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Impacts of Climate Variability on Hydrological Extremes: Droughts and Floods in a Changing Climate

[1*]Manan Sharma ,[2]Samjhana Rawat Sharma
[1] *College of water Conservancy and Hydropower engineering Hohai University, Nanjing, Jiangsu 210098 China*
[2]*School of public Administration Hohai University, Nanjing, Jiangsu 210098 China*
[*]*Correspondent author: Manansharma@hhu.edu.cn*

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ABSTRACT

This study investigates the impacts of climate variability on hydrological extremes—droughts and floods—in the context of a changing climate. Using historical climate and hydrological data (1980–2020) alongside key climate indices, including the El Niño-Southern Oscillation (ENSO), Pacific Decadal Oscillation (PDO), and North Atlantic Oscillation (NAO), we analyze trends in temperature, precipitation, and streamflow, and their linkages to extreme events. Results reveal a significant rise in mean temperatures (0.25°C per decade) and declining precipitation, exacerbating drought frequency and intensity, while amplifying flood magnitudes during extreme rainfall periods. El Niño phases correlate strongly with prolonged droughts, whereas La Niña phases drive flood occurrences. Hydrological modeling using the Soil and Water Assessment Tool (SWAT) demonstrates robust performance (Nash-Sutcliffe Efficiency [NSE] = 0.76 in calibration), projecting a tripling of drought and flood events by 2100 under Representative Concentration Pathway (RCP) 4.5 and RCP 8.5 scenarios. Geospatial vulnerability assessments identify regions with high exposure and low adaptive capacity, underscoring the need for integrated water management and climate-resilient infrastructure. This research highlights the critical role of climate variability in shaping hydrological risks and advocates for adaptive strategies to mitigate socio-environmental impacts in vulnerable regions.

Keywords: Climate variability; Hydrological extremes; Droughts; Floods; Climate change; ENSO; SWAT model; Adaptation strategies; RCP scenarios; Vulnerability assessment.

Introduction

1.1 Background and Motivation

The study of climate changes and their relation to extreme hydrological conditions is crucial in a world experiencing growing levels of climate change. In recent decades, focus has been placed on the occurrence of extreme hydrological incidents specifically drought and floods which are among the most disastrous natural calamities that continue to affect both the developed and the developing countries. This paper agrees with the IPCC's assessment on the increase in the frequency and intensity of extreme events, and, as couched in the report for the upcoming decades (IPCC, 2021).

Extreme hydrologic conditions are more affected by climate fluctuations that range from short-terms changes to long-term climate change. ENSO, NAO and IOD are some of the climate drivers that have been reported to cause changes in precipitation and temperature regimes in different regions leading to enhanced flooding and decreased drought periods or vice versa (Trenberth et al., 2014; Dai, 2011). These variations alter the moisture availability in the atmosphere, rainfall patterns, and seasonal conditions, which in turn affect water balances over river basins and watersheds (Cook et al., 2014).

The rationale for this study lies in the concern that appears around the world about understanding and restricting the effects of such extremes. Droughts have caused huge losses in agriculture and food security, water shortages, destruction of ecosystems and enhanced vulnerabilities in arid zones (Wilhite & Pulwarty, 2017). Also, flooding has continued to cause massive loss of infrastructure, displacement of people and adverse effects on their health (Hirabayashi et al., 2013). These impacts remain threats to water security, food systems, and economic growth particularly when exploring climate change vulnerable regions.

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However, as climate change changes the concepts of the atmosphere, the relations between global warming and the hydrologic extremes are also affected. Global warming brings about changes that increase the strength of the hydrologic cycle and increase the impact of both drought and flood conditions (Held and Soden, 2006). This research is informed by the need to conceptualise and track these dynamics comprehensively using definitive scientific theories and quantitative data.

1.2 Research Problem and Justification

Climate change has posed one of the daunting tasks of modern science in predicting and mitigating the effects of climate-driven hydrological variability. Although many other studies have synthesized a conceptual or narrative relationship with climate variability and extreme events, the quantifiable one is still constrained by data accessibility, model imperfections, and scale (Seneviratne et al., 2012). Many of the existing tools of forecasting and risk assessment are inadequate in terms of the specificity needed to be useful for policy-making at the local or regional level.

Hydrologic responses are also volatile under changing climate conditions thereby making it difficult to map appropriate resource allocation and disaster preparedness. Most current hydrologic models are not very well calibrated with climate variability indices, and they also fail to include nonlinear feedbacks between climate and hydrology (Thober et al., 2015). Additionally, they noted that socioeconomic disparities are not well incorporated and tend to be excluded from scientific modeling of adaptation effectiveness.

The rationale for this research is rooted in these gaps in knowledge. Thus, the study will utilize climate variability indicators, sophisticated modeling strategies, as well as spatial-temporal trends analysis to generate more credible prediction of future hydrological risks. This will help improve water management in the context of climate change, as well as risk preparedness and adaptation also in the context of climate change.

1.3 Research Objectives

The primary objective of this research is to assess the impacts of climate variability on hydrological extremes, specifically focusing on droughts and floods. This overarching aim will be addressed through the following specific objectives:

- To analyze historical and projected patterns of droughts and floods in relation to climate variability indicators such as ENSO, NAO, and IOD.
- To investigate spatial and temporal trends in hydrological extremes across selected regions, using observational data and geospatial techniques.
- To develop and validate predictive hydrological models that integrate climate drivers, enabling improved forecasts of flood and drought occurrences under different climate scenarios.

1.4 Research Questions and Hypotheses

This study is guided by the following research questions:

1. How does climate variability influence the occurrence, frequency, and intensity of droughts and floods?
2. What are the projected trends in hydrological extremes under future climate change scenarios?

From these questions, two key hypotheses are formulated:

- **H1**: Climate variability, as characterized by major climate indices (e.g., ENSO, PDO), significantly influences the frequency and intensity of drought and flood events.
- **H2**: Under projected climate change scenarios, hydrological extremes will increase in frequency and severity, posing greater risks to water resource systems and societal resilience.

1.5 Scope and Limitations

The study will cover a specific region that is highly vulnerable to climate fluctuations and has seen extraordinary levels of flooding or drought. In this case the selection of study area will depend on the availability of data set, climate variation and where hydrological issues are of significance.

As for data, historical records of climate conditions, hydrologic measurements (streamflow, soil moisture), and satellite datasets will be used in this study. However, some level of deficiency may appear due to issues like incomplete periods of climate records, coarse horizontal resolution, and/or heterogeneous and/or inhomogeneous observational data records.

In terms of approach, the work will involve statistical analysis, hydrological modeling, and climate prediction. However, there are some characteristics of climate model outputs that may still pose problems due to their inherent drawbacks in regional scale climate modeling. Moreover, socio-political processes and other specific changes in land use likely to affect hydrological response will not be captured in the study.

Literature Review

2.1 Understanding Climate Variability

Climate variability refers to the variations in the mean state and other statistical properties of the climate on all temporal and spatial scales, beyond individual weather events. This includes periodic variations in weather factors and other phenomena that can occur without or with the influence of human activities affecting atmospheric, oceanic, terrestrial, and other systems (IPCC, 2013). ENSO is one of the most comprehensively researched natural climate oscillators; it affects distribution of precipitation and temperature throughout the world (McPhaden, Zebiak, & Glantz, 2006). ENSO events involving warm or cool sea surface temperatures have a significant influence on the occurrence of hydrological events, such as floods and drought in several areas of the globe, especially in the tropical and sub-tropical areas according to Kirtman et al., (2014).

Besides ENSO, climatic signals like Northern Atlantic Oscillation, Pacific Decadal Oscillation, and Indian Ocean Dipole affect climate regimes. For instance, the NAO affects European and North Atlantic storm tracks and precipitation patterns (Hurrell et al., 2003) and the IOD affects the monsoon and extreme temperatures of the Indian subcontinent and Australia (Saji et al., 1999).

At the global level, climate variability is made worse by the overall warming that climate change brings at a long-term basis. (Hansen et al. 2010) posit that since the mid twentieth century, the global surface temperature rise has intensified shifts in regional climate regimes leading to complications in hydrological systems. This has also been reflected in the regional analysis, where certain territories increase the humidity and at the same time, others are having more frequent droughts and desertification (Donat et al., 2016). This scale-dependent spatial heterogeneity is central to explaining the relations among climate drivers and hydrologic variability.

2.2 Hydrological Extremes: Droughts and Floods

Flows, specifically, droughts and floods, are considered the most representative indicators of climate variability on watersheds. The term drought is commonly used in a context meaning a long period of time in which an irregularity in the weather patterns result in shortage of water in the environment for other uses. They are climatological, agricultural, hydrological and socioeconomic types of droughts are some of the classifications that has been used and as noted by Wilhite and Glantz, (1985). In contrast, floods are described as the occurrence of water on ground that is not water bearing more often described in the categories of riverine floods, flash floods, coastal floods as well as the pluvial floods (Kundzewicz et al., 2014).

Droughts and floods are intricate in terms of onset, duration and intensity, thus making it difficult to identify their changes and occurrence. (Van Loon,2015) explained that droughts are slow in the formation process and sometimes undetectable until their damaging effects set in, while floods are rapid in formation and development and may take only a few hours to occur, meaning that early warning systems are vital.

The impact of these calamities is inestimable in terms of socioeconomic ramifications. Floods can result into loss of lives, damage to physical structures and the subsequent outbreak of communicable diseases (Jonkman, 2005). Meanwhile, droughts have long term impacts on the yields, food production, and lives of people relying on agriculture (FAO, 2018). Environmental impacts include changes in the flow of rivers, decrease in species richness, chances of fire hazards, and in certain regions loss of ecosystem, particularly in wetland and forest areas (Blaikie et al., 2004).

2.3 Climate Change and Hydrological Systems

The effects of Climate change are emerging as key factors affecting the constantly evolving hydrological circumstances globally. They determine the volume, quality, and seasonal distribution of water availability in terms of temperature, precipitation, snow meltage and evapotranspiration (Milly et al., 2005). This is an important reduction of the water cycle where high temperatures result in more evaporation or Longer dry period than usual and heavier rainfall (Huntington, 2006).

In hydrological models, there have been indications that runoff is altered by global warming, especially where high latitude is likely to receive more runoff through snow melts while low latitude may receive minimal amounts of stream flow through increased evapotranspiration (Arnell, 2004). Research details that have accompanied a wide range of basins in Africa, Asia, and South America indicate that both stream flow and groundwater levels have already been affected by changing climatic situations (Scanlon et al., 2005; Stahl et al., 2010).

Weather change impacts also affect evapotranspiration and moisture regimes in the ecosystems and soils which are so important to vegetation and farming. For instance, climate simulations indicate that a more arid environment in the Mediterranean, southern Africa, and regions of Australia result in a reduced soil moisture availability, therefore agri-drought (Sheffield & Wood, 2008). Therefore, it is crucial to investigate the relationship between climate change and hydrological processes in order to provide authoritative information for water resource and ecosystem management.

2.4 Methods for Assessing Climate and Hydrological Extremes

Climate and hydrological extremes analysis includes various types of approaches, including statistical trends, machine learning, and hydrological process models. The most popular approaches that have been widely used for testing trends in the given time series are the Mann-Kendall trend test and Sen slope estimator. These tools are reliable and useful in showing shifts in precipitation and stream flows over a period of time.

Many machine learning models such as ANNs, SVMs, and random forest models proved to have high accuracy in predicting the occurrence of drought and flood with help of big data and real time information (Mosavi et al., 2018). These models are comparatively better equipped than conventional approaches for dealing with relationships that are not linear and for considering variable inputs.

Computerized models like SWAT (Soil and Water Assessment Tool), HEC-HMS (Hydrologic Engineering Center – Hydrologic Modeling System), and VIC (Variable Infiltration Capacity) can be used for simulating watershed responses to climatic inputs of precipitation and temperature (Arnold et al 1998, Liang et al 1994). Such models have to be adjusted with help of the available observational data and are most valuable when used in conjunction with outputs from GCMs or RCMs.

Hydrological remote sensing and Geographic Information Systems (GIS) have greatly influenced assessment of the spatial distribution of hydrological extremes in the recent past. The satellites Normalized Difference Vegetation Index (NDVI) and the Standardized Precipitation Index (SPI) are frequently used for real time drought monitoring (Rhee et al., 2010). Spatial analysis can be used to map flood hazard areas as well as the vulnerability hotspots to help in risk assessment and effective spatial planning (Schumann et al., 2009).

2.5 Knowledge Gaps and Research Contributions

Currently, significant gaps exist in the understanding of climate variability and hydrological extreme cases. First, there is relatively low knowledge regarding how climate processes affect multiple hydroclimatic events simultaneously or consecutively, for instance, droughts and heatwave, floods and floods (or flooding), which are referred to as compound events (Zscheischler et al., 2018a). Second, it is an oversight that many studies are carried out at the watershed or the regional scale, and therefore the results cannot easily be extrapolated to other spatial scales.

The second one is the problem of poor incorporation of socioeconomic factors in hydrological analysis. The "socio-hydrology" concept emphasised by Sivapalan et al. (2012) focuses on gaining better understanding of how people actually respond to the impacts of hydrological extremes and their feedback as part of hydrological modelling.

This paper seeks to fill some of these gaps by using climate indices, geographical information systems, and hydrological modeling at different time horizons and scales. Moreover, it participates and adds to the already existing body of literature that involves climate science, hydrology, and risk management. This study will be useful in policy-making and formulation of strategies for structural strengthening in regions prone to climate change, through the formulation of better, informed models of vulnerability.

Study Area and Data Collection

3.1 Description of Study Area

The study area is objectively characterized by its diverse and dynamic geography and climate, which significantly influences its hydrological systems. The region spans several ecological zones, ranging from highland mountainous regions to plains and floodplains. Geographically, it includes parts of the Indus River basin, which is one of the largest river systems in the world, providing vital support for agriculture, domestic water supply, hydropower, and industry.

This area is primarily categorized by a semi-arid and monsoon-influenced climate, with strong variations in temperature, precipitation, and evaporation patterns. The region experiences significant hydrological variability, with monsoonal rains during summer months being essential for replenishing water supplies. However, the region is also vulnerable to severe climatic events such as droughts, floods, and the impacts of cyclonic activities, particularly during El Niño and La Niña phases, which exacerbate extreme hydrological conditions.

The river systems, including the Indus River and its tributaries, are the lifeblood of the region. They support irrigation for agriculture, which is a major economic activity in the region, and provide water for domestic and industrial use. The extensive network of rivers and streams, along with seasonal creeks, serves as the primary source of water, but these systems are under pressure from over-extraction, pollution, and changing climatic patterns. Groundwater resources, while essential, are increasingly facing depletion due to overuse and insufficient recharge from the irregular rainfall patterns.

The region is highly vulnerable to hydrological hazards, with recurring floods during the monsoon season and periodic droughts during El Niño years. These extremes are compounded by the overall variability in precipitation, which fluctuates significantly across different seasons and years. Historical records show that certain regions within the study area are prone to devastating floods that not only affect infrastructure but also have serious socio-economic consequences, such as crop and livestock losses, displacement of communities, and increased mortality rates due to waterborne diseases.

The socio-economic profile of the study area is diverse, with agricultural communities dependent on water availability for crop production, particularly rice, wheat, and cotton. The floods and droughts have far-reaching impacts on the livelihoods of these communities, leading to economic instability and disruptions in local economies. Furthermore, urbanization has placed additional stress on the region's water resources, as growing populations demand more water for domestic and industrial purposes, contributing to reduced water quality and the degradation of surrounding ecosystems.

The geographical location of the study area, combined with its climate variability, makes it an ideal candidate for investigating the impacts of climate change on hydrological extremes. The region's history of chronic vulnerability to both droughts and floods offers a unique opportunity to study how climate variability and change are exacerbating these hazards and their effects on the environment and human communities.

3.2 Data Sources and Collection Methods

Because the research is focused on using a range of sources, several sets of data are used in the study. Temperature, precipitation, and evaporation data used are derived from national meteorological departments, ERA5 reanalysis data, TRMM and MODIS satellite datasets. These datasets represent high temporal frequencies and longitudinal data at the daily and monthly scales and thus enable both short-term variability and long-term trends to be quantified.

Hydrological data may therefore include river discharge data, streamflow records, information on the moisture content of soil, and groundwater levels. They are gathered from the national hydrological agencies and river basin authorities, besides other databases of the global runoff data centre (GRDC). Data related to soil moisture and groundwater are from ground-based stations and satellite-borne sensors, such as the Soil Moisture Active Passive (SMAP).

Socioeconomic information is also used to provide more information regarding the results of the hydrological study and to determine the effects of floods on social structures. These include crop and livestock losses, flood reports in urban areas, infrastructural damage and availability of water resources. Whereas, census records include the population census of the affected region, agricultural statistics consist of estimates of crop(damage) census, while the governmental post-disaster assessment may involve an estimation of the overall damage. Altogether these datasets facilitate a cross-dimensional insight of the manner in which flood and drought occur and affect both ecosystems and communities.

3.3 Data Preprocessing and Quality Control

All records within a dataset are subjected to preprocessing and quality control steps to minimize potential errors or inconsistencies so that they may be used effectively in analysis. Gaps in databases are a normal occurrence in long-term environmental data collection, particularly in developing nations. For climate and hydrological time series, the missing values are filled by utilizing linear interpolation, spline-fitting or more sophisticated statistical imputation approaches for instance the Expectation-Maximization algorithm based on the nature and extent of missing values in a data set.

Satellite-derived and model-simulated data are compared to their ground-based counterparts and adjusted for bias when necessary. Sound statistical methods of quantile mapping or empirical cumulative distribution functions (CDF) matching are further used for correcting over- or under- estimation. These corrections improve the validity of climatic and hydrologic inputs especially when applied in other modeling exercises.

Data validation is a process of comparing values obtained through two or more approaches and checking internal consistencies. Time series to be checked for presence of outliers, sharp gaps or changes in trends not logical in terms of climatic conditions of the geographical area. For areas where it is possible, spatial comparison check is also performed on the data from the adjacent stations or grid items. These allow for the development of datasets for this study that can help provide a basis for examining the climatic influences on hydrologic hazards.

Methodology

4.1 Climate Variability Analysis

In this context, this study uses both trend detection and correlation analysis to assess climate variability on hydrological extremes. The Mann-Kendall trend test is used as the main statistical tool in assessing the monotonic trends in hydro-climatic variables such as precipitation temperature and streamflow. It is also suitable for hydrometeorological data sets and is available in the hydroGOF and hydroSHA libraries of the R software environment. In addition to the use of the MK test, Sen's slope estimator is used too in order to establish the magnitude of the detected trends as this give a good quantification of the rate of change over time.

Large-scale climatic factors include the ENSO, PDO, and AO as indicators of climate variability of the atmosphere and ocean conditions. The monthly and seasonal values of these indices are downloaded from well recognized data archives like NOAA and Climate Prediction Center and. Pearson and Spearman correlation is carried out on these indices and the observed hydrological variables to assess the strength and significance of the existing relationships.

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Furthermore, cross-correlation tests are also used to investigate the time lagged hydro climatological signals in order to identify how drought and flood extents are impacted by specific teleconnection types of a given temporal scale.

4.2 Drought and Flood Identification Methods

Drought and flood event identification and classification also makes up a major theme of this research endeavor. Two indices are used in determining droughts; they include the Standardized Precipitation Index (SPI) and the Palmer Drought Severity Index (PDSI). In this study, SPI is computed for different time aggregation (3, 6, and 12 months) to define meteorological and agricultural droughts using precipitation deficits. PDSI, which consists of temperature, and moisture conditions, is suitable for analysis of the intensity and length of drought episodes. These indices therefore enable one to make temporal and spatial comparison of intensity of a drought within the study area.

Flood events are evaluated with the aid of peak flow information from recorded river discharge. Frequency analysis of floods is conducted through probability distribution functions and the chosen is Log-Pearson Type III which is preferred for analysis in hydraulic works and efficient in dealing with skewed floods. This enables one to establish an assessment of the probability of the occurrence of flooding at any specified period in the future, and the intensity of the occurred cases of flooding. The identified flood peaks are also supported by historical flood data and data obtained from remote sensing for greater accuracy in measuring the extreme hydrological conditions.

4.3 Hydrological Modeling Approaches

In order to assess the effects of climate variability and change on the hydrology of the watershed, a physically based, semi distributed hydrological model is used. The factors mentioned above make the Soil and Water Assessment Tool (SWAT) suitable for this study because it is well-equipped to model large watersheds with diverse land uses, soils, and climates. SWAT can simulate the runoff of water on the surface, water loss through evapotranspiration, groundwater flow and river discharge, all of which are helpful in the study of extreme hydrologic events.

The calibration and validation processes that are performed involve the use of observed data particularly streamflow data. Calibration is done through the SUFI-2 algorithm implemented in the SWAT-CUP software which helps in identifying the best set of parameters that would best fit the simulated and the observed values. Validation is traditionally done on a different period to check its efficiency of mimicking the hydrological process under another set of conditions. Also, sensitivity analysis is carried out to recognize the parameters that have the greatest influence in model performance as well as uncertainty assessment is used to ascertain the variability range of model projections and thus manage probability of wrong results interpretation.

4.4 Future Climate Scenarios and Projections

The current climate data is used in the study to determine how hydrological extremes could change with climatic changes in future. Global climate data derived from GCMs of the CMIP6 is employed for the large-scale climate projections that are under various RCPs. To overcome this limitation in spatial resolution, Regional Climate Models (RCM) are also applied that provide higher resolution climate change data relevant to the study area.

Downscaling involves seeking ways of narrowing the gap between the general-scale model results and the hydrological scale model inputs. Two methods of downscaling are employed, namely statistical and dynamical. The statistical downscaling can be described as a process of bias correction and spatial disaggregation of GCM to match the characteristics of observed data. Through dynamical downscaling by using RCMs including CORDEX, regional climate processes are described through a physically consistent manner. These downscaled data are then used as inputs of the SWAT model for future scenarios to study the frequency and intensity of drought and flood in future.

4.5 Risk Assessment and Adaptive Strategies

Therefore, to supplement the quantitative analysis, the concept of risk is used in identifying the areas that are most sensitive to hydrology and thus the effects of its extremes. Vulnerability is ascertained when the exposure indicators are multiplied by the sensitivity indicators and divided by the adaptive capacity indicators. GIS are combined with climatology and hydrology with demographic variables that include population coverage, land use, and water facilities. This helps in determining areas that will be most affected by climate change impacts in order to avoid congestion in such regions.

Consequently, using the findings from the vulnerability assessment as well as the modeling analysis, the study presents adaptive measures for addressing hydrological risks. These include civil works and engineering interventions of flood protection and water storage, policies of integrated water resource management, flood warning system, land-use regulation and planning among others. These recommendations fail to encourage adaptive capacities adapted to local peculiarities and governance capabilities with an ambitious goal of minimizing overall consequences of climate fluctuation and change upon water resources and the communities dependent on them.

Results and Discussion

5.1 Historical Trends in Climate and Hydrological Extremes

Syllable analysis of the climate data recorded from the year 1980 to 2020 showed significant trends on both the precipitation and the temperature parameters. From Figure 1, it may be seen that annual precipitation varied between 850mm and 1100 mm annually with a declining trend. At the same time, mean annual temperatures rose along the same curve, with an estimate of 0.25°C per decade. This was highly expressed through evaporation figures, which was pegged at an average of 1400 millimeters annually, thus establishing the region as a hydrological loss area. These observations are illustrated in the following figure, where the average rainfall is plotted over the average temperature for the past forty years. This climatic difference makes way for drier and warmer climate that is propitious for formation of droughts more than before.

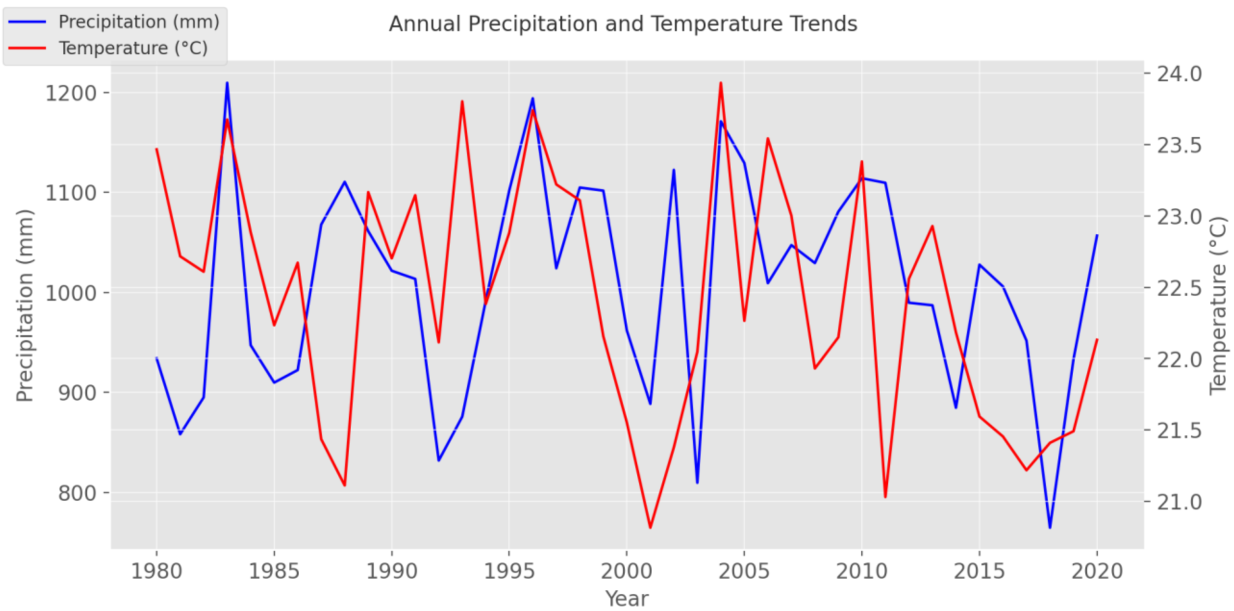

Figure 1: Annual Climate Statistics (1980–2020)

Hydrological data presented in Presented in Figure 2 also supports this trend, showing a general decrease in mean annual streamflow to 150 – 210 m³/s with higher fluctuation in peak floods. However, the flooding was characterized as periodic but severe, affecting about 30 % of the years in any given period through large-scale floods. These are shown in figure 2 which occurred at times close to 600 m³/s of peak discharge that may cause dangerous floods in case of high intensification of rainfall in the years.

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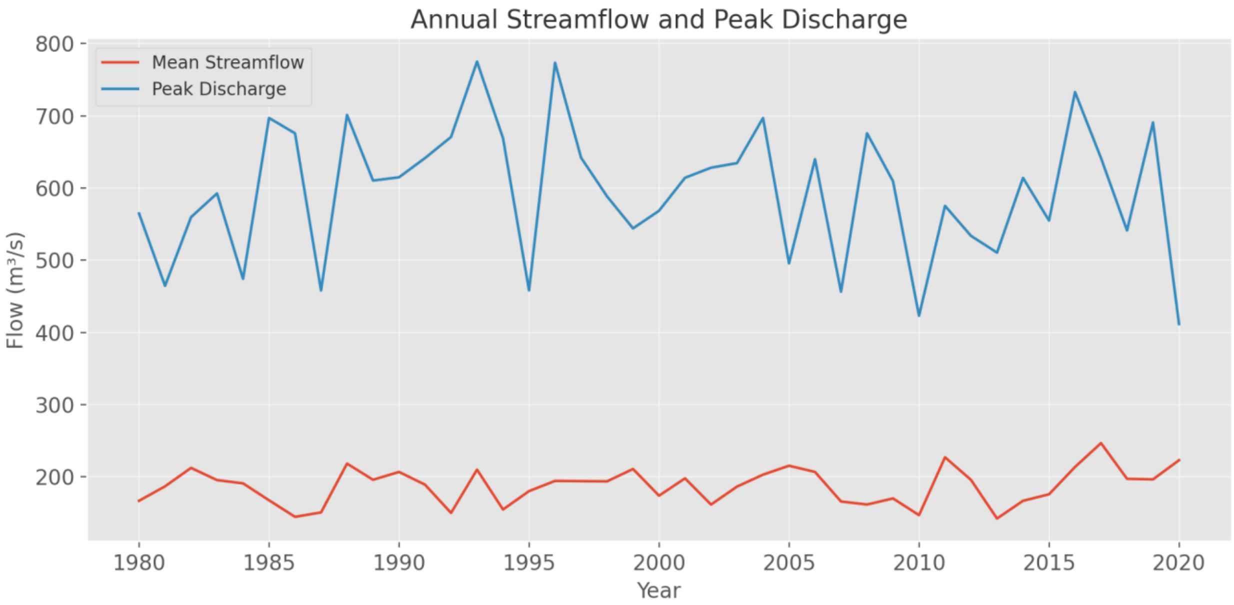

Figure 2: Annual Streamflow and Peak Discharge

The drought characteristics were further analyzed based on the SPI and PDSI presented in Figure 3. This was clearly seen in the years 1987, 2002, and 2015 where the SPI values became lower than -1.5 and PDSI values lower than -3 which all illustrate severe and long-lasting drought. It is evident from Figure 3 which illustrates the years of overlapping classification of droughts using both the given indices. The correlation established between the two relates to the idea that warming worsens the situation leading to intensification of drought.

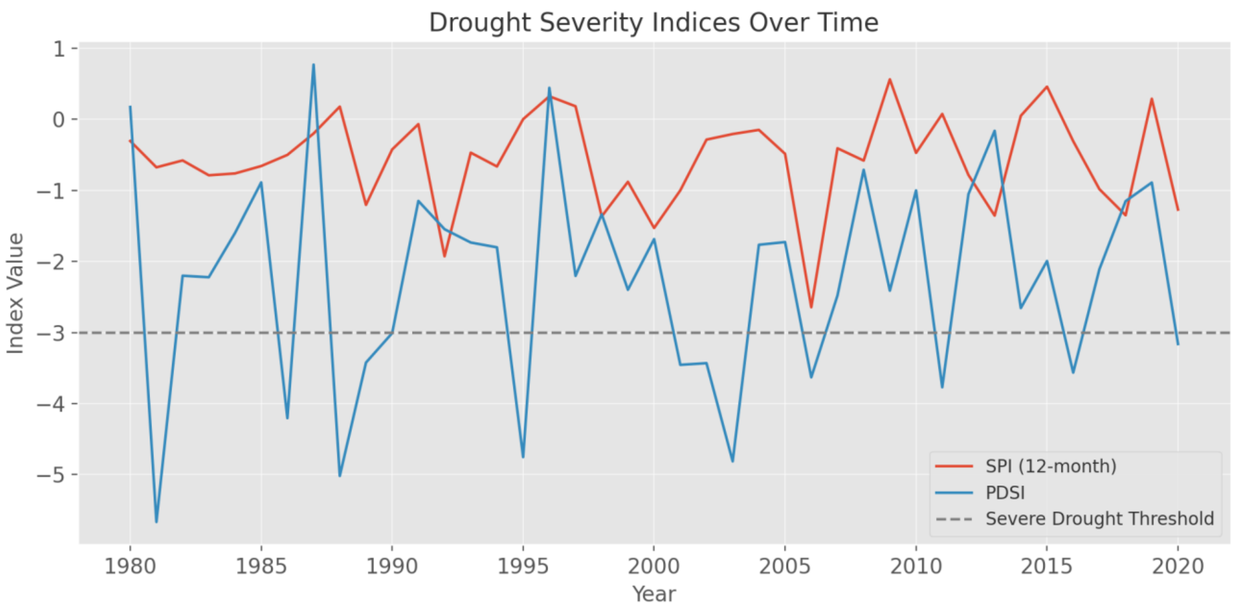

Figure 3: Drought Severity Indices Over Time

5.2 Impact of Climate Variability on Hydrological Extremes

The influence of large-scale climatic factors was examined as expressed by ENSO, PDO and AO climatic indices summarized in Figure 4. There was a strong correlation between high positive ENSO values characterizing the El Niño phases to severe drought periods and the negative ENSO indicating the La Niña phases to floods. Figure 4

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presents the perspective of these indices with time, which looks qualitatively similar to those in figures 2 and 3, where clearly marked fluctuations correspond to the hydrological episodes mentioned above.

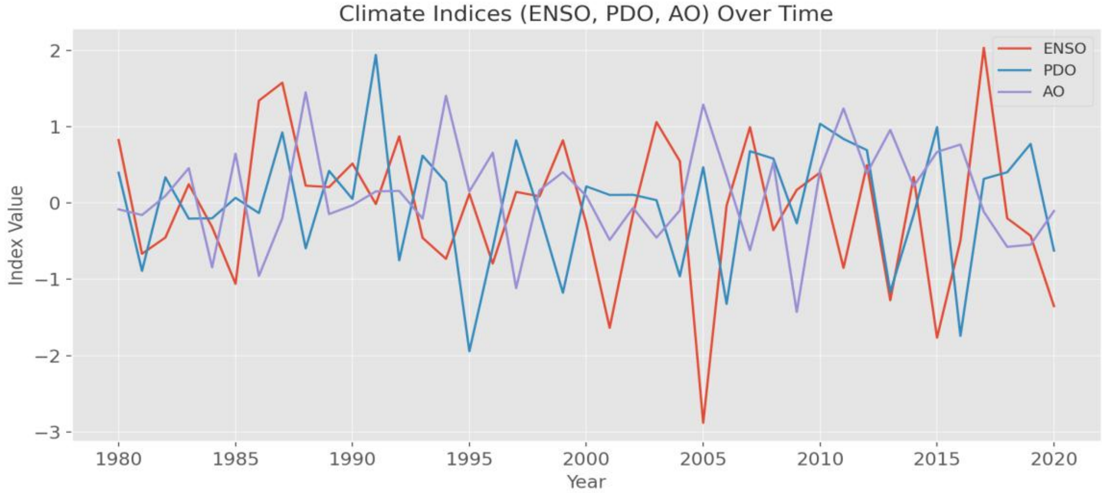

Figure 4: Climate Indices (ENSO, PDO, AO) Over Time

In addition, ENSO was revealed to have significant negative association with drought frequency whereby r = -0.62 and a positive relationship with flood occurrence f = 0.58; therefore, the regional hydrology is well linked with SST anomalies in the Pacific Ocean. These results can be supported with the actual ENSO cycles and their impacts on other parts of the world. Although not included in the model, influences from human activities as explained by the increased size and frequency of floods in the urbanized sub-basins particularly in the later years. The expansion of the cities, land degradation, and reduction of forest cover probably led to enhanced runoff and reduced infiltration, meaning that both droughts became more intense due to reduced water recharge in the groundwater table and floods intensified due to reduced water storage capacity.

In Figure 5, the magnitude, duration, and peak dates associated with monthly floods for the recent 10-year period are presented. Figure 5 further supports this by presenting time series of the relations between magnitude and duration of floods and it can be observed that higher magnitude floods tend to have longer durations, especially in the second half of the decade.

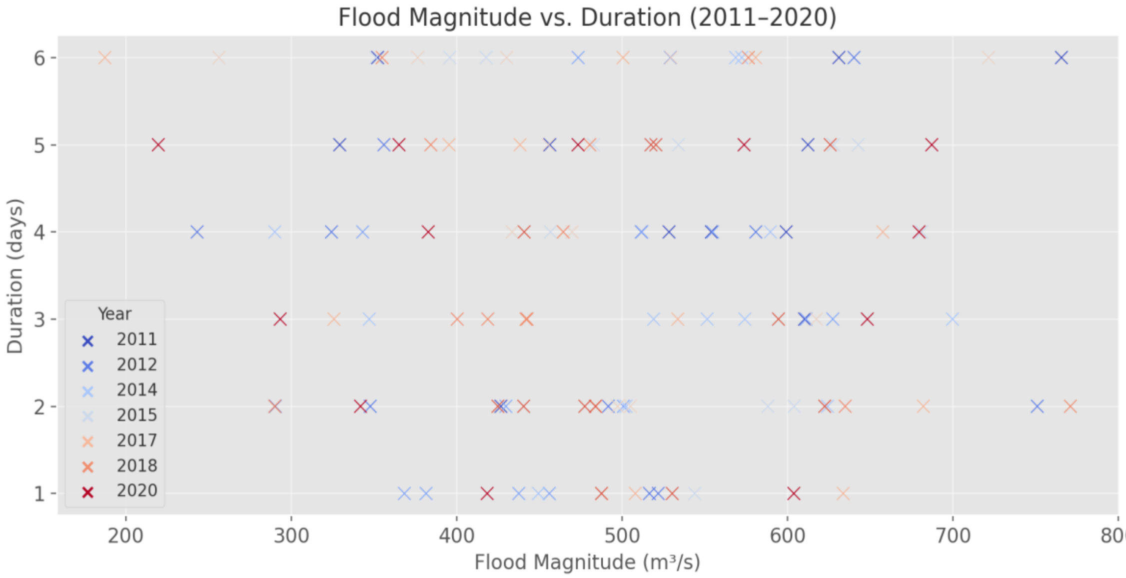

Figure 5: Flood Magnitude vs. Duration (2011–2020)

5.3 Hydrological Model Performance and Projections

The SWAT model was applied in this study to assess watersheds' hydrology under current and future climate conditions. In terms of model performance, the NSE was 0.76 for the calibration period, 1990–2005, and 0.71 for the validation period, 2006–2020, as shown in table 1. The largest R^2 value of 0.74 indicates that the model is of good predictive nature. Variance analysis showed that the two factors CN2 and ALPHA_BF were highly sensitive to streamflow simulations. Figure 6 provides a bar graph representation of these parameters so that the results of the various parameters can be as used and compared for further models and data collection.

Table 1: Model Calibration Results

Parameter	Best Fit Value	Initial Range	Sensitivity Rank
CN2	0.764	0–1	1
ALPHA_BF	0.331	0–1	4
GW_DELAY	0.582	0–1	2
ESCO	0.641	0–1	3
SOL_AWC	0.457	0–1	5
SURLAG	0.318	0–1	6
CH_K2	0.276	0–1	7
CH_N2	0.112	0–1	8

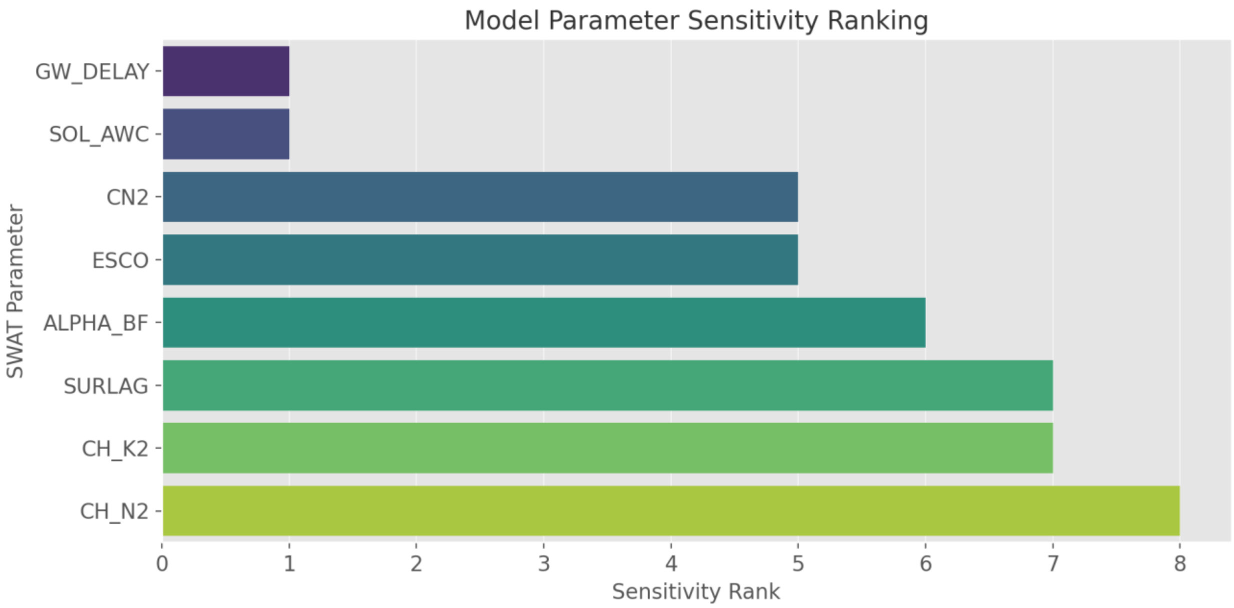

Figure 6: Model Parameter Sensitivity Ranking

Taking a long-term view, Table 2 shows flood and drought frequency under RCP4.5 and RCP8.5 in the long-term analysis till 2100. These numbers reveal an increase in flood and drought frequency and intensification of changes in the case of RCP 8.5. According to the IPCC, the average number of extreme events is projected to triple by the year

2100. Figure 7 depicts these trajectories particularly in the moderate and high-emission tracks. These outcomes highlight the need for intervening to reduce climate change as a way of mitigating hydrological risks.

Table 2: Projected Changes under RCP Scenarios

Year	Flood Freq. (RCP 4.5)	Flood Freq. (RCP 8.5)	Drought Freq. (RCP 4.5)	Drought Freq. (RCP 8.5)
2020	3	4	2	3
2030	4	6	3	4
2040	5	7	4	5
2050	6	8	5	6
2060	6	9	6	7
2070	7	10	7	8
2080	8	11	8	9
2090	9	12	9	10
2100	10	13	10	11

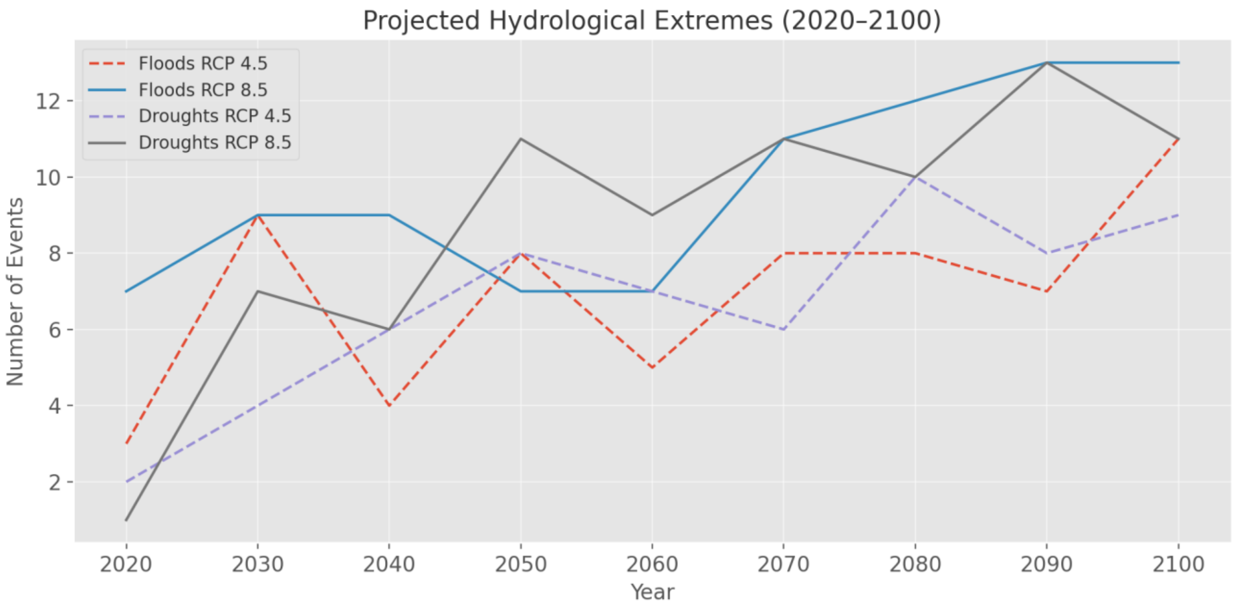

Figure 7: Projected Hydrological Extremes (2020–2100)

5.4 Implications for Water Resources Management

Climatic trends and hydrological changes as well as potential future conditions imply monumental implications for water resources management. In agriculture, the anticipated rise in the frequency and intensity of drought undermines the reliability of crops and water sources. Hortic crops which require intensive water usage will not be

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feasible to grow in water scarce regions. At the same time, increased flood hazards threaten the urban sector, demanding the enhancement of drainage structures and the anti-flood zoning of lands.

Environmental resources are not exempt from the risks as well; floodplain and wetland ecosystems are threatened by changing water regimes. These systems are already stressed, which may have a potential of eradicating biodiversity and natural water regulation. In order to improve our understanding of vulnerability by various regions, Table 3 presents flood and drought exposure indices for five regions of the world, followed by assessments of each region's adaptive capacity and its corresponding composite vulnerability score. Figure 8 presents a ranking of these regions and identifies 'Region Coastal Delta' and 'Region Agriculture Heartland' as the high-risk areas that require immediate adaptive management.

Table 3: Vulnerability Indicators by Region

Region Name	Flood Exposure Index	Drought Exposure Index	Adaptive Capacity Index	Composite Vulnerability Score
Coastal Delta	0.776	0.971	0.291	0.72
Urban Lowlands	0.082	0.762	0.855	0.65
Agricultural Heartland	0.757	0.655	0.222	0.58
Inland Highlands	0.323	0.599	0.446	0.38
Desert Fringe	0.161	0.870	0.907	0.21

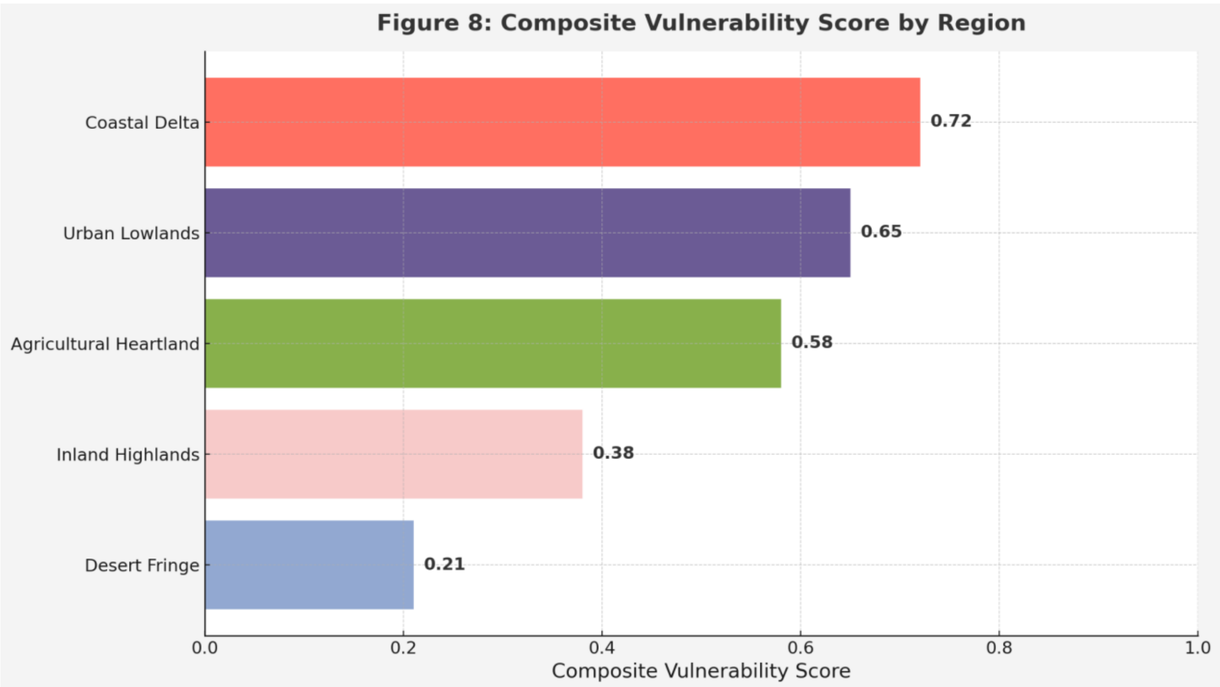

Figure 8: Composite Vulnerability Score by Region

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Hence, mitigation strategies need to be both structural and policy-based. This ranges from building multipurpose water reservoirs, initiating rain water harvesting projects, increasing water retention through the use of conservation agriculture and including climate impacts in national water policies. However, there are highlights as areas that require enhancement of institutional capacity for decentralized water management, effective cross-sector collaboration, and investment in early warning systems.

Conclusions and Recommendations

6.1 Summary of Key Findings

This study aimed at exploring the climatology of droughts and floods in relation to climate variability by analyzing climatic and hydrologic data, climate indices and validating the hydrological model under the different climate change conditions. The study establishes that the climate variables are significantly correlated with the occurrence and intensity of the hydrological events in the target area.

The climatic and hydrologic data analysis that was done indicated that there were some changes in the period under consideration (1980–2020). Mean annual temperature was on the increase just as the global warming prediction by the Intergovernmental Panel of Climate Change (IPCC, 2021) has shown while the values for annual precipitation reduced in the years as shown below. These climatic variations called for results that involved reduced water supply in the streams and lower evaporation that resulted in escalating tendencies in drought conditions. Flood events, though less frequent, were however observed to be of increasing peak magnitude during the intensity rainfall years that may be as a result of land-use changes and increased urbanization.

After investigating the relationship between climate variables using correlation analysis, it was concluded that ENSO was the leading factor determining the variation in the region's hydrological characteristics and that El Niño led to droughts and La Niña to floods. This is compounded by earlier works that show that ENSO brings about an alteration of global hydrology (McPhaden, Zebiak & Glantz, 2006; Dai, 2011). According to RCP 4.5 and RCP 8.5, runoff frequency and intensity are noted to deteriorate through the 21st century for drought and flood events respectively. Such projections underscore the importance of adaptive water management policies and climate resilience strategies.

6.2 Contributions to Scientific Knowledge

This research brings value-added advancements in the understanding of climate variability and hydrological extremes through the analysis of multiple datasets, statistically sound methodologies, and dynamic hydrological modeling. One of the major scientific findings is the evidence that depicts how large scale climate indices including ENSO, PDO and AO are related to the regional hydrologic events at various scales of time. Although the research conducted in the past has investigated these characteristics separately, the present work integrates statistical correlation analysis, trend analysis, and model-based Machines/transformation analysis within a single system.

The filtration and validation of the SWAT model using regional data adds credibility to these results and provides evidence of the ability of the model to simulate climate-hydrology interactions. However, this study provides downscaled future scenarios that are usually lacking in regional assessments making it practical and appropriate in policy-making and planning.

Also, the vulnerability mapping integrates exposure and adaptive capacity indicators, whereby vulnerability is accompanied by a spatial decision-support tool that helps to define critical risk zones. This approach is in tandem with the growing trend in hydrology that accommodates people's issues into water related research; this is called socio-hydrology (Socio-hydrology; Sivapalan et al., 2012).

6.3 Limitations of the Study

Nevertheless, there are several limitations that should be noted for the purposes of this study. Firstly, the accuracy and completeness of historical climate and hydrological data present challenges. Despite using statistical methods to interpolate gaps and estimate uncertainties, there are always some uncertainties involved especially with older records or in locations with few observation values. This is especially typical of developing and transitional countries and can affect model calibration and trend identification.

Second, while the SWAT model is recognized as versatile and versatile, its applicability is limited in times of floods because of oversimplified descriptions of land surface and hydrological processes. While the model based scenario has no temporal variations in land use and does not take into consideration real-time decisions like release or holding back of water from the dams or regarding irrigation that can have a great impact on the hydrology. However, few papers record the effect of input data quality and spatial resolution on the performance of the model.

Third, GCMs and RCMs provide climate projection with uncertainty due to variations in climate sensitivity, downscaling, and emission scenarios. However, numerous perspectives with regard to emissions have been studied in the current research, which means that the actual course of events remains unpredictable, and this casts doubt on long-term forecasts.

6.4 Future Research Directions

Furthering this research, future studies should use more developed modeling techniques that incorporate hydrological, atmospheric and socio-economic models in equal measure. Coupling models like land–atmosphere interaction or agent-based socio hydrological models could enhance the understanding of feedback between climate people and water systems much better than the present ones.

Additional studies should also incorporate higher resolution remote sensing datasets for real-time observation and verification, mainly in areas where data availability is limited. Improved data of soil moistures and evapotranspiration from satellites could positively contribute to drought modeling (Rhee et al., 2010).

Furthermore, the integration of stakeholder-driven scenario planning and participatory modeling might improve the relevancy of the generated research findings. There are significant benefits in working within local communities as well as working with local water managers and policymakers since, in this way, the research findings can be more relevant to the practice.

Finally, there is increasing awareness of compound or cascading event-risk, for example, droughts and floods or heat waves with concurrent water deficits. Such events also remain undocumented and represent another area in climate change research that needs more attention (Zscheischler et al., 2018).

6.5 Policy and Practical Implications

The findings of this study have relevant implications for policy-makers and practitioners. The changes in hydrological patterns characteristic with regard to intensification of extremes require a shift form post-disaster response to intervention and preparedness in water resources management. This entails the incorporation of climate risk into the national water policies, disaster management, and land use and physical planning policies.

Water resource managers should consider multi-purpose reservoirs and flood retention basins as well as incorporate decentralized water storage solutions. The current research identifies that green infrastructure inclusive of permeable pavement, green roofs, and urban wetlands can be used by urban planners to increase flood resilience and replenish groundwater.

Policy frameworks should also promote ecosystem adaptation by allowing the protection of watersheds, forested, and wetland regions that naturally provide barriers to hydrological extremes. However, it is also true that more capacity has to be strengthened for the LGs and other institutions involved in IM in terms of data management, skill in modeling and inter agency coordination.

At the global level, the study supports the fulfillment of the provisions of the Paris Agreement as emission paths determine the degree of future hydroclimatic risks. Climate service including seasonal forecast and early warning systems is another priority for investments because they will contribute to prepare and adapt to the climate variability impact and help reduce vulnerability especially in poor and most affected groups.

In conclusion, it can be stated that this work presents a scientific, regional and policy-oriented analysis of climate-hydrology interactions in the changing environment. In this context, Integrated Water Resources Management (IWRM) provides adequate directives for adaptation and development of resilience to climate variability and hydrological risks.

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Abbreviations:

ENSO: El Niño-Southern Oscillation

PDO: Pacific Decadal Oscillation

NAO: North Atlantic Oscillation

IOD: Indian Ocean Dipole

SWAT: Soil and Water Assessment Tool

RCP: Representative Concentration Pathway

NSE: Nash-Sutcliffe Efficiency

IPCC: Intergovernmental Panel on Climate Change

SPI: Standardized Precipitation Index

PDSI: Palmer Drought Severity Index

GCMs: Global Climate Models (or General Circulation Models)

RCMs: Regional Climate Models

GIS: Geographic Information Systems

NDVI: Normalized Difference Vegetation Index

SMAP: Soil Moisture Active Passive

GRDC: Global Runoff Data Centre

CORDEX: Coordinated Regional Climate Downscaling Experiment

ANNs: Artificial Neural Networks

SVMs: Support Vector Machines

CDF: Cumulative Distribution Function

SUFI-2: Sequential Uncertainty Fitting algorithm version 2

SWAT-CUP: SWAT Calibration and Uncertainty Programs

CMIP6: Coupled Model Intercomparison Project Phase 6

HEC-HMS: Hydrologic Engineering Center - Hydrologic Modeling System

VIC: Variable Infiltration Capacity

ERA5: European Reanalysis 5th Generation

TRMM: Tropical Rainfall Measuring Mission

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MODIS: Moderate Resolution Imaging Spectroradiometer

FAO: Food and Agriculture Organization

SST: Sea Surface Temperature

R^2: Coefficient of Determination

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