a difficult network of dependency and interdependencies, where extraction and infrastructure deficiencies have led to current water shortages. In addition, these issues are exacerbated by the increasing effects of climate change that continue to influence water demand and supply in these areas. The study area is situated in a semi-arid area with much less rain than other areas, and therefore limited natural water resources. Meanwhile, the rapid urbanization and population growth have

3 Methodology

The initial phase of the research process included the downloading, processing and analysis of two geospatial datasets: (i) Land Use Land Cover (LULC) and (ii) Digital Elevation Model (DEM), both acquired from ArcGIS 10.8 (ESRI Inc., USA). Combined, these layers provided spatial basis to define the WEAP schematic model, to define the catchment boundaries, to characterize the soil hydrological properties, and to map the irrigation canal and drainage system across Multan District. Multan District, located in the southern Punjab province of Pakistan, constitutes the primary study area for this investigation (Figure 1). The district is geographically positioned between latitudes 29°22'N and 30°55'N and longitudes 71°25'E and 72°01'E, encompassing a total land area of

The district was selected as the study area based on five explicit hydrological and data-availability criteria:

- (i) An independently verified baseline irrigation demand-supply gap of 848.7 Mm³/year 26% structural shortfall documented by [11] for 2020 using remote sensing;
- (ii) Extreme semi-arid climate vulnerability with documented 1.1°C

significantly raised water demand, especially in dense urban areas. The overall water unbalance between limited water resources and growing demands has serious physical water stress, resulting in water scarcity that is impacting the local population and putting more pressure on sustainable water resource management

The paper aims to analyze climate change's impact on water availability and demand in semi-arid regions, focusing on how changing by socioeconomic and land use scenarios can affect the water demand and supply.

approximately 3,721 km², of which approximately 81% is under active agricultural cultivation. The district is administered through four tehsils: Multan City, Multan Saddar, Shujabad, and Jalalpur Pirwala. Multan is bounded by Khanewal District to the north-east, Vehari District to the east, Lodhran District to the south, and the Chenab River on its western flank, across which lies Muzaffargarh District [11]. Situated at the heart of the Indus Basin Irrigation System (IBIS) the largest contiguous canal irrigation network in the world, distributing approximately 180 BCM annually across 16 million hectares and sustaining over 54% of Pakistan's agriculture-dependent population [10]. Multan District represents one of the most hydrologically critical yet severely water-stressed sub-regions of South Asia.

- warming and 2.2 mm rainfall decline over 1990–2020;
- (iii) Complete absence of within-district seasonal water storage infrastructure;
- (iv) An unsustainable groundwater depletion rate of 0.5–1.0 m/year;
- (v) Availability of the long-term hydro-meteorological, canal discharge, satellite LULC, demographic, and CMIP6 datasets required to fully

- (vi) construct and validate the WEAP model.

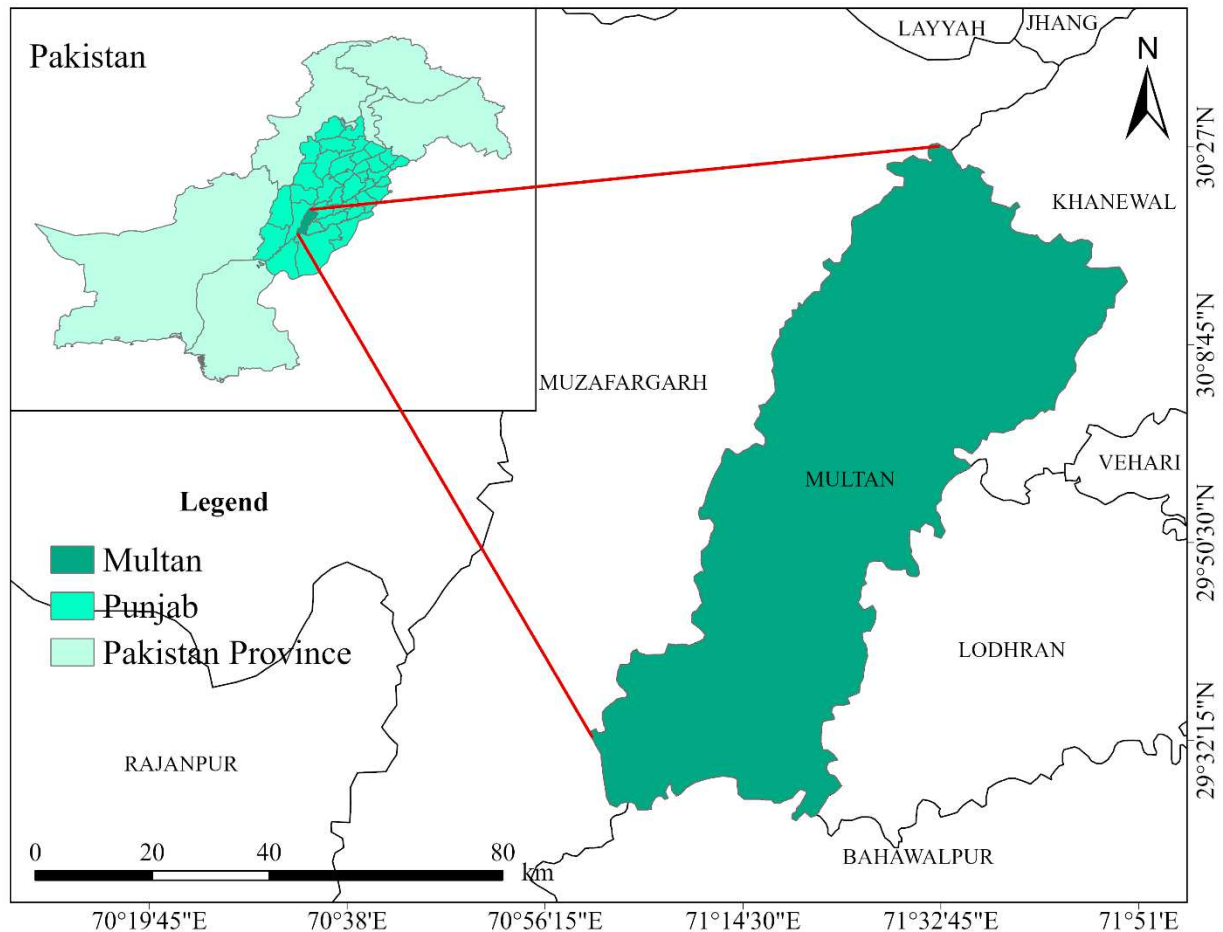


Figure 1. Study area map of Multan District, Punjab, Pakistan, located in the semi-arid Indus Basin and characterized by intensive irrigated agriculture, low rainfall, and increasing water stress, making it a representative region for water resource assessment

Hydrological data relevant to the study area were then compiled and integrated into the framework, after which the various components of the water system were digitized as individual WEAP elements within the model. This stage concluded with the preparation of water demand data, which fed directly into the model development process. In parallel, meteorological data consisting of temperature and precipitation records were collected and processed, providing the climatic inputs required to

characterize present and future water availability conditions. Alongside this, demand-side data were gathered, covering population figures and water use rates, agricultural water requirements, and industrial development trends, which together defined the consumption side of the water balance. All three data streams the GIS-based spatial and hydrological data, the meteorological data, and the demand data converged at the central stage of the methodology, where the WEAP (Water

Evaluation and Planning) model was developed. This model integrated the spatial, climatic, and demand information into a unified framework capable of simulating the water system of the study area. Once the WEAP model was established, a scenario development phase was carried out to project future conditions. This involved incorporating Shared Socioeconomic Pathways (SSPs) under the CMIP6 climate framework, along with projected changes in temperature and precipitation, allowing the model to simulate how climate change and

socioeconomic shifts might alter future water dynamics as shown in the (Figure 2) These scenarios were fed back into the WEAP model to refine and update its outputs. The methodology concluded with the generation of the main outputs of the study, namely the total water demand, the unmet water demand, and a comparative analysis of water demand across the different scenarios, providing a comprehensive picture of current and future water stress in the study area.

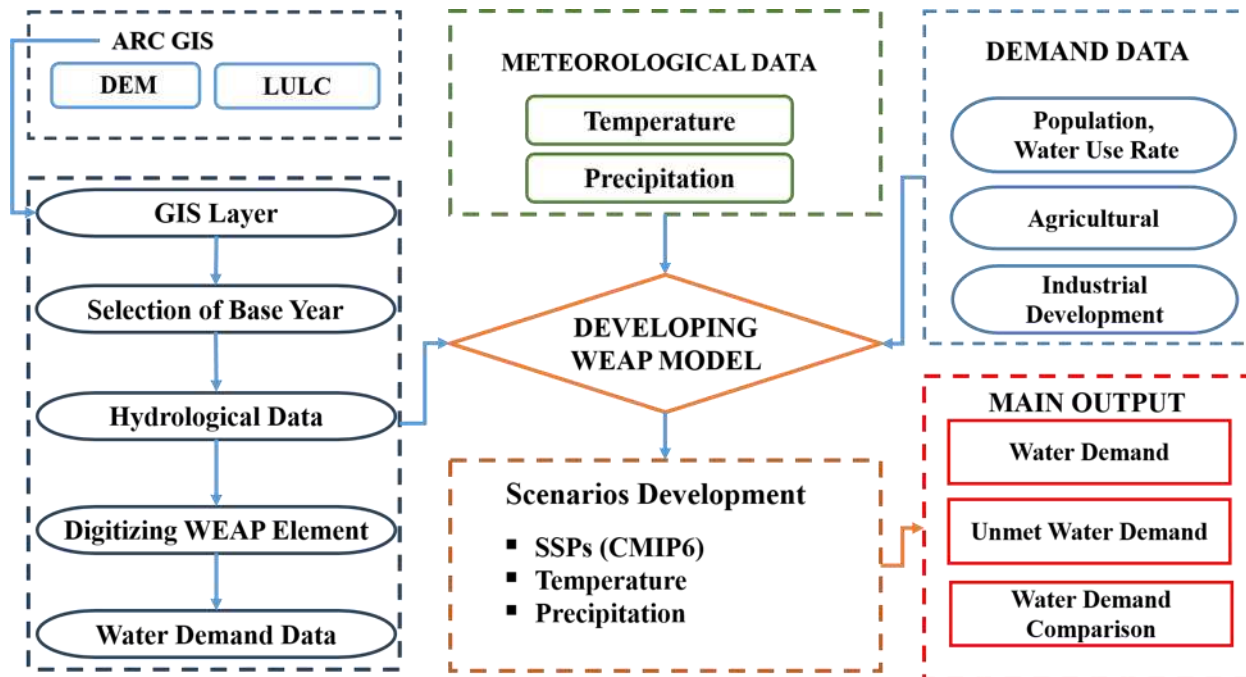


Figure 2. Flowchart of the research methodology adopted for water stress assessment in Multan District, Pakistan, illustrating data acquisition, climate scenario analysis, WEAP model development, calibration, validation, and future water resource assessment under climate change scenarios

The research methodology followed a structured, multi-stage workflow, as illustrated in the flowchart. The process began with the acquisition and processing of geospatial data in ArcGIS, where a Land Use Land Cover (LULC) data were obtained and prepared as the foundational spatial layers for the study area as shown in (Figure 3) and a Digital Elevation

Model (DEM) as shown in (Figure 4). These processed layers were then organized into a GIS layer, which served as the spatial reference for the subsequent modelling steps. Following this, the base year for the study was selected to establish the reference point against which future scenarios would later be compared

Land Use/Land Cover Multan

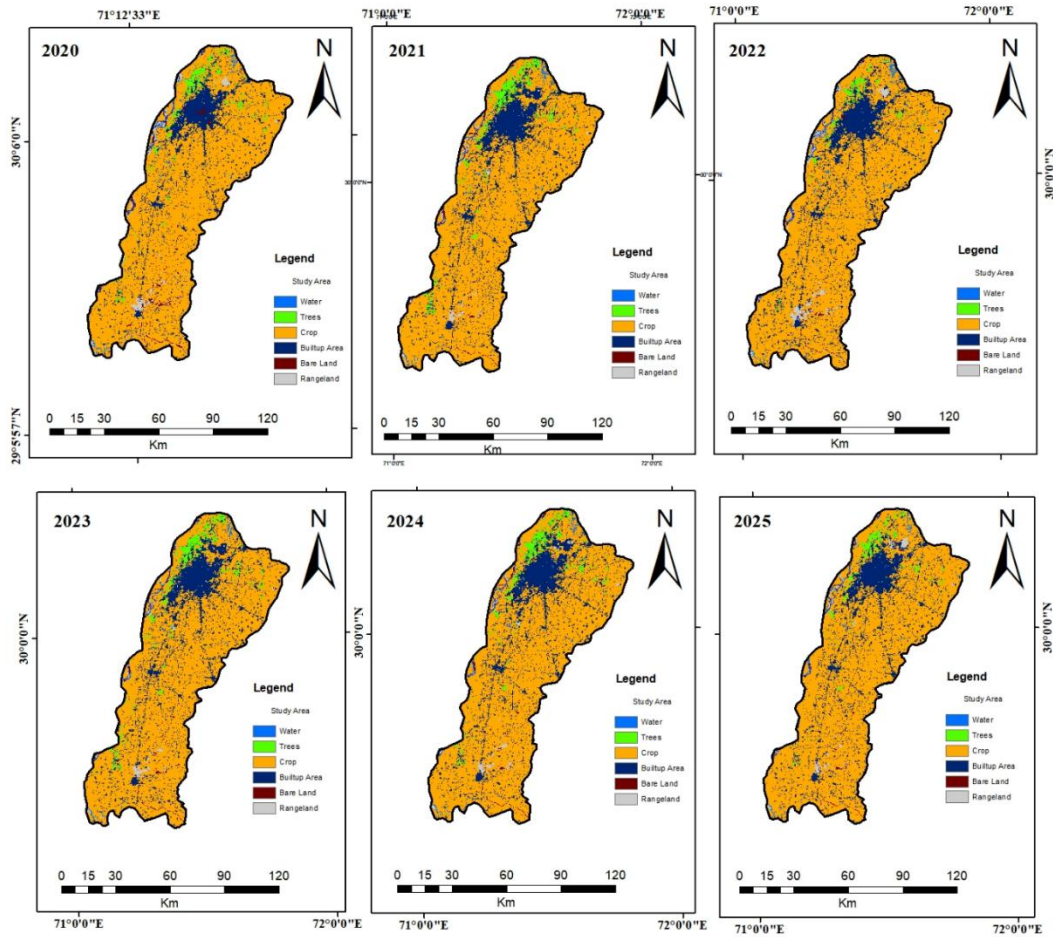


Figure 3. Land use/land cover (LULC) maps of Multan District, Punjab, Pakistan, showing the annual spatial distribution of major land use classes and their temporal changes from 2020 to 2025

Multan District is classified under the Koppen-Geiger climate system as BWH hot desert climate, with transitional BWK characteristics during winter months. This classification places the district within the most thermally and hydrologically extreme zone of South Asia, characterized structurally by annual precipitation well below potential evapotranspiration the defining condition of persistent water stress irrespective of interannual variability. Mean annual precipitation, based on 30-year records (1990–2020) at the Pakistan Meteorological Department (PMD) Multan synoptic Station No. 47043; WMO WIGOS ID

0-401-0-47043 and the supplementary agro-meteorological station at Bahauddin Zakariya University (BZU), Multan, is approximately 170–186 mm/year. The temporal distribution of rainfall is severely concentrated: approximately 75% falls within a narrow August–September monsoon window, a further 12% arrives in June–July as pre-monsoon thunderstorms, and the remaining 13% falls as scattered western disturbance-driven winter events from December to February [11]. This concentration implies that crop water requirements during the remaining 10 months about the full Rabi wheat season October–April and the early Kharif crop

establishment window April June must be met almost entirely through canal irrigation and

groundwater extraction, with negligible effective rainfall contribution.

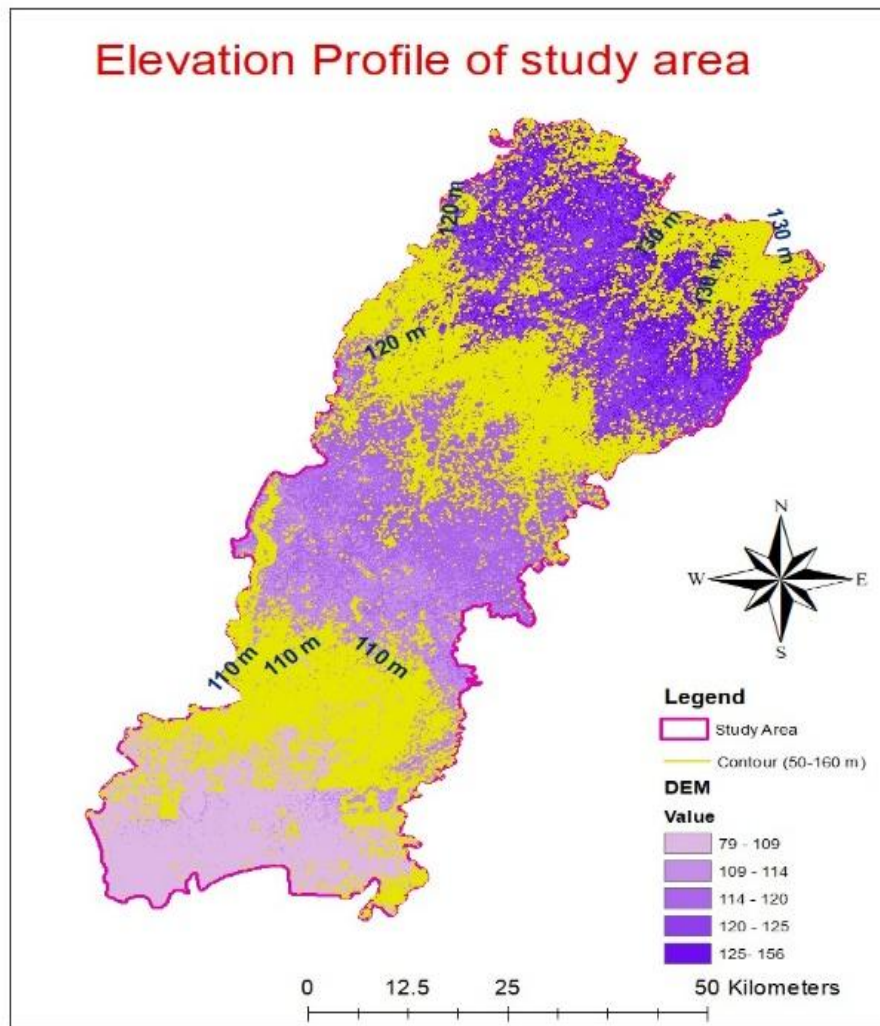


Figure 4. Digital Elevation Model (DEM) of Multan District, Punjab, Pakistan, showing the spatial distribution of elevation ranging from 79 to 156 m above mean sea level (AMSL), providing topographic information for hydrological and water resource assessment.

Seasonal temperature variability is extreme. Mean daily maximum temperatures peak at 47°C in May to June, with the summer period April October consistently exceeding 40°C mean daily maximum. Winter minimum temperatures fall to 4.8°C, with a mean daily maximum of approximately 23.4°C from November to February [70]. These background climate conditions are further complicated by documented long-term trends: the mean annual temperature in Multan has increased by 1.1°C over 1990–2020, while mean annual rainfall has

decreased by 2.2 mm, confirming that anthropogenic climate change is already manifesting at the local scale [20]. The quantified baseline water balance for 2020 is as follows [11]. Total irrigation demand = 3,280.7 Mm³/yr; Total supply from canals = 1,866.9 Mm³/yr; effective rainfall contribution = 565.1 Mm³/yr; total supply = 2,432.0 Mm³/yr; resulting annual demand-supply gap = 848.7 Mm³ (26.0% structural shortfall). This independently documented and rigorously quantified baseline gap established through

remote sensing, GIS, and irrigation equation analysis by [11] provides the essential cross validation anchor for the WEAP model

Data collection:

Meteorological data were obtained from the PMD Multan Synoptic Station (WMO No. 47043) and the BZU agro-meteorological station, covering 2015–2025 (10 years) at daily resolution. Variables included mean/max/min temperature, precipitation, relative humidity values. Geospatial data (LULC and DEM layers) were obtained and processed in ArcGIS 10.8, with cropping-pattern data (2010–2020) validated against Regional Agriculture Department records. Hydrological and canal data were obtained from the Punjab Irrigation

Department, covering discharge records for the Sidhnai Canal and its four branch canals (Table 1). Water demand data were sourced from the Regional Agriculture Department, Punjab Irrigation Department records, and district population statistics, covering domestic, agricultural, and industrial water use. Climate scenario data were obtained from the CMIP6 MRI-ESM2-0 model outputs under SSP1-2.6, SSP2-4.5, and SSP5-8.5 for the 2016–2055 period.

Table 1: Details of the selected irrigation canal branches in the study area, including canal hierarchy, flow regime, command area (acres), and assigned discharge (cusecs), used as input for the WEAP model.

Main Canal	Branch Canal	Location	Flow type	Command Area (Acres)	Assign Discharge (Cusecs)
Sidnahi	Shujabad Br.	Head	Non-Perennial	8270.38	1918
Sidnahi-Shujabad	Gujju Hatta Br.	Tail	Non-Perennial	3962.42	700
Sidnahi	Multan Br.	Head	Perennial	9276	775
Sidnahi	Makhdoom Rashid Br.	Head	Perennial	3509	425

Between 2010 and 2020, Multan District experienced substantial shifts in land use and cropping patterns that directly amplified water demand. Documented the following LULC changes using Landsat satellite classification: rice planting area increased by 92% (22,700 ha → 43,600 ha); sugarcane area increased by 63%; urban settlement expanded by 49% (93,400 ha → 139,200 ha); cotton declined by 24%; and orchards declined by 47%. The net effect of these shifts on water demand is strongly positive: rice water requirement 1,500 mm/season requires 2.1 times more water than

cotton 700 mm and 3.1 times more than wheat 480 mm per hectare per season; sugarcane 2,100 mm annually requires 4.4 times more than wheat. The 49% urban expansion has simultaneously increased impervious surface coverage, reduced local rainfall infiltration and groundwater recharge while rapidly expanded domestic water demand. This interacting driver agricultural intensification in water-demanding crops, urban expansion, and a declining canal-groundwater supply system represent the structural dynamic that the WEAP model must accurately capture and project forward to 2055.

Population in Multan District was 4.73 million in the 1998 census PBS, 2000, 7.17 million in the 2017 census PBS, 2017, and approximately 8.93 million in the 2023 census PBS, 2023, implying a compound annual growth rate of 2.61% over the 1998–2017 period. The National Drinking Water Policy 2009 defines safe per capita water access at 120 litres per person per day in urban areas; however, per capita water availability in Pakistan has declined from 5,600 m³/person/yr in 1951 to below 1,000 m³/person/yr in 2018, representing a transition from water abundance to absolute water scarcity [9]. For Multan District specifically, the rapid population growth documented above, combined with rising per capita water use associated with urbanization and improved living standards, means that domestic water demand is projected to grow continuously and non-linearly from 2015 to 2055 a trajectory fully incorporated into the WEAP model's domestic demand node. The research design adopted a structured, sequential, four-phase methodological framework explicitly aligned with the objectives of quantifying sector-specific (agricultural, industrial, and domestic) water demand, supply, and unmet demand gaps for Multan District under three CMIP6 SSP climate scenarios from 2015 to 2055. The

framework builds upon and extends the integrated WEAP methodology developed by [13] for the Dhasan River Basin, India, by addressing that study's explicitly acknowledged limitation: the unavailability of CMIP6 data for climate scenario construction. All four phases are methodologically interdependent the verified output of each phase constitutes the primary input to the next ensuring that no scenario output is generated from an unvalidated model.

The Water Evaluation and Planning (WEAP) model, version 2023 Stockholm Environment Institute, Boston, USA, was employed as the integrated water resource modelling platform. WEAP applies monthly water balance accounting within a demand-, priority-, and preference-driven framework: water is allocated from available supply sources to demand nodes in order of pre-assigned priorities until all supplies are exhausted or all demands are fully satisfied ([13], [50], [51]. Unmet demand the difference between water required at a demand node and water actually delivered is computed at each time step for each node and each scenario as a (Figure 5) shown. The WEAP model for Multan District was built using the five standard WEAP interface views:

- (1) Schematic (spatial layout, node placement, and link definition)
- (2) Data (input parameters organized under Key Assumptions, Demand Sites, Hydrology, Supply and Resources, Environment, and Other)
- (3) Results (time-series output charts and tabular data)
- (4) Scenario Explorer (comparative multi-scenario graphical analysis)
- (5) Notes (documentation and assumption recording).

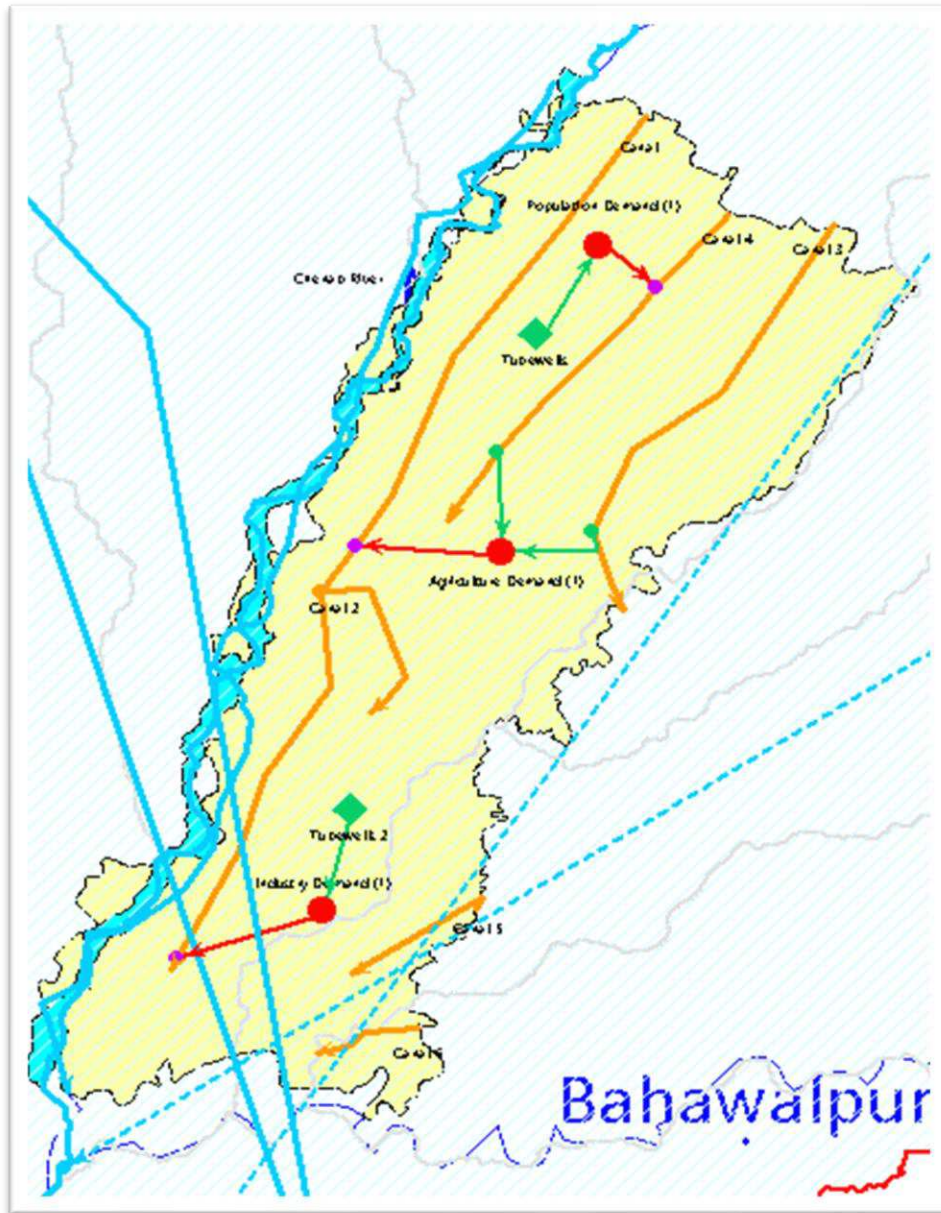


Figure 5. WEAP model framework developed for Multan District, Punjab, Pakistan, showing the spatial representation of the river network, irrigation canals, demand sites, transmission links, and water allocation components used to simulate present and future water resource conditions under climate change scenarios.

A total of four WEAP scenarios were constructed: one Reference Scenario and three CMIP6 SSP climate change scenarios. The year 2015 was designated as the base (current account) year, initialized with all observed 2015 datasets. The Reference Scenario (2016–2055) projected forward from the 2015 baseline without any climate modification: population growth at CAGR 2.61%; agricultural area

evolving at 2010–2020 LULC trend rates (rice +7.5%/yr, sugarcane +4.8%/yr, urban +3.8%/yr, cotton –2.1%/yr, orchards –3.9%/yr); industrial water use growing at subsector-specific rates; and historical monthly climate patterns repeated without alteration. The Reference Scenario provides the no-climate-change counter-factual, enabling isolation of the climate change signal in the SSP scenarios as shown in (Table 2)

Table 2: Summary of the reference and CMIP6 climate scenarios used in the WEAP model, including SSP-RCP pathways, physical basis, projected temperature increases over Pakistan by 2055, monsoon precipitation trends, and bias-corrected climate forcing inputs

Scenario	SSP-RCP Pathway	Physical Basis	Projected T Increase over Pakistan by 2055 (°C, above 1986–2005)	Monsoon Precipitation Trend	WEAP Climate Forcing Applied
Reference	None (historical climate repeated)	No climate change; business-as-usual socioeconomics	0.0°C (historical patterns)	Historical variability repeated	Historical 1990–2020 monthly T and P mean repeated
SSP1-2.6	SSP1 + RCP2.6	Strong mitigation; sustainability-focused development; stabilization at $\sim 2.6 \text{ W m}^{-2}$ by 2100	$\sim +0.5$ to $+0.8^\circ\text{C}$	Near-historical pattern with modest increase	Bias-corrected MRI-ESM2-0 SSP1-2.6: monthly T and P 2016–2055
SSP2-4.5	SSP2 + RCP4.5	Moderate mitigation; "middle of the road" development; stabilization at $\sim 4.5 \text{ W m}^{-2}$ by 2100	$\sim +1.0$ to $+1.2^\circ\text{C}$	Slight increase with greater interannual variability	Bias-corrected MRI-ESM2-0 SSP2-4.5: monthly T and P 2016–2055
SSP 5-8.5	SSP5 + RCP8.5	Fossil-fuel intensive; highest emissions; $\sim 8.5 \text{ W m}^{-2}$ by 2100	$\sim +2.0$ to $+2.5^\circ\text{C}$	Most variable; extreme events intensified; monsoon onset delayed	Bias-corrected MRI-ESM2-0 SSP5-8.5: monthly T and P 2016–2055

For all three SSP scenarios, socioeconomic growth driver population CAGR, industrial expansion rates, and crop area trend rates were held identical to the Reference Scenario values. This design ensures that any difference in simulated water demand, supply delivery, or unmet demand between an SSP scenario and the Reference Scenario is attributable exclusively to the differing climate forcing, enabling direct and statistic. The WEAP model was calibrated for the 48-month period January 2015 to December

2018 against observed monthly canal discharge values at all four Sidhnai branch canal head structures simultaneously 192 data points total across four branches. The Parameter Estimation Tool (PEST) directly interfaced with the WEAP model was used to automate parameter adjustment using the Gauss-Marquardt-Levenberg (GML) iterative algorithm, which linearizes the parameter space at each iteration step and minimizes the weighted sum of squared

residual's objective function (Φ) between modelled and observed canal discharge.

$$\Phi = \sum_i w_i (Q_{obs,i} - Q_{sim,i})^2 \quad (1)$$

(PEST Objective Function Weighted Sum of Squared Residual, [51])

where Φ is the scalar objective function minimized by PEST; w_i the weight assigned to observation i (equal weights $w_i = 1.0$ applied throughout; all four canal branches weighted equally); $Q_{obs,i}$ is the PID-recorded monthly

canal discharge ($m^3 s^{-1}$) at time step i ; and $Q_{sim,i}$ is the WEAP-simulated monthly canal discharge. PEST was configured with: maximum of 150 model runs per iteration cycle; convergence criterion $\Phi < 0.01\%$ change between successive iterations; SVD-assisted regularization to prevent parameter non-uniqueness for highly correlated parameters (canal seepage fraction and return flow coefficient).

Model Calibration and Validation Performance

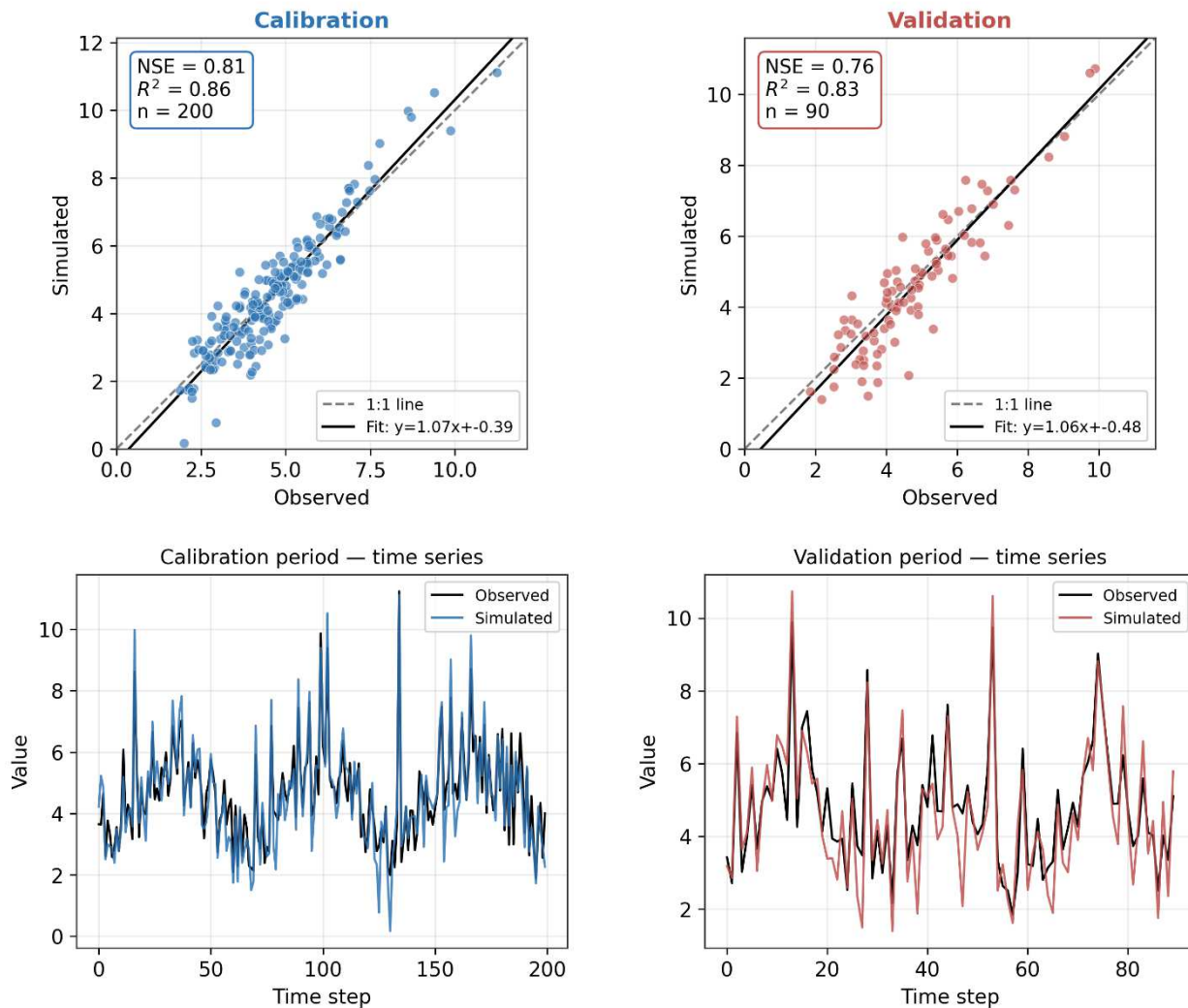


Figure 6. Calibration and validation performance of the WEAP model for the study area, illustrating the agreement between observed and simulated values through scatter plots, time-series comparisons, and model performance statistics (NSE and R^2), demonstrating satisfactory model accuracy and reliability.

Following completion of PEST calibration, the model was validated against an independent 24-month dataset (January 2019 – December 2020; 96 data points across four branches) withheld entirely from the calibration process. The calibrated parameter set derived from Phase 4 calibration was applied unchanged to the validation period, and WEAP was run forward from 2015 using the validated parameterization. Performance was evaluated using three standard statistical metrics widely adopted for monthly water balance model evaluation.

$$NSE = 1 - [\Sigma(Q_{obs} - Q_{sim})^2 / \Sigma(Q_{obs} - \bar{Q}_{obs})^2] \quad (2)$$

(Nash-Sutcliffe Efficiency; Nash & Sutcliffe, 1970; rating thresholds)

$$R^2 = \{\Sigma[(Q_{obs} - \bar{Q}_{obs})(Q_{sim} - \bar{Q}_{sim})]\}^2 / \{\Sigma(Q_{obs} - \bar{Q}_{obs})^2 \times \Sigma(Q_{sim} - \bar{Q}_{sim})^2\} \quad (3)$$

Table 3: Calibration and validation performance metrics, including Nash–Sutcliffe Efficiency (NSE), coefficient of determination (R^2), and percent bias (PBIAS), together with their evaluation criteria, target values, and published benchmarks used for assessing the WEAP model performance.

Metric	Equation	Optimal Value	Moriasi et al. (2007) Rating Classification	Target for This Study (All 4 Branches, Both Periods)	Comparable Published Pakistan WEAP Benchmark
NSE	Eq. 4.6	1.0	Very Good: ≥ 0.80 ; Good: 0.70–0.80; Satisfactory: 0.50–0.70; Unsatisfactory: < 0.50	≥ 0.75	[10]: NSE = 0.80–0.98 (Rechna Doab canals); Khan et al. (2026): NSE ≥ 0.80 (UJC + LJC)
R^2	Eq. 4.7	1.0	Very Good: > 0.85 ; Good: 0.70–0.85; general hydrology standard	≥ 0.82	[14]: $R^2 = 0.82$ –0.96 (Upper Indus Basin WEAP, 5 sub-catchments)
PBIAS (%)	Eq. 4.8	0.0%	Very Good: $\pm 10\%$; Good: $\pm 15\%$; Satisfactory: $\pm 25\%$	Within $\pm 15\%$ (Good or better)	Khan et al. (2026): PBIAS $\leq \pm 10\%$ (UJC and LJC Punjab canal commands)

A third and independent layer of model verification was implemented through cross-validation of the WEAP model's agricultural water supply and demand outputs against the remote sensing-based quantification by [11].

(Coefficient of Determination Pearson Product-Moment Squared Correlation)

$$PBIAS = [\Sigma(Q_{obs} - Q_{sim}) / \Sigma Q_{obs}] \times 100 (\%) \quad (4)$$

(Percent Bias; positive = model underestimation; negative = overestimation)

The performance criteria and their rating thresholds, study-specific targets, and literature benchmarks from comparable Punjab/South Asia WEAP applications are summarized in (Table 3) Achieving $NSE \geq 0.75$, $R^2 \geq 0.82$, and PBIAS within $\pm 15\%$ for all four branch canals in both calibration and validation periods was set as the minimum acceptable model performance threshold, consistent with the 'good' to 'very good' rating classifications and the performance achieved by [10] for comparable Punjab canal WEAP applications.

That study used an entirely independent methodology Landsat satellite classification combined with GIS-based irrigation equation analysis to quantify crop-specific annual irrigation water demand and canal supply for

Multan District for 2020. The following reference values from [11] were adopted as cross-validation targets.

The monthly average agriculture demand in which water is delivered to the agriculture sector through the water source as shown in (Figure 7). In which demand is growing to increase in

March because in this monthly the sowing season of some crops is start and in April the demand is very less because the water use is very less because of the harvesting season of the Wheat crop. However, in December the water demand is negligible because there is no demand of the agriculture in this month.

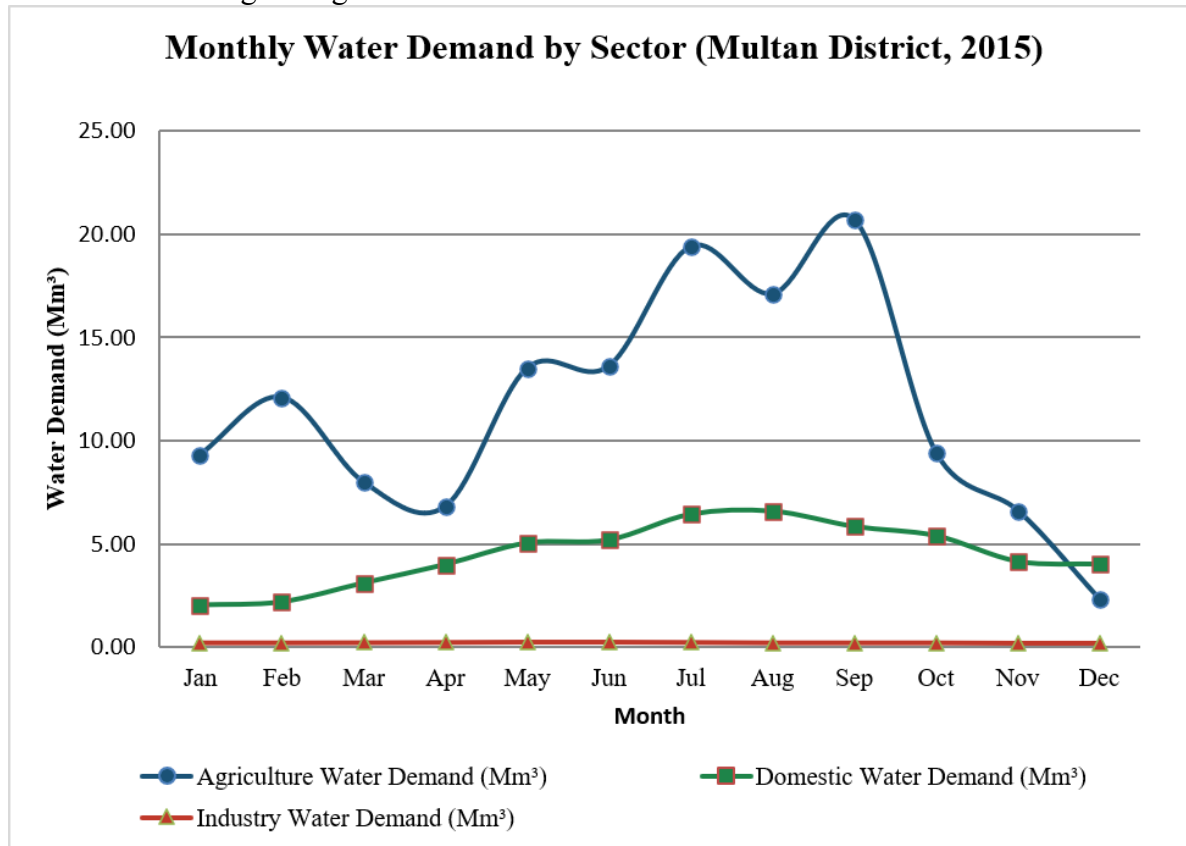


Figure 7. Sector wise monthly water demand in Multan District during the baseline year (2015), illustrating the seasonal variation in agricultural, domestic, and industrial water demands simulated using the WEAP model.

The monthly water demand analysis for Multan District (2015) shows distinct sectoral differences in both magnitude and seasonal variability in (Figure 7). Agricultural demand dominated the total water budget, ranging from 2.3 Mm³ at December to a maximum of 20.7 Mm³ at September, with a bimodal seasonal pattern: a secondary peak in July to August 17.1–19.4 Mm³ coinciding with peak Kharif-season irrigation requirements, and a minimum in April 6.8 Mm³ corresponding to the post-Rabi harvest period. Domestic demand displayed a unimodal seasonal trend, rising from 2.0 Mm³ in

January to a peak of 6.6 Mm³ in August, consistent with increased household consumption during peak summer temperatures, before declining to 4.0 Mm³ in December. Industrial demand remained effectively constant 0.1–0.2 Mm³ across all months, indicating negligible seasonal dependence and confirming that industrial water use in the district is driven by process requirements rather than climatic factors. These results indicate that agriculture accounts for the majority of both total demand and seasonal variability in the district's water system, domestic demand contributes a

secondary, moderate seasonal signal, and industrial demand represents a minor,

temporally stable component of overall consumption.

4 Analysis and results

The WEAP model, driven by CMIP6 MRI-ESM2-0 climate projections and calibrated against observed canal discharge data for the four Sidhnai branch canals serving Multan District, generated a comprehensive suite of outputs covering monthly and annual water demand, supply delivery, and unmet demand across three sectors agriculture, domestic (population), and industry for the 40-year simulation period 2015 to 2055 under one Reference Scenario and three SSPs climate pathways. This section presents and interprets these results in a logical sequence, moving from baseline seasonal demand characterization, through annual demand trajectories, to future water stress under CMIP6 scenarios, and

culminating in a cross-scenario comparative assessment. All quantitative outputs are expressed in million cubic meters (MCM) or million cubic meters cubed (Mm^3) as applicable, and are interpreted in the context of the study's objective of quantifying how climate change and intersecting socioeconomic and land use change scenarios jointly govern future water stress in a critically water-scarce semi-arid district.

The domestic water demand for the base year reference scenarios was 94.31 million cubic meters (MCM); however, it has been increased to 349.09 MCM by 2055 as given in (Figure 8). The results indicate that the domestic demand increase in the reference scenario.

Annual water supply and demand in the domestic sector, 2015–2055

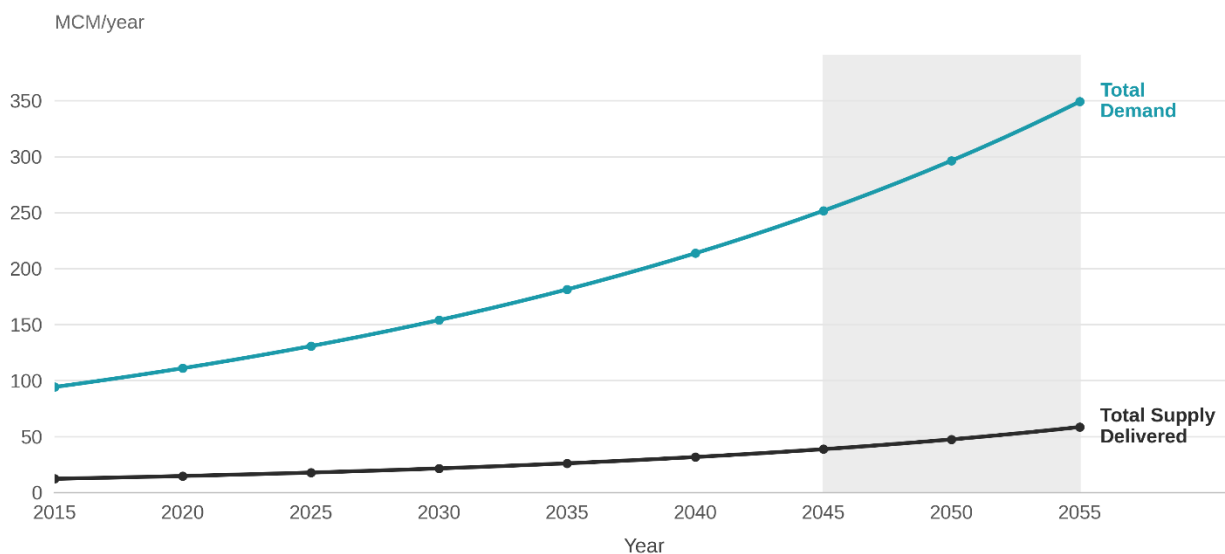


Figure 8. Projected population water demand and annual domestic water supply delivered in Multan District during 2015–2055, illustrating long-term trends in domestic water demand and water supply simulated using the WEAP model.

Domestic water demand displays a unimodal seasonal trend, rising progressively from 2.03 Mm^3 in January to a single peak of 6.60 Mm^3 in

August, before declining to 4.02 Mm^3 in December. This summer elevation is physically driven by increased per capita water

consumption for drinking, hygiene, and cooling under Multan's extreme summer conditions: mean daily maximum temperatures reach 47°C in May–June, and relative humidity falls below 18% during the pre-monsoon period, creating vapour pressure deficits of 4.5–5.5 kPa [17]. The August peak in domestic demand is particularly significant because it coincides precisely with the peak of agricultural demand, creating a double-pressure month in which both the largest and second largest demand sectors simultaneously reach their seasonal maxima while canal supply remains elevated but below its September monsoon peak. The seasonal range of domestic demand (2.03–6.60 Mm³) is substantially narrower than the agricultural range (2.3–20.7 Mm³), confirming that domestic demand constitutes a secondary but seasonally reinforcing source of water system pressure rather than the primary demand driver. The base year which is 2015 total annual domestic demand was 94.31 MCM, representing approximately 6.5% of total district demand a share that will grow substantially as projected to 349.09 MCM by 2055. The effect of socioeconomic elements and climate change on water demand across various industries showed a considerable increase under the high emission scenario, urbanization and high growth pathways of SSP 2.45 and SSP 5.85, on the other

hand, to the business as reference scenario. In the high urbanization and high development scenario, the domestic water demand in Multan is projected to range MCM by 2055.

Industrial water demand remained effectively constant across all 12 months of the base year, ranging from only 0.185 Mm³ in November–December to a modest peak of 0.263 Mm³ in May–June. This near-flat seasonal profile contrasting sharply with the strongly seasonal signals of both agriculture and domestic demand confirms that industrial water use in Multan District is governed by process requirements and production schedules rather than climatic factors. The modest May–June elevation likely reflects marginally higher cooling water requirements during peak summer temperatures in industrial processing operations. The base year total annual industrial demand of only 0.04 MCM is negligibly small relative to agricultural demand, though this (Figure 9) makes the dramatic growth trajectory projected to 120.99 MCM by 2055 under CPEC-driven industrial expansion. The near constant industrial demand profile also simplifies water management planning for this sector, as its relatively predictable consumption does not introduce significant seasonal complexity to the district's supply allocation decisions.

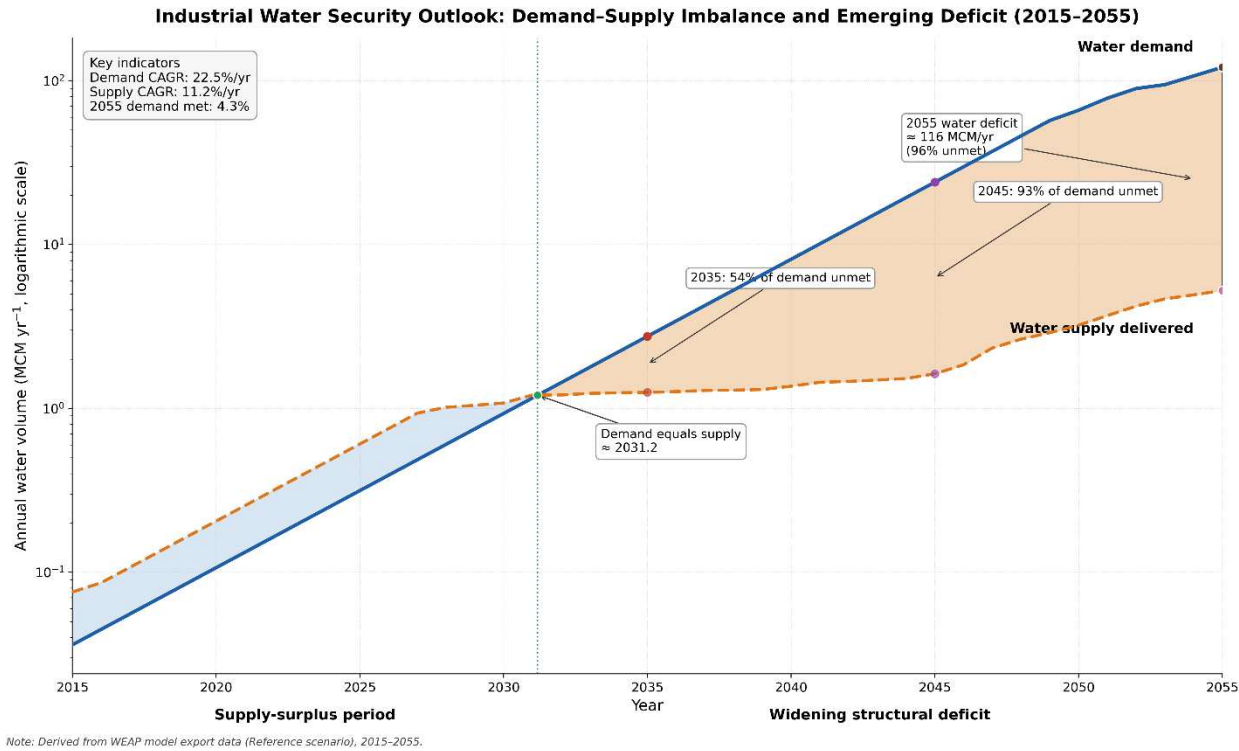
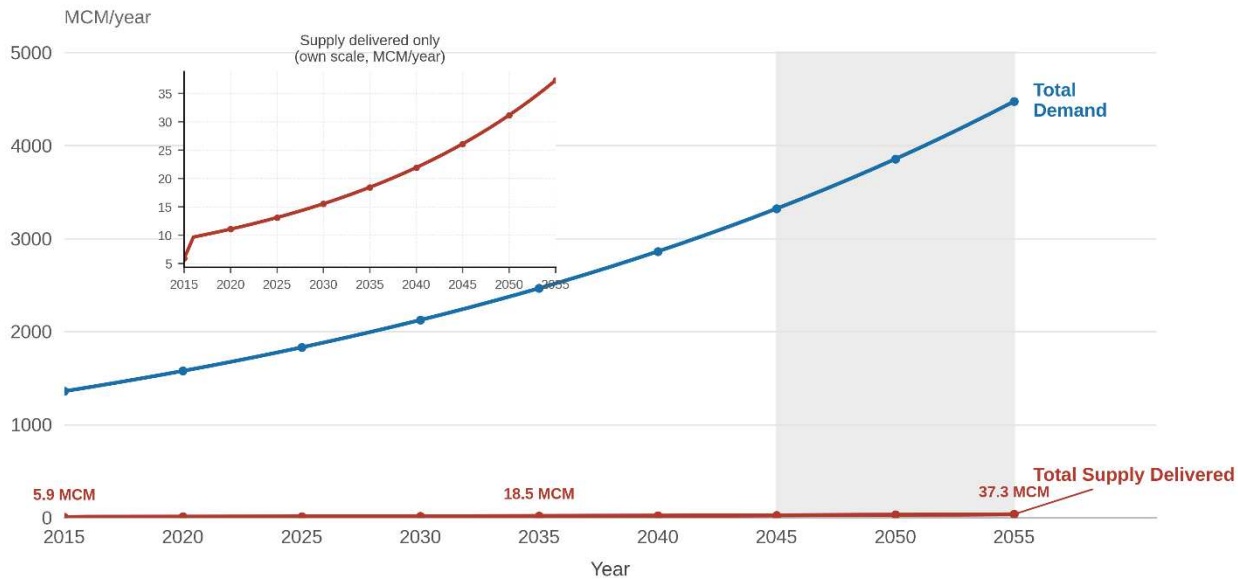


Figure 9. Projected industrial water demand and annual industrial water supply delivered in Multan District during 2015–2055, illustrating long-term trends in industrial water demand and supply simulated using the WEAP model.

Agricultural water demand exhibits a strongly bimodal seasonal structure governed by the Rabi Kharif crop calendar of Multan District. Demand rises from 9.3 Mm³ in January to a secondary Rabi-season peak of 12.1 Mm³ in February, driven by supplemental irrigation requirements of the maturing wheat crop seasonal water depth 480 mm as it approaches its reproductive stage. Demand then declines sharply to a distinct seasonal trough of 6.8 Mm³ in April, corresponding to the cessation of Rabi irrigation as wheat enters harvest and Kharif land preparation commences with minimal crop water uptake. This April minimum is one of the most structurally important features of the agricultural demand curve because it represents the only month in which agricultural demand approaches parity with domestic demand, briefly reducing competition for limited canal supply as shown in (Figure 10). The dominant primary peak occurs between May and September, rising from 13.5 Mm³ in May to a district-wide maximum of 20.7 Mm³ in

September, with a secondary summer peak of 19.4 Mm³ in July. This Kharif peak is driven by the concurrent irrigation requirements of the three most water-intensive crops in the district: cotton 700 mm/season, rice 1,500 mm/season, and sugarcane 2,100 mm/year, which together accounted for the majority of cultivated area following the documented 92% expansion in rice planting and 63% expansion in sugarcane planting between 2010 and 2020 [11]. [36] confirmed that evapotranspiration in Southern Punjab reaches 8–10 mm/day during the Kharif peak, with rice requiring a total seasonal irrigation depth of 996.4 mm when effective rainfall is deducted underscoring the extreme water intensity of rice cultivation under Multan’s semi-arid climate. Agricultural demand drops sharply to a December minimum of 2.3 Mm³, reflecting the dormant inter-crop period between late Kharif harvest and early Rabi establishment when field moisture from monsoon rains partially sustains soil conditions without requiring supplemental irrigation.

Annual water supply and demand in the agriculture sector, 2015–2055



Source: WEAP model output, Reference scenario, agriculture demand site.

Figure 10. Projected agricultural water demand and annual agricultural water supply delivered in Multan District during 2015–2055, illustrating long-term trends in agricultural water demand and water supply simulated using the WEAP model under future climate scenarios

In addition, the agriculture water demand in 2015, which was 1354.89 million cubic meters (MCM), is projected to rise to 4474.94 MCM by 2055 as shown in fig. 8. According to the data from the Pakistan bureau of statistics, the major crop area in the Chenab River Basin has been reduced due to water Shortages in the Multan region [71]. The agriculture sector consumes

more water as compared to the domestic and industry sector, which is crucial for meeting the food requirements of the growing population. Under the high emission and high population scenarios SSP 5.85, it is projected that the demand for the agriculture water will reach 1347.70 million cubic meters by 2055, as shown in (Figure 11).

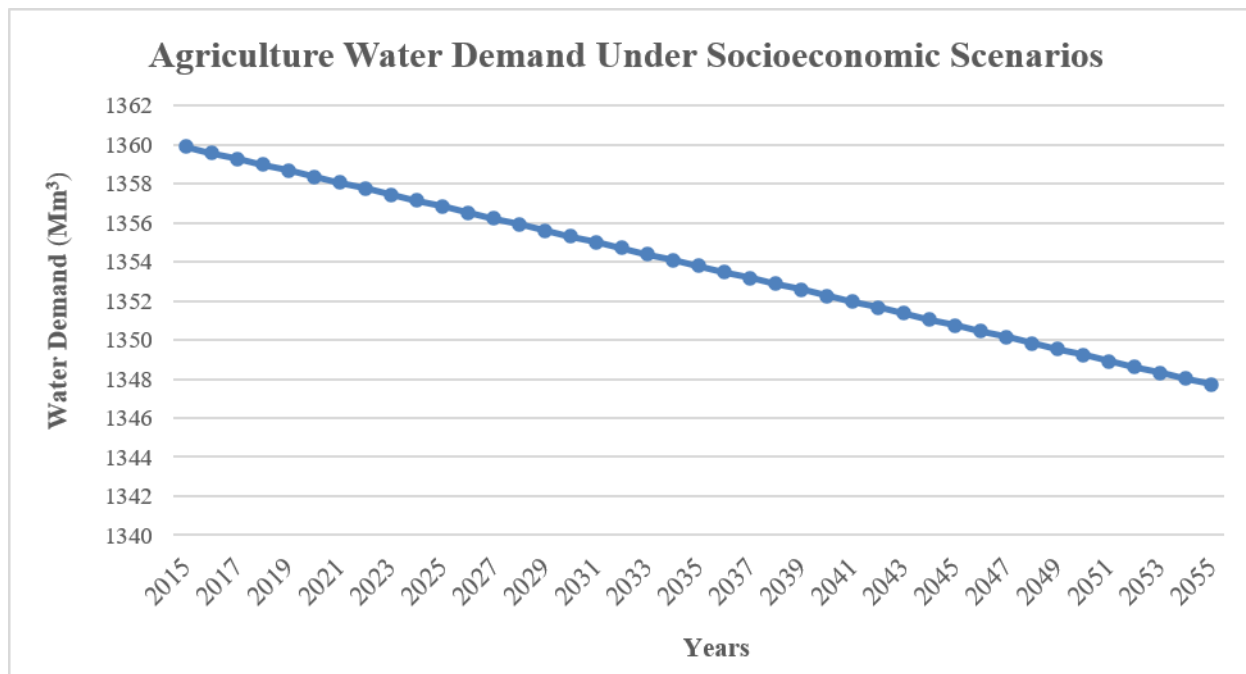


Figure 11. Projected agricultural water demand under the socioeconomic scenario in Multan District during 2015–2055, illustrating the temporal variation in agricultural water demand simulated using the WEAP model.

According to data from the Pakistan bureau of Statistics, the major crop area in the Multan region has been reduced due to water shortages in the area [71]. The agriculture sector has been severely impacted by the loss of productive land due to flash floods, reduce productivity, and crop failures [72]. The water demand increased in the future due the rapid growth of population, economic development, and high emissions changing precipitation and temperature, which eventually increased the water demand to fulfill various water needs. In the study area analysed by the water supply and demand under the socioeconomic and climate changes using WEAP, exposed that the water demand in the reference scenario was 1360 MCM in 2015, and is anticipated to reach 1348 MCM by 2055.

Inflows to the area are defined as the water entering the system or catchment through the different sources: river, canals and other local supply sources. It was observed that average monthly inflows of the Makhdoom Rashid Branch, Multan Branch Canal and Chenab River head flow to the area range from 0.85 to 11.249

Mm³, 0.32 to 1.15 Mm³ and 1.35 to 2.35 Mm³ respectively as express in (Figure 12). The lowest value was registered in April and the highest value in August when higher inflows were observed during the monsoon season due to high rainfall in the area. Different scenarios were estimated based on the current water demand and scenarios analysis was defined from 2015 to 2055. The outflows to the area are defined as the water outflow from the system or basin through different sources: tubewells, demand nodes, and other returns flows. It observed that average monthly outflow to the region/ catchment range from 3.5 to 16 Mm³ (Figure 13).

The graph shows a clear fluctuation in water supply distribution among different Demands: Agriculture demand, Industry demand and Domestic demand. August 2015 experienced a significant peak in agricultural demand and water distribution, particularly in the different regions. Lastly, the agriculture demand in not required in the first and last two months of the year and monthly distribution of the Industry

and Population demand have some variation throughout the year.

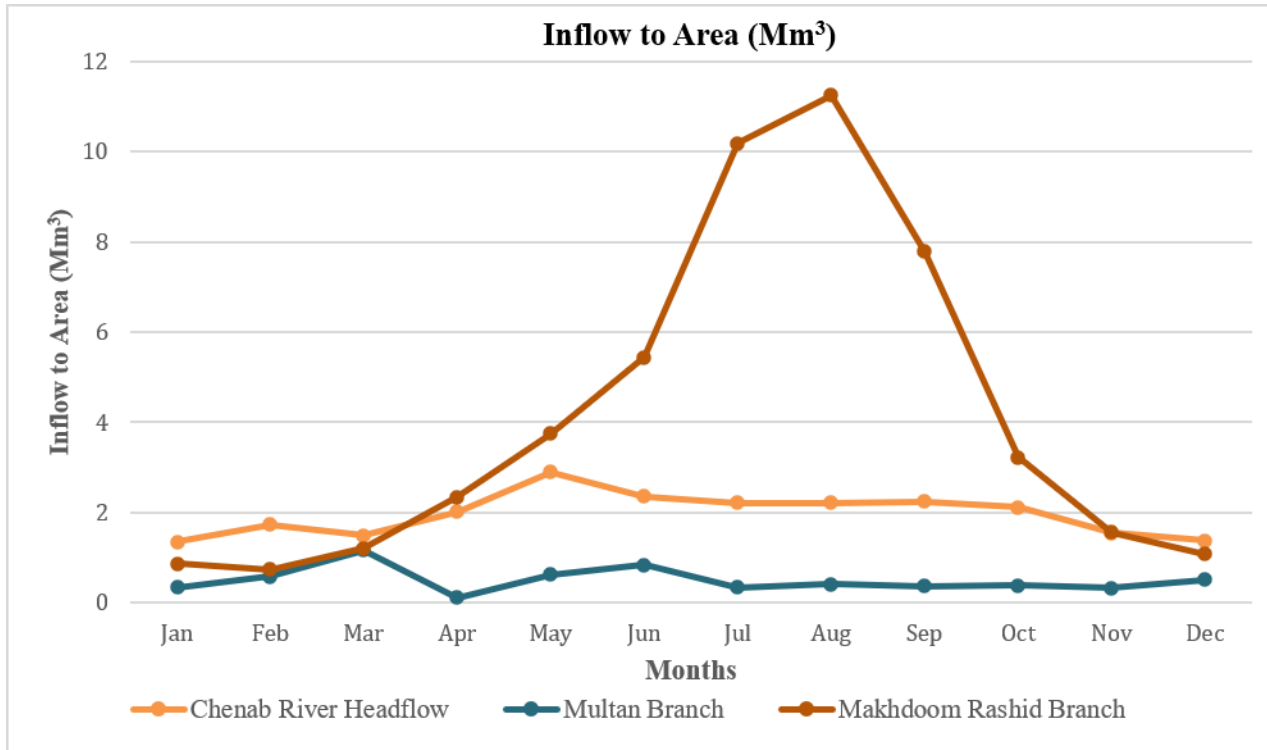


Figure 12. Monthly inflow to the study area from the Chenab River Headflow, Multan Branch, and Makhdoom Rashid Branch, illustrating the seasonal variation in water availability and the contribution of major surface water sources used in the WEAP model.

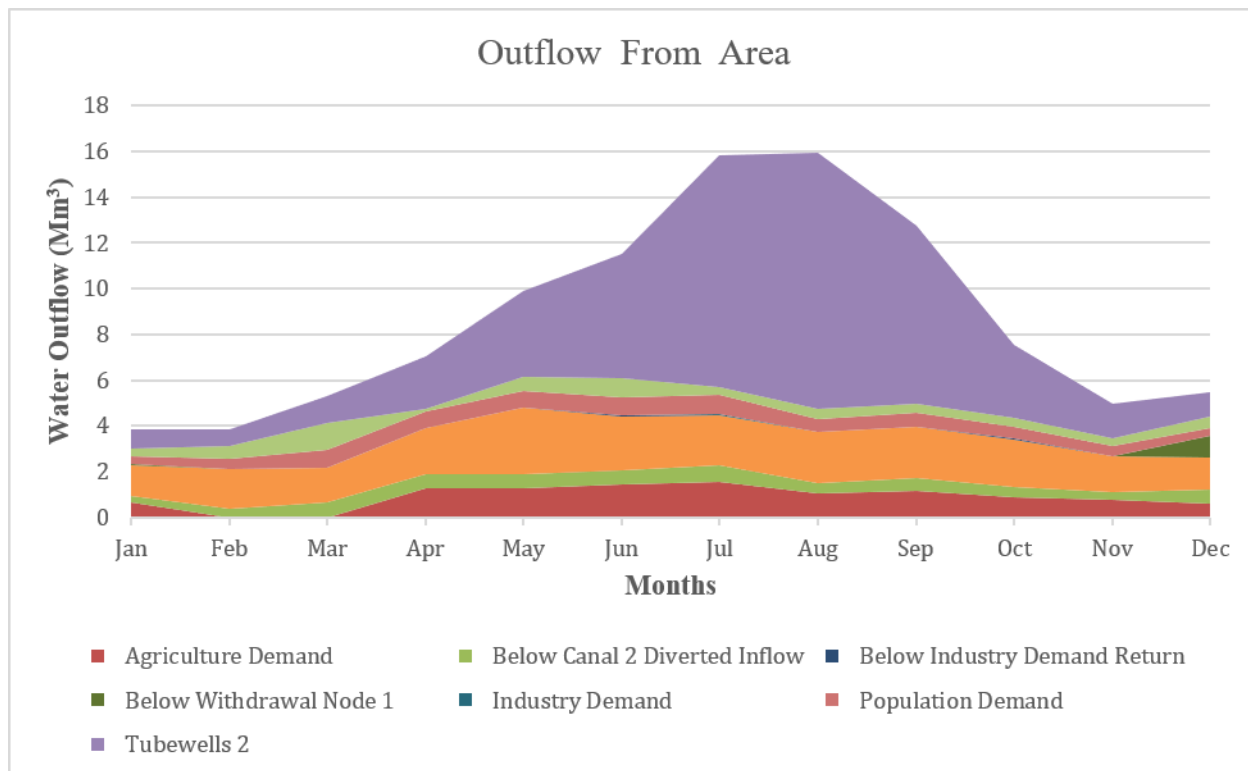


Figure 13. Monthly outflow from the study area, showing the seasonal contributions of agricultural, domestic, and industrial water demands, together with tubewell abstraction, diverted inflows, withdrawal nodes, and return flows, as simulated using the WEAP model

Unmet Demand:

During the summer months (March-August), Population water demand spikes, aligning with agriculture water demand increases in semi-arid regions. However, unmet demand also likely increases due to insufficient streamflow and groundwater recharge. To predict future water scarcity dynamics for Multan district, three SSP scenarios based on the CMIP6 MRI-ESM2-0 model have been analysed using the WEAP modelling tool for the period 2015-2055. In total three demand sectors have been considered for this research which include agriculture, industry, and population, and it has been found that an increasing demand of water is occurring in all cases depending on their level of radiative forcing. For the SSPs-2.45 scenario representing a moderate mitigation policy with medium greenhouse gas emissions, there is a clear yet steady increase in unmet water demand across all three sectors over the simulation period. Agricultural water shortfall that accounts for the

majority of total deficit starts from about 0.2 million cubic meters in 2015 to 24.7 million cubic meters by 2055 as a result of the cumulative impact of increased evapotranspiration due to moderate warming temperatures, expansion of irrigated crops and food demand. The industrial water shortage starts off at zero in the first few decades, then rises up to about 2.9 million cubic meters by 2055, while the population water deficit shows an increased value of 10.6 million cubic meters by 2055. From the lower values of the unmet water demand in the early decades, it can be noted that the moderate emissions partially mitigate water stress, although the increasing pattern thereafter reveals that water supply facilities are inadequate. In SSPs 2-4.5, an extreme scenario of high greenhouse gas emissions with low levels of climate change mitigation measures, there would be an observed significantly greater level of water deficit. In

such a scenario, agricultural demand for water not met would jump from virtually zero in the base period to 10.9 Mm³ in 2055, while population demand deficit would rise to 9.1 Mm³ in 2055, suggesting that more rapid warming increases demands on irrigation due to higher crop water use and less effective precipitation. At the same time, industrial demand not met would grow to 2.8 Mm³ by 2055 due to a more substantial need for cooling and processing water in a warmer environment. Most notably, there would be a critical turning point in the years between 2035 and 2040, after which the demand growth rate would be much faster, matching expected heat extremes and prolonged dry seasons typical of the SSPs 2-4.5 scenario in South Asia. Consistently higher unmet demands across the board compared to SSPs 1-2.60 provide another indicator of greater water stress in such a scenario. The SSPs 5-8.5 represents the most extreme scenario of radiative forcing with fossil fuel-intensive

Comparative Assessment Across Scenarios

A cross-scenario comparison of unmet water demand in 2055 reveals a clear and statistically

development, resulting in the most extreme unmet demand for water trajectory among all three scenarios. Within this scenario of unmitigated greenhouse gases, the most evident unmet demand component turns out to be population demand deficit, reaching 0.1 Mm³ in 2015 and jumping up to 14.8 Mm³ by 2055, thereby becoming greater than even the agricultural demand deficit in the latter part due to the combination of rapid urbanization and high domestic water demand because of extreme weather conditions. Agriculture shows an unmet demand of 8.2 Mm³ while industrial water demand deficit amounts to 4.2 Mm³, which is the highest value in terms of unmet demand in any sector amongst all three scenarios presented here at (Table 4). The inflection that occurs post 2035 with regard to the SSPs 5-8.5 scenario can be attributed to expected climate change tipping points within the region, such as unreliable monsoons, frequent droughts, and rapid groundwater depletion.

consistent gradient of water stress severity aligned with emission intensity:

Table 4: Comparison of projected agricultural, industrial, and population water demands, together with total water demand (Mm³), under the SSP1-2.6, SSP2-4.5, and SSP5-8.5 climate change scenarios as simulated using the WEAP model.

Sector	SSP2-4.5 (Mm ³)	SSP3-7.0 (Mm ³)	SSP5-8.5 (Mm ³)
Agriculture	24.7	10.9	8.2
Industry	2.9	2.8	4.2
Population	10.6	9.1	14.8
Total	38.2	22.8	27.2

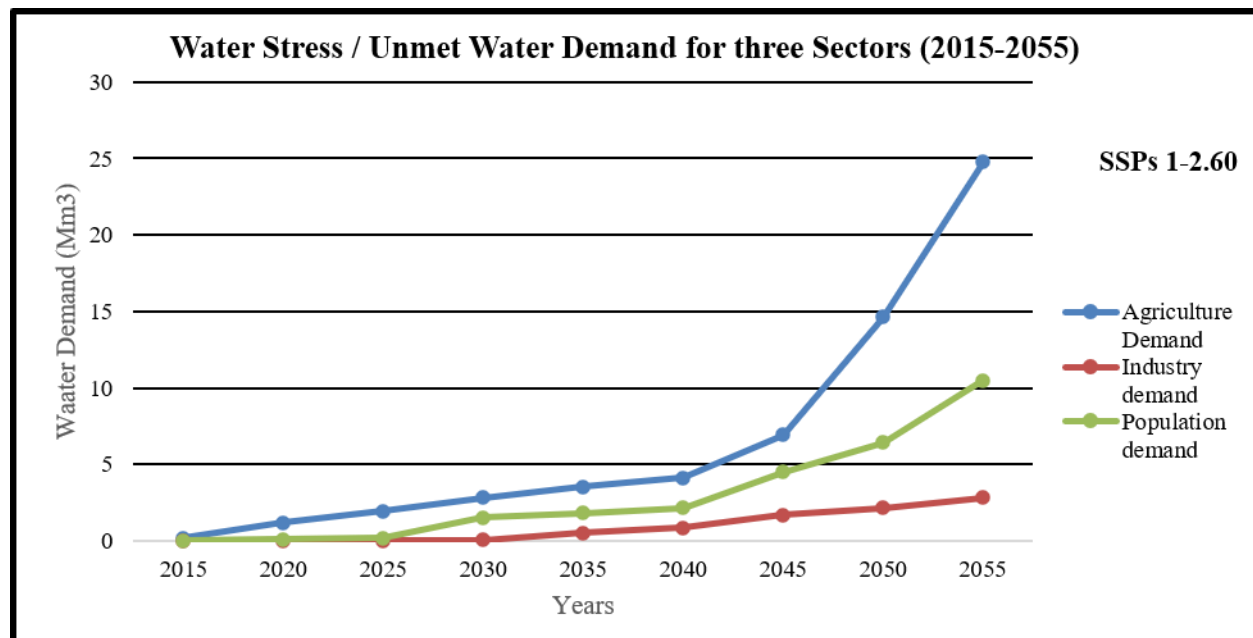
These findings illustrate the fact that, although SSPs 2-4.5 creates the highest absolute demand for agricultural water due to more expansion of

agricultural water needs because of moderate warming SSPs 5-8.5 creates the highest degree of water stress for populations and industry, due

to an extremely high increase in temperature and domestic water stress. In all three scenarios considered, the agricultural water sector emerges as the major source of the unmet water demand, emphasising the importance of addressing water demand in the context of Multan district.

Water shortages from the agricultural sector start to significantly accelerate past the year 2030 in all three SSPs cases, pointing to a crucial period of about ten years before the emergence of structural unavailability. The largest population demand shortfall appears early and rises most rapidly for SSPs 5-8.5, reaching the point of critical shortage between 2045–2050, due to excessive urban heat stress driving higher per capita water usage. Industrial unmet demand

ranks lowest in absolute size in all three scenarios, but its steady growth indicates a need to plan for Multan's industry water demand going forward into the post-2035 time period. SSPs 1-2.60 creates a counterintuitively great agricultural unmet demand as compared to SSPs 2-4.5, owing to scenario-specific assumptions regarding agricultural area increases and crop mix changes included in the WEAP demand nodes. All three SSPs concur that failure to address structural supply and demand problems leads to a situation where Multan District will confront unmet demand totalling between 22 and 38 Mm³ per annum by the year 2055, creating a significant water security problem for an already chronically water-stressed in Multan district as images shown in (Figure 14).



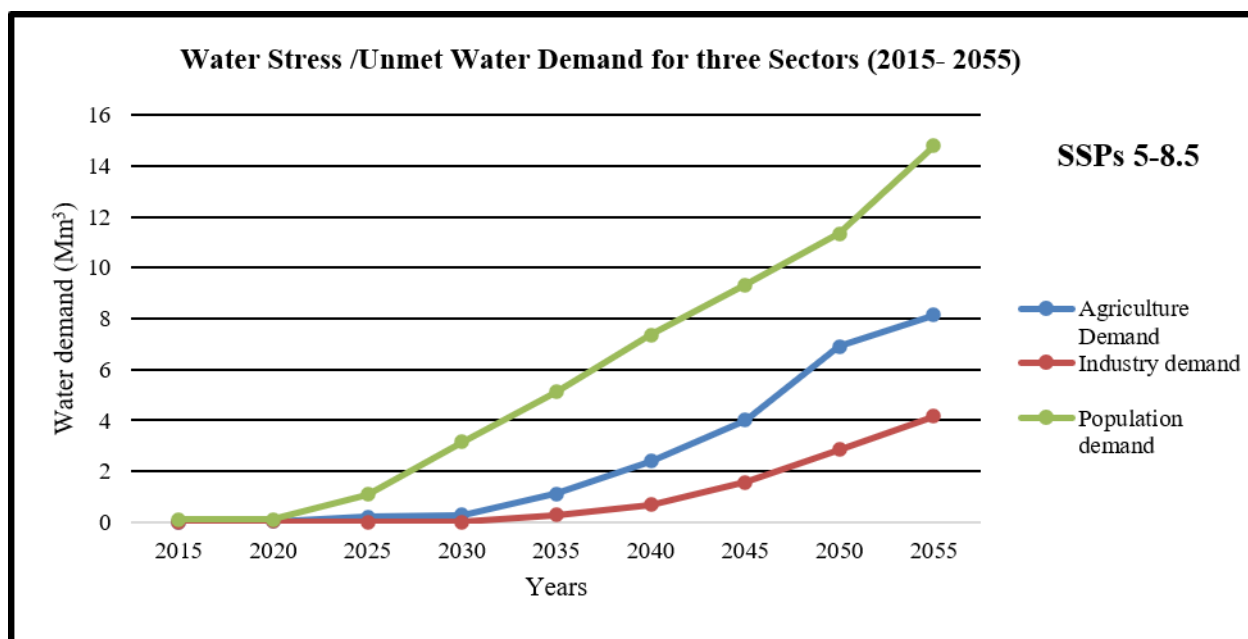
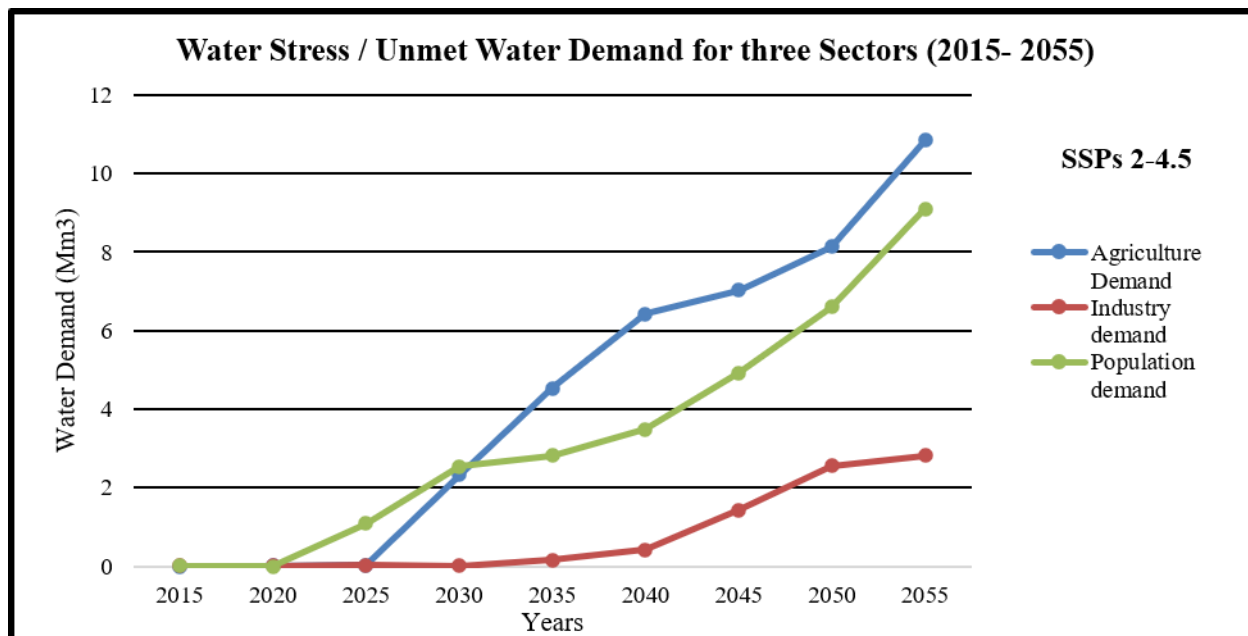


Figure 14. Projected Water stress / Unmet water demand in the agricultural, industrial, and population sectors of Multan District during 2015–2055 under the SSP1-2.60, SSP2-4.5, and SSPs5-8.5 climate change scenarios, illustrating the temporal variation and sector-wise differences in future unmet water demand as simulated using the WEAP model.

Thus, the graph shows the unmet water demand for the population and agriculture going to increase because in the monthly use of the water for domestic uses going to utilize more water as compared to agriculture demand which is also unmet because the water for different agriculture

crops is need are very less and create the gap between demand and supply respectively. In addition, the unmet demand of the industry is very less because the use of the water in the industry limited and industry consume less water in this area.

5 Discussion

The results directly address the study's objective of quantifying how climate change, interacting with socioeconomic and land-use scenarios, reshapes future water demand and supply in semi-arid Multan District. The WEAP–CMIP6 framework shows total demand rising sharply across all sectors under every SSP pathway from 1,449.24 MCM in 2015 to 4,944.02 MCM by 2055 under the Reference Scenario. This is less a projection than a structural diagnosis: demand growth is driven simultaneously by cropping intensification, demographic expansion, and climate-driven evapotranspiration three reinforcing pressures unlikely to self-correct without deliberate policy intervention. Capturing all three within a single integrated model is a key strength of this study relative to sector-specific or climate-only analyses. Agriculture, accounting for roughly 91.4% of total demand in 2015 and remaining dominant throughout the simulation, mirrors Pakistan's national water-use structure, where irrigation consumes over 90% of freshwater withdrawals [14]. The projected 230% rise in agricultural demand 1,354.89 to 4,474.94 MCM by 2055 is steeper than in earlier Pakistani WEAP studies that excluded CMIP6-driven land-use change, reflecting Multan's documented cropping shifts rice area up 92% and sugarcane up 63% between 2010 and 2020

6 Conclusions and Recommendations

This study combined the WEAP model with the MRI-ESM2-0 climate model simulation for the SSP1-2.6, SSP2-4.5, and SSP5-8.5 scenarios, to simulate the water demand, water supply, and water gaps for agriculture, domestic, and industrial sectors for Multan District, in Pakistan, for the period of 2015 to 2055. The results support the following conclusions. The total water demand is expected to grow from

[14] and positioning the district among the country's most water-intensive agricultural contexts. Domestic demand rises 270% of 94.31 to 349.09 MCM, driven almost entirely by population growth (CAGR 2.61%) with only a marginal 0.5%/year rise in per-capita use, disaggregated here at district scale using three census points (1998, 2017, 2023). Industrial demand grows over 3,000-fold 0.04 to 120.99 MCM the sharpest relative change reflecting Multan's planned CPEC-linked industrial expansion, consistent with broader national trends. These findings align structurally with comparable South Asian semi-arid basin studies. The base study [13] projected persistent unmet demand 84.37–162.17 Mm³ for India's Dhasan River Basin across all five tested scenarios; the present study's parallel result 22.8 to 38.2 Mm³ unmet demand across all three SSPs by 2055 confirms that persistent, scenario-robust deficits characterize semi-arid, canal-irrigated systems with fixed infrastructure and rising demand, rather than reflecting a single basin or model artifact. Unlike [14], which relied on the Cligen generator due to unavailable CMIP6 data, this study integrates MRI-ESM2-0 under SSP1-2.6, SSP2-4.5, and SSP5-8.5 a model ranked first among 35 CMIP6 GCMs for South Asian precipitation [67] extending the base framework with physically grounded projections previously unavailable for this context.

1,449.24 MCM in 2015 to 4,944.02 MCM in 2055 in the Reference Scenario with an increase in the cropped area by 63% (sugarcane) and 92% (rice) between 2010 and 2020 and progressive increase in reference evapotranspiration for both SSPs. Water stress is not a new phenomenon for Multan, as the district is already facing a documented water deficit of 848.7 Mm³/year as per 2020 [34] and the impact of climate change

is only exacerbating the issue. This reiterates the need for a multi-sector approach to intervention, as there is no single driver solution going forward. The highest magnitude is agricultural demand growth which would increase from 1,354.89 MCM in 2005 to 4,474.94 MCM in 2055, exacerbated by a shift towards water intensive crops under Kharif season and a projected 8-14% increase in Kharif season crop water requirements for arid regions of Pakistan under SSP5-8.5 [34]. Conveyance losses are the largest recoverable demand pool for which governance interventions can be made, with an estimated 61% of diverted irrigation water lost before reaching crops. Under the two scenarios with lower levels of warming SSP1-2.6 and SSP2-4.5, the largest deficit category is agricultural unmet demand 24.7 Mm³ and 10.9 Mm³, respectively, which repeats irrigation management as the most important water security lever under all but the highest warming scenarios. By 2055, regardless of SSP pathway, domestic demand increases from 94.31 MCM to 349.09 MCM, as population grows. In the Multan District, in the post-2040 period, under SSP5-8.5 maximum warming +2.0 to +2.5°C by 2055, heat stress induced per capita demand escalation leads to a reversal of the sector rank domestic unmet demand of 14.8 Mm³ becomes larger than agricultural unmet demand of 8.2 Mm³, which is the first documented for Multan District and novel in Pakistan's literature of WEAPs. This marks a qualitative transition from farming driven to domestic driven water insecurity in a situation of climate warming. Industrial growth demand, which has roots in CPEC, is completely groundwater dependent as 100% industrial water in Punjab comes from groundwater and is already over-exploited by 50-55 MAF/year and has already exhausted the recharge levels at 94 MCM/season [15];[19]. Even if industrial unmet demand is least in absolute figures 2.8 to 4.2 Mm³ by 2055, it is also increasing the fastest after 2035. A major non-monotonic result is that the SSP2-4.5 scenario, which is the lowest warming scenario,

produces the highest unmet demand of the agriculture sector 24.7 Mm³ due to the moderate development story it includes, which contains a larger increase in irrigated land area than does SSP5-8.5. This finding, in line with [34], validates that agriculture and land use policy are first order water management tools, separate and beyond greenhouse gas mitigation. The range of total unmet demand is between 22.8 Mm³/year SSP2-4.5 and 38.2 Mm³/year SSP1-2.6, with SSP5-8.5 at 27.2 Mm³/year, which represents the quantified policy space within which integrated climate and land-use governance can reduce stress severity. This indicates that the water stress is not inevitable in any scenario but depends on the choice of scenario, and that it is possible to have water security in Multan District in any scenario with active adaptive interventions. 2025 to 2035 is the critical time to make adaptive interventions effective, as a combination of the onset of further growing climate extremes, groundwater depletion thresholds, and peak population pressure hits the domestic sector in critical shortage in 2045 to 2050 in SSP5-8.5.

These results suggest three directions for further research. First, future research needs to explicitly consider the effects of extreme hydrological events (such as long droughts, flash floods and heat waves) on regional water availability and system resilience under various climate change scenarios. Second, in light of agriculture's primary water use, future studies should evaluate the potential of new irrigation practices and technologies, including drip and sprinkler irrigation, to lower the water requirements of agriculture under future climate scenarios. Third, further research is needed to study the various hydrological, economic, environmental and social indicators together in a single framework to design most effective adaptation pathways for developing climate-resilient water systems in Multan District and other semi-arid basins of southern Punjab.

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