Dissertation Summary

Integrated Assessment of Climate Change Impact on Drought Severity, Water Sustainability, and Agriculture Potential in Afghanistan

Background

The escalation of climate change significantly influences the pervasiveness and intensity of extreme climatic events like heatwaves, heavy precipitation, prolonged droughts, and floods, as highlighted by IPCC (2022). Especially noteworthy is the exacerbation of drought occurrences which pose considerable threats to water resources, food security, and economies, predominantly under the looming global warming scenario. The detrimental impacts of droughts are particularly pronounced in developing, agriculture-centric nations such as Afghanistan, Pakistan, Iran, and India, where lower adaptive capacities intertwine with high population density, accentuating the vulnerability to drought risks. Droughts, being multi-faceted, encompass meteorological, hydrological, agricultural, and socio-economic dimensions, each ensuing from a persistent precipitation deficit and ensuing into cascading impacts across natural and human systems. An adept understanding of climate-induced drought characteristics is imperative for devising efficacious adaptation and mitigation strategies aimed at sustainable water resource and agricultural management. Employing hydrological models like the Soil and Water Assessment Tool (SWAT) and MIKE SHE, alongside the Water Evaluation and Planning System (WEAP), is pivotal for a holistic assessment of water resources, particularly under varying climate change scenarios. These assessments are geared towards enhancing reliability, resilience, and reducing vulnerability (RRV) within water resource and drought management frameworks. Furthermore, utilizing General Circulation Models (GCMs) aids in foreseeing climatic variables, thereby facilitating a precise evaluation of present and prospective water resource sustainability under changing climatic conditions. Given the intricate interplay between climate change, elevation variability, and agriculture, assessing the agricultural potential concerning climatic boundaries and elevational variances is integral for crafting effective adaptation strategies. This understanding is crucial for safeguarding water resources, agriculture, and livelihoods in regions susceptible to climate change impacts, thereby significantly contributing to the broader understanding of drought phenomena and its management in the face of climate change.

Objectives

This study aims to delve into the repercussions of climate change on drought severity, water resources sustainability, and agricultural potential in Afghanistan by employing the Standardized Precipitation Evapotranspiration Index (SPEI) and an ensemble of CMIP6-GCMs. Additionally, it strives to examine water sustainability through the lens of Reliability, Resilience, and Vulnerability (RRV) metrics grounded on the Standardized Runoff Evapotranspiration Index (SRI), alongside assessing shifts in agricultural climate boundaries considering climate change and elevation effects.

To fulfill the aforementioned objectives, this study seeks to answer the following research questions:

1. How do extreme climate events exacerbate drought conditions across Afghanistan's diverse climatic regions?
2. What are the projected future climate impacts over Afghanistan under different SSP scenarios as envisioned by an ensemble of CMIP6-GCMs?
3. How does the novel methodology integrating the SRI and RRV framework augment our understanding of climate change impacts on water resources sustainability?
4. How do climate change and elevation-induced shifts in agricultural climate boundaries affect potential future agricultural zones in Afghanistan?

Methodology

Framework

The methodology for this research is structured to deeply investigate the effects of climate change and drought on Afghanistan's resources and agriculture. Initially, an assessment of gridded datasets lays the groundwork for further analyses. The drought conditions are examined employing the Standardized Precipitation Evapotranspiration Index (SPEI) alongside trend analysis techniques like Sen's Slope Estimator and the Modified Mann-Kendall Trend Test. Extremes of precipitation and temperature and their impact on drought events are also scrutinized.

In the Climate Modeling section, the research focuses on the selection and evaluation of General Circulation Models (GCMs), detailing the downscaling, bias correction, GCM ensemble creation, and the projection of future rainfall and temperature based on this ensemble. Transitioning to the modeling of climate change impacts on water resources sustainability, the SWAT (Soil and Water Assessment Tool) model is implemented and calibrated. Drought indices are calculated and sustainability assessed using the Robustness, Reliability, and Vulnerability (RRV) concept.

The final segments of the methodology are dedicated to assessing the potential and suitability of agricultural areas under changing climatic conditions and the influence of elevation. Historical agricultural areas are analyzed and potential effects of future climate scenarios are examined.

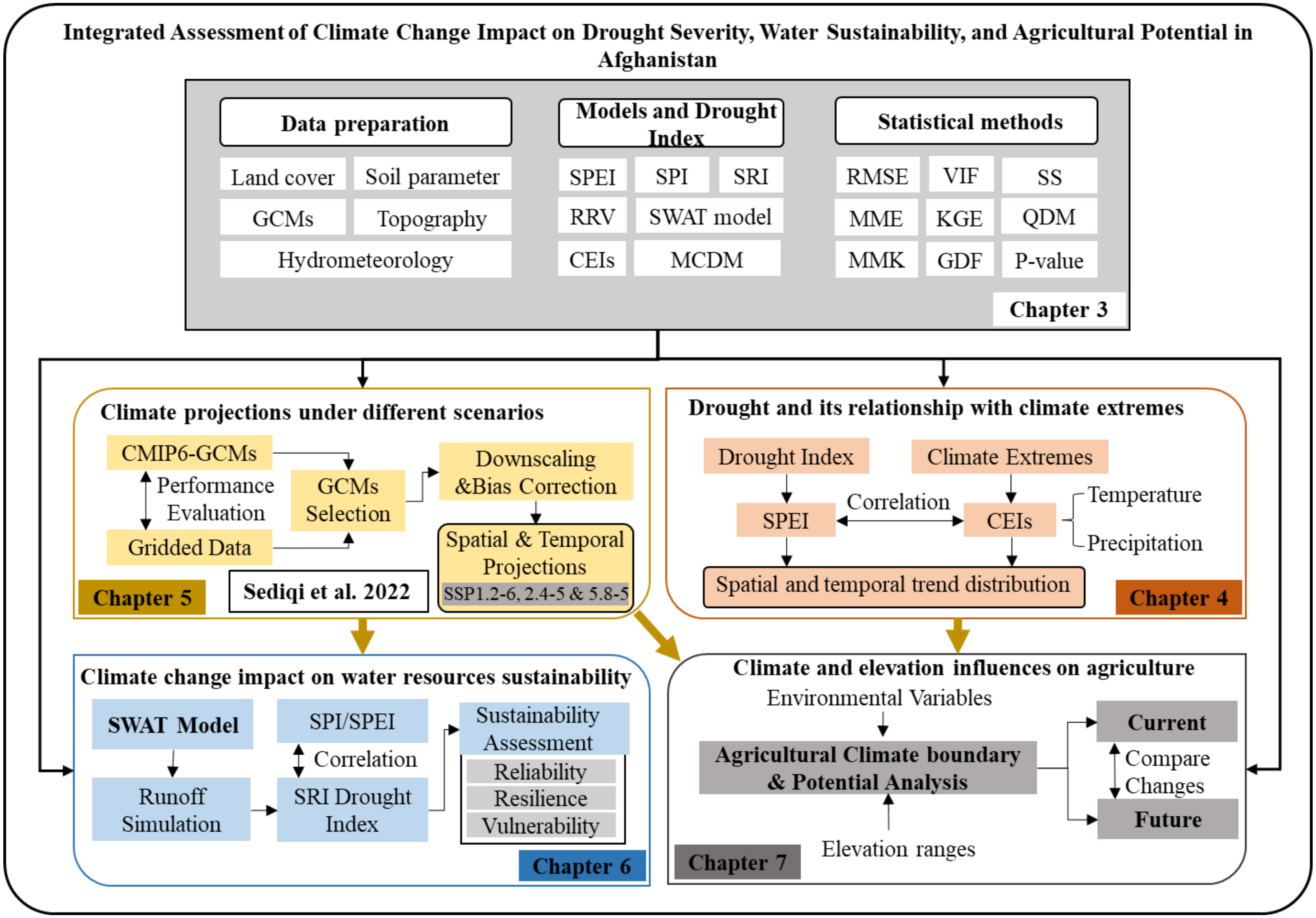

Figure: The methodological framework adopted for this study

Datasets

Historical gridded climate data are obtained from the Climatic Research Unit (CRU), the Global Precipitation Climatology Centre (GPCC), and the ERA5 reanalysis dataset, chosen for their widespread acceptance, accuracy, and comprehensive coverage. For future climate conditions, 19 General Circulation Models (GCMs) from the Coupled Model Intercomparison Project Phase 6 (CMIP6) are selected based on various factors including timescale, specific scenarios, and data availability. These models provide projections of future climate conditions to assess the potential impacts of climate change on Afghanistan's water resources and agriculture. The study plans to evaluate the performance of these GCMs in the later stages, selecting an ensemble based on their ability to represent the historical climate among other relevant criteria.

Table: An overview of the sources and descriptions of each gridded climate data type

Data Type	Source	Data Description	Resolution	Time Coverage
CRU	Climatic Research Unit (CRU)	Provides global climate data including temperature and precipitation. https://crudata.uea.ac.uk/cru/data/hrg/	0.5°	1901-Present
GPCC	Global Precipitation Climatology Centre (GPCC)	Provides global precipitation data. https://www.dwd.de/EN/ourservices/gpcc/gpcc.html	0.5°	1891-2016
ERA5	ECMWF's ERA5 Reanalysis	Provides global hourly climate data. https://cds.climate.copernicus.eu/cdsapp#!/dataset/reanalysis-era5-single-levels?tab=form	0.25°	1979-Present

Table: The selected General Circulation Models (GCMs) from the Coupled Model Intercomparison Project Phase 6 (CMIP6)

No	CMIP6 Model	Country	Resolution (Lon × Lat)
1	ACCESS-CM2	Australia	1.9° × 1.3°
2	ACCESS-ESM1-5	Australia	1.9° × 1.2°
3	AWI-CM-1-1-MR	Germany	0.9° × 1.9
4	BCC-CSM2-MR	China	1.1° × 1.1°
5	CanESM5	Canada	2.8° × 2.8°
6	CIESM	China	0.9° × 1.3°
7	CMCC-CM2-SR5	Italy	1.3° × 0.9°
8	EC-Earth3	Europe	0.7° × 0.7°
9	EC-Earth3-Veg	Europe	0.7° × 0.7°
10	FGOALS-g3	China	2.0° × 2.3°
11	FIO-ESM-2-0	China	1.3° × 0.9°
12	INM-CM4-8	Russia	2.0 × 1.5°
13	INM-CM5-0	Russia	2.0 × 1.5°
14	IPSL-CM6A-LR	France	2.5 × 1.3°
15	MIROC6	Japan	1.4 × 1.4°
16	MPI-ESM1-2-HR	Germany	0.9 × 0.9°
17	MPI-ESM1-2-LR	Germany	1.9 × 1.9°
18	MRI-ESM2-0	Japan	1.1 × 1.1°
19	NESM3	China	1.9 × 1.9°

Drought Assessment

This section delves into the investigation of spatial and temporal trends of droughts in Afghanistan over the period 1975 to 2014 using the Standardized Precipitation Evapotranspiration Index (SPEI). SPEI is chosen due to its ability to holistically represent drought conditions considering both precipitation and potential evapotranspiration. The study relies on ERA5 reanalysis gridded data for its enhanced spatial resolution, temporal coverage, and data assimilation scheme, particularly beneficial in data-sparse regions like Afghanistan. The subsequent parts elaborate on the calculation and methodological rationale of the SPEI.

Climate Modeling

Focused on understanding and predicting Afghanistan's climate, this section utilizes advanced simulation techniques. The methodology involves using Global Climate Models (GCMs) to simulate future climate scenarios based on different variables like greenhouse gas emissions and land-use changes. The selection of suitable GCMs is crucial for accurate precipitation and temperature trend simulation. Post selection, downscaling and bias correction are conducted to translate large-scale predictions to local projections and align models' predictions with observed data. An ensemble approach combines various model outputs to address uncertainties and provide a more accurate mean prediction. The changes in precipitation and temperature are projected using the ensemble, enabling predictions of climate evolution across different ecological zones in Afghanistan.

Examination of Climate Change Impacts on Water Resources Sustainability

The particular section of the thesis places its focus on the Kabul River Basin (KRB) to scrutinize the influence of climate change on the sustainability of water resources utilizing a hydrological model. The selection of KRB stems from its distinctive climatic variability, socioeconomic engagements, and unique geographical features. The basin manifests a sharp dichotomy between its upstream regions characterized by substantial snow accumulation and the downstream arid areas. The KRB holds the title of the most densely populated basin in Afghanistan, accentuating the importance of its water resources. The methodology tailored for the KRB is conjectured to be scalable and adaptable for other river basins within Afghanistan, augmenting the pragmatic relevance of this study.

A four-tiered methodology is deployed in the study. The inaugural step encompasses the utilization of chosen CMIP6 GCMs and crucial land surface data to activate the SWAT model for both historical and forthcoming periods across the KRB. Progressing to the second step, the study simulates runoff during historical and prospective periods under a spectrum of SSP scenarios, employing a multi-model ensemble of the elected CMIP6 GCMs. This structured approach seeks to provide a comprehensive understanding of the climate change impacts on water resource sustainability in the KRB, thus contributing to the broader climate resilience discourse in Afghanistan.

Assessment of Climate Boundary Shifts and Agricultural Potential

Targeting the future changes in climatic boundaries and agricultural potential in Afghanistan, this section emphasizes the impact of elevation and climate change on major crops - winter wheat and rice. Analysis is carried out separately for each climatic region to accurately predict potential agricultural areas and climatic boundary shifts. Key climate variables influencing crop growth are considered for two distinct timeframes: historical (1975-2014) and future (2060-2099). The spatial analysis focuses on historical agricultural areas for the historical period, while future analysis aims to identify potential agricultural expansion areas. Elevation range analysis evaluates the relationship between climatic boundary shifts and elevation changes. Projected future agricultural areas are defined based on the alignment of future climate variables with historical climate boundaries, providing insight into potential agricultural suitability amidst changing climate variables.

Results

The main findings and contributions of this work associated with the research questions (RQ) of this study is concluded below:

RQ 1: How do extreme climate events contribute to drought conditions in diverse climatic regions of Afghanistan?

The analysis of the Standardized Precipitation Evapotranspiration Index (SPEI) from 1975 to 2104 depicted a clear spatial variation in drought conditions across different climatic regions of Afghanistan. Particularly, a negative shift in SPEI-12 was observed in the southwestern desert regions, signifying moderate drought conditions, while the northern and northeastern mountainous regions showed less severe or non-existent drought conditions. The arid desert regions were the hardest hit, experiencing moderate to severe drought conditions for a substantial period.

Furthermore, the correlation analysis between SPEI-12 and various climate extreme indices indicated that temperature extremes, specifically an increase in extremely hot days and tropical nights, had a strong negative correlation with SPEI-12 in the arid desert zone, suggesting that temperature extremes worsen drought conditions in such climates. Conversely, in the polar tundra zone, the correlations were generally weaker, reflecting the different climatic influences on drought conditions in this region.

The study also highlighted the significance of region-specific climate change mitigation and adaptation strategies due to the varying severity of drought conditions across different topographical zones in Afghanistan. Moreover, an increased spatial disparity in precipitation and temperature across Afghanistan was discerned, calling for targeted interventions for effective water resource management and agricultural practices, particularly in the arid desert and steppe regions.

RQ 2: What are the future climate impacts over Afghanistan under different SSP scenarios as projected by an ensemble of CMIP6-GCMs?

The Multi-Model Ensemble (MME) analysis reveals significant spatial disparities in future precipitation and temperature projections across Afghanistan under various Shared Socioeconomic Pathways (SSPs). The arid regions are anticipated to see a notable reduction in precipitation, potentially exacerbating existing water scarcity issues, while high-altitude areas may experience a substantial increase in precipitation, particularly under the high-end emission scenario SSP5-8.5, which could lead to more severe flood events.

Temperature projections depict a uniform rising trend across all scenarios and regions, with maximum (Tmx) and minimum (Tmn) temperatures expected to increase considerably. This has implications for the length of the growing season, frost days, and human health. The higher-end emission scenarios show a substantial potential for temperature extremes and heatwaves, emphasizing the need for regionally targeted adaptation and mitigation strategies.

The seasonal projections across different climatic zones indicate a potential future with more extreme temperatures and increased precipitation, especially under the SSP585 scenario. The projections suggest longer dry periods and increased warm spell durations in arid regions, while the polar regions could see shorter cold seasons.

RQ 3: How does the integration of the SRI and RRV framework enhance our understanding of the impacts of climate change on water resources sustainability?

The integration of the Standardized Runoff Index (SRI) and Reliability-Resilience-Vulnerability (RRV) framework significantly enhances our understanding of the impacts of climate change on water resources sustainability within the Kabul River Basin (KRB). Utilizing a grid-based analysis, this integrated approach provides a detailed spatial representation of hydrological processes, effectively capturing the complex interplay between snowmelt, surface runoff, and groundwater recharge across diverse topographical and climatic conditions.

The assessment under various Shared Socioeconomic Pathways (SSPs) reveals that different future climate scenarios significantly affect the basin's sustainability. Specifically, a substantial portion of the basin, especially in downstream regions, is projected to fall into low sustainability categories under more severe climate conditions, reflecting concerns regarding water availability. However, under a drier threshold (-0.7), substantial improvements in sustainability levels are anticipated, especially under the SSP2-4.5 scenario, indicating a potential for enhanced water resource sustainability even under challenging conditions.

Moreover, the study provides insights into the effects of runoff variability on sustainability, crucial for water resource management and agricultural practices, especially regarding irrigation strategies. By evaluating the basin sustainability concerning runoff variability across two distinct time scales (3-month and 12-month SRI), the study reveals a higher vulnerability in the short-term, emphasizing the need for robust water management strategies to mitigate climate impacts.

The research suggests that this novel SRI-RRV approach offers a more precise understanding of water resource sustainability under varying climate scenarios, thus providing crucial information for the development of adaptive strategies to better manage water resources amidst climate uncertainties. This enhanced understanding is instrumental in addressing the challenges posed by climate change on water resources sustainability, aiding in the formulation of region-specific adaptation measures to ensure water availability and sustainability in the KRB.

RQ 4: How will shifts in agricultural climate boundaries, influenced by climate change and elevation, impact the potential future agricultural areas in Afghanistan?

The investigation into the shifts in agricultural climate boundaries in Afghanistan, influenced by climate change and elevation, revealed significant implications for future agricultural zones in the region. By analyzing historical and projected climatic conditions across different elevation ranges within each climatic region, patterns emerged that highlighted the potential impact of temperature and precipitation shifts on wheat and rice cultivation.

The elevation-dependent climatic variations study showed that with global warming, lower elevations' current climates might shift to higher elevations, possibly mandating a change in the altitude at which certain crops are cultivated. A notable outcome was that wheat cultivation might face significant challenges due to projected temperature extremes, impacting the grain formation stage crucial for yield and quality.

On the other hand, rice cultivation, which requires abundant water, presented a more nuanced scenario. Although facing climate extremes, particularly during its growing season from May to November, effective irrigation could potentially mitigate adverse effects of increasing temperatures, aligning with findings by Hendrawan et al., (2023). This underlines the necessity of effective water management in sustaining rice cultivation amidst climate change.

A key takeaway is that despite the anticipated climatic alterations, around 54.79% and 52.75% of the existing agricultural regions for wheat and rice respectively are projected to remain within suitable climatic boundaries. However, a significant portion (45.09% for wheat and 47.17% for rice) are predicted to experience unfamiliar temperature extremes, which could severely strain traditional farming practices and overall crop yields.

The findings from this study underscore the importance of developing adaptive strategies to manage climatic extremes. These should not only focus on regions predicted to face unprecedented climatic challenges but also aim to bolster the resilience and sustainability of regions continuing as potential agricultural zones. Implementing such strategies is vital to ensuring the sustenance of agricultural productivity in Afghanistan amidst changing climatic conditions.

Recommendation

The detailed spatial analysis of drought conditions, temperature variations, water resource sustainability, and agricultural suitability conducted in this study underscores the nuanced complexities inherent within Afghanistan's diverse climate and geography. The study brings to light that vulnerability to climate extremes can vary greatly across different regions within Afghanistan, making a localized understanding and approach to address these issues crucial.

Future research should aim to refine the accuracy of gridded datasets, such as the GPCC, CRU, and ERA5. These datasets have displayed particular biases in certain regions of Afghanistan, indicating the necessity for ongoing efforts to minimize these biases and thus more accurately represent the country's diverse climatic conditions.

The study exposes an increased spatial disparity in precipitation and temperature across different regions in Afghanistan, highlighting the need for region-specific interventions in water resource management and agricultural practices. By adapting these practices to the unique climate conditions of each region, it may be possible to mitigate the negative impacts of climate change not only in Afghanistan but also in other regions with similar climatic patterns and vulnerabilities.

The selection of CMIP6 GCMs in this study has proven valuable for generating climate projections for Afghanistan, yet it is advisable for future work to assess the relative skills of CMIP6 and CMIP5 to inform policy adaptations both within Afghanistan and in regions with similar climatic futures. The GCMs selected in this study can be used to further explore the implications of climate change on hydrometeorological hazards.

In order to develop a more nuanced understanding of water resources performance and sustainability under different climate change scenarios, future research should consider using higher-resolution GCMs and appropriate thresholds based on diverse climatic conditions, drought time scales, and drought conditions within each region. This approach would assist policymakers not only in Afghanistan but also in other countries with similar geographic and climatic contexts, aiding them in devising effective strategies for water resource management and climate change adaptation.

Given the anticipated upward shift of climatic boundaries, strategies should be developed to support cereal cultivation at higher elevations in Afghanistan. This adaptation will require farmers to adjust to new climatic conditions, potentially impacting crop productivity and farming practices. Future research should focus on projecting potential agricultural areas based on shifts in climate boundaries. Areas with predicted maximum temperatures exceeding historical climate boundaries might face significant challenges and unfamiliar climate extremes. These findings stress the need for robust adaptive strategies to sustain agricultural productivity and ensure food security amidst changing climate conditions. Understanding the dynamics of elevation-dependent climate changes and their impact on agricultural potential is vital. This study indicates that current low-elevation climates could shift to higher elevations due to global warming, affecting crop cultivation patterns.

Overall, this study provides a roadmap for future climate change adaptation and mitigation strategies not only specific to Afghanistan but also applicable to regions with similar climatic and geographical characteristics. It emphasizes the urgent need for robust water resource management, resilient agricultural practices, and stringent climate action plans. The study underlines the potential for strategies that enhance resilience and transform high vulnerability areas into lower vulnerability regions. This research lays the groundwork for more comprehensive studies in the field, supporting measures aimed at achieving water and food security in the face of challenging climate conditions in Afghanistan and regions sharing similar climatic and geographical challenges.