Natural streamflow reconstruction and quantification of hydrological drought in the Soan River basin, Pakistan

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RESEARCH ARTICLE

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Natural streamflow reconstruction and quantification of hydrological drought in the Soan River basin, Pakistan

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Abstract

Climate change and rapid socioeconomic development have exacerbated the damage caused by hydrological droughts. To ensure effective drought defense and infrastructure development, it is essential to investigate variations in hydrological droughts. The primary objective of this study is to reconstruct the natural streamflow by using Soil and Water Assessment Tool (SWAT) hydrological modeling. The hydrological drought at different time scales (1, 3, 6, and 12 months) were measured using the streamflow drought index (SDI). The statistical parameters, including Nash–Sutcliffe Efficiency and the Coefficient of Determination, which yielded values of 0.84 and 0.82 during the calibration period and 0.78 and 0.76 during the validation period, respectively, showed a satisfactory SWAT model performance. Additionally, the Pettit test was used to identify a change point in streamflow within the 1991–2015 timeframe, leading to the division of the study period into two distinct phases: an undisturbed period (1991–1998) and a disturbed period (1999–2015). The SDI index-based analysis revealed 9.39% moderate drought and 3.13% severe drought during the undisturbed period, while 11.76% moderate drought and 7.35% severe drought may happen due to the human influences that occurred in the disturbed period. These findings enhance the understanding of the hydrological drought variations in the Soan River basin for optimizing the water resources management system and effectively preventing and mitigating drought-related damages.

KEYWORDS
hydrological drought, streamflow drought index, SWAT model, Soan River basin

1 | INTRODUCTION

Droughts are repetitive natural disasters that can manifest in any climatic zone (Mishra & Singh, 2010). Droughts, under the evolving environmental conditions, have emerged as the limiting factor for socioeconomic development. Hence, the characterization of the drought

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Research Impact Statement

The streamflow drought index for 3 months predicted more severe droughts and catching a comprehensive attention as compared to 1-, 6-, and 12-month time scales.

process holds paramount importance in managing water resources and implementing an efficient disaster risk management system during periods of water scarcity (Hao et al., 2018; Pedro-Monzonís et al., 2015). Basically, drought is defined as a deficit in available water. Droughts have been classified into four types: meteorological, hydrological, agricultural, and socioeconomic droughts (Mishra & Singh, 2010; Wilhite et al., 2000). The World Bank (2018) the strain on its freshwater resources is increasing as time passes (Malik & Ahsan, 2016). The Emergency Events Database showed that between 2000 and 2019, droughts comprised 5% of the overall recorded disaster events, affecting roughly 1.43 billion individuals (United Nations Office for Disarmament Affairs, 2020). Similar to many other regions globally, Pakistan is also facing water scarcity, and this issue is particularly significant for the country due to its agrarian nature, contributing 22% to the gross domestic product, and its large population, which stands at 212 million. Over the past several decades, fluctuations in rainfall patterns, combined with an increasing population, have become a significant hazard to the flow of the Soan River basin. Streamflow plays a crucial role in the hydrological cycle, offering a comprehensive reflection of how a watershed responds to meteorological conditions and various basin characteristics. Streamflow functions as a crucial input for the management of water resources. Furthermore, the flow within rivers is vital for sustaining human activities and ecosystems reliant on river systems (Ficklin et al., 2016). Conducting a long-term evaluation of streamflow is imperative to analyze variations, assess the effects of climate change, and ensure environmental protection (Rumsey et al., 2020; Sadeghi et al., 2019).

Hydrological models are important tools for improving the understanding of hydrological processes (Clark et al., 2016) such as flooding and sedimentation, etc. (Feng et al., 2015). Hydrological models, such as the Soil and Water Assessment Tool (SWAT) model, have found extensive application in watershed management, contributing significantly to the enhancement of water resource security and quality (Arnold et al., 1998; Eshtawi et al., 2016; Lee et al., 2021; Malik et al., 2020). Several studies have been conducted on the streamflow (Ghoraba, 2015). The SWAT model was utilized to estimate the monthly volume of inflow into Simly Dam, and this model underwent calibration and validation using precipitation data to ensure that the simulated discharge was closely aligned with the precipitation data. Ahmad et al. (2015) established a correlation between precipitation data from two climate stations, specifically Murree and Islamabad, and the discharge data of the Soan River. Ashraf (2013) and Ashraf and Routray (2015) conducted research on hydrological changes resulting from alterations in land cover using the SWAT model for the contiguous Rawal watershed, which serves as a subwatershed within the larger Soan watershed. Due to its significant threat to both the ecosystem and society, numerous studies have endeavored to examine the spatial–temporal attributes of hydrological droughts (Chen et al., 2020; Kourgialas, 2021; Zhang & Jin, 2021). Various indicators were employed to identify hydrological droughts, including measures such as discharge quantile (e.g., Q95), standardized water-level index, surface water supply index, aggregate dryness index, and standardized runoff index (Gonçalves et al., 2023; Wang et al., 2022; Waseem et al., 2015; Zhang et al., 2017). Zhao et al. (2020) utilized a Streamflow drought index (SDI) with a 1-month duration to characterize hydrological droughts. Wang et al. (2022) used the flow below the 95th percentile (Q95) as the benchmark for low flow to evaluate potential changes in hydrological droughts.

The research gap in the context of the Soan River basin can be summarized as follows: Despite the widespread application of hydrological models in various river basins, the Soan River basin stands as an underexplored region with limited hydrological modeling efforts. This gap is critical because it hinders the development and validation of hydrological models tailored to the unique characteristics of the basin. Additionally, the basin faces challenges related to inadequate streamflow reconstruction due to a lack of long-term, reliable data for calibration, necessitating innovative methods for reconstructing natural streamflow in data-scarce regions (Ghoraba, 2015; Hussain et al., 2021). Moreover, the incorporation of climate change factors into hydrological models for the basin is notably lacking, especially in terms of assessing future hydrological drought scenarios under changing climatic conditions (Muhammad et al., 2020). Due to the reasons mentioned above, this study conducts natural streamflow reconstruction and quantification of hydrological drought in the Soan River basin.

A few studies have been conducted on the streamflow Muhammad et al. (2020) and Sarwar et al. (2022), but reconstruction of natural streamflow could not be done in the Soan River basin. That's why reconstructing natural streamflow by using the SWAT hydrological model is the novelty of this study. The objectives of this study are: (1) Reconstruction of natural streamflow by using hydrological modeling; (2) quantification of hydrological drought at different time scales. These findings will be valuable for policy makers in devising strategies to mitigate the damages caused by drought.

2 | MATERIALS AND METHODS

2.1 | Study area

The Soan River basin, originating in the Murree Mountains, serves as a significant tributary of the Indus River and plays a vital role as a water source for Pakistan's Potohar region. The Soan River basin is situated within the coordinates of approximately 71°45′ to 73°35′ East longitude and 32°45′ to 33°55′ North latitude. Before joining the Indus River, the Soan River passes through hydrological gauging stations at the Chirah and Dhoke Pathan basins. This basin covers a total drainage area of 6842 km^2, with elevations ranging from 265 to 2274 m. The annual average rainfall in the Soan River basin amounts to 1465 mm, the mean annual temperature fluctuate between 8 and 22°C, and the streamflow measures 214 mm at the Dhoke Pathan basin. The Soan River, stretching over 250 km (160 miles) in length, is infrequently employed for irrigation due to its mountainous path and shallow riverbed (Planning & Development Board, n.d.). The Dhoke Pathan sub-catchment experiences the presence of northwestern thorn scrub forests and falls within the xeric shrub land ecoregion of Pakistan. Just over half of the area consists of flat to gentle slopes, while more than 20% is characterized by medium slopes. The remaining portion of the region features either steep or very steep slopes. The northern part of the Soan River basin is primarily characterized by humid and sub-humid climates, whereas the southern regions are marked by arid and semiarid climates (Hussain et al., 2021). In recent years, a notable increase in migration from rural to urban areas has led to a substantial rise in the population of the study region, posing a persistent threat to water resources and drought occurrence (Figure 1).

2.2 | Datasets

2.2.1 | Hydrological data

This research utilized the discharge data for the Dhoke Pathan basin from 1991 to 2015. This data were collected from the Water and Power Development Authority.

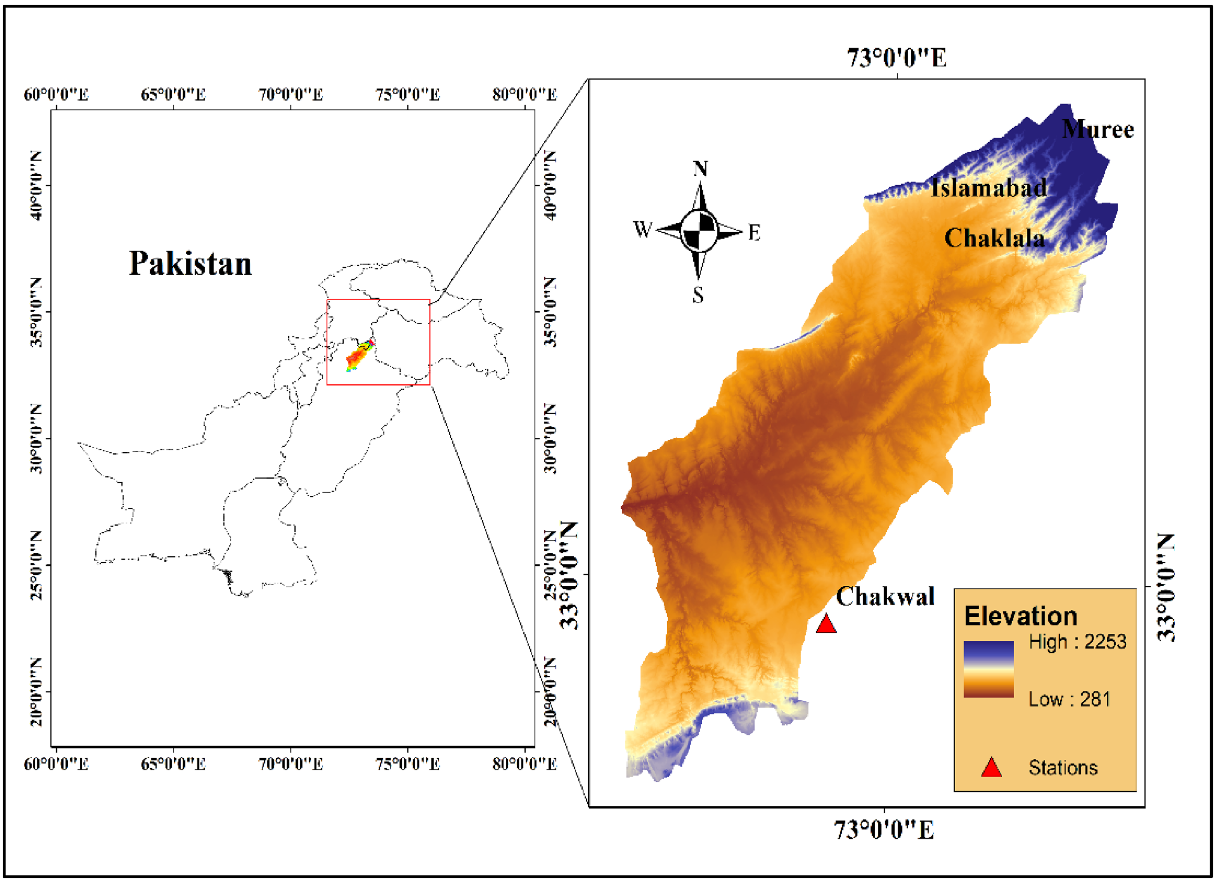

FIGURE 1 Location map of the Soan River basin and distribution of meteorological station.

2.2.2 | Climatological data

The climatological data of daily precipitation, relative humidity, maximum temperature, minimum temperature, solar radiation, and wind speed from 1991 to 2015 was collected from the Pakistan Metrological Department. Four meteorological stations named as Murree, Islamabad, Chaklala, and Chakwal in the Soan River basin were included in this study.

2.2.3 | Geospatial data

The digital elevation model (DEM) was acquired from NASA Shuttle Radar Topography Mission datasets with 30 m of spatial resolution (http://srtm.csi.cgiar.org/). Basically, DEM provides the elevation information, and for the study area, the elevation ranges are shown in Figure 2a. Land use and land cover data were collected from Landsat by using the Earth explorer USGS (https://earthexplorer.usgs.gov/). Supervised classification was performed for SWAT model land use and land cover maps. The land use and land cover classes were shown in Figure 2b. The soil data were downloaded from the FAO website. Basically, FAO is the food and agriculture organization that provides soil data globally. Different soil types were occurred in Figure 2c. All the study's data are listed in Table 1.

2.3 | Methods

The streamflow reconstruction was executed through the implementation of the SWAT hydrological model. Subsequently, the streamflow data underwent segmentation into two distinct periods: undisturbed and disturbed. The categorization into these periods was accomplished using the Pettitt test, a change point analysis method. The reconstructed streamflow data, both observed and simulated, were then employed in the computation of the SDI. The study followed the methodology depicted in Figure 3 to ensure a systematic approach to the analysis.

2.3.1 | Reconstruction of a natural streamflow by using SWAT model

The SWAT model, developed by the Agricultural Research Service of the United States Department of Agriculture (USDA), is a semi-distributed, mechanism-based model (Arnold et al., 1998; Mengistu et al., 2019). It functions at the watershed level to replicate the continuous evolution of hydrological procedures, erosion, vegetation productivity, and water quality while assessing the consequences of land management strategies. The model necessitates geospatial data, including topographic, land use, and soil information, as well as temporal data encompassing precipitation, temperature, wind speed, humidity, and solar radiation. Initially, it utilizes the topographic data to outline the designated watershed and establish the watershed outlet.

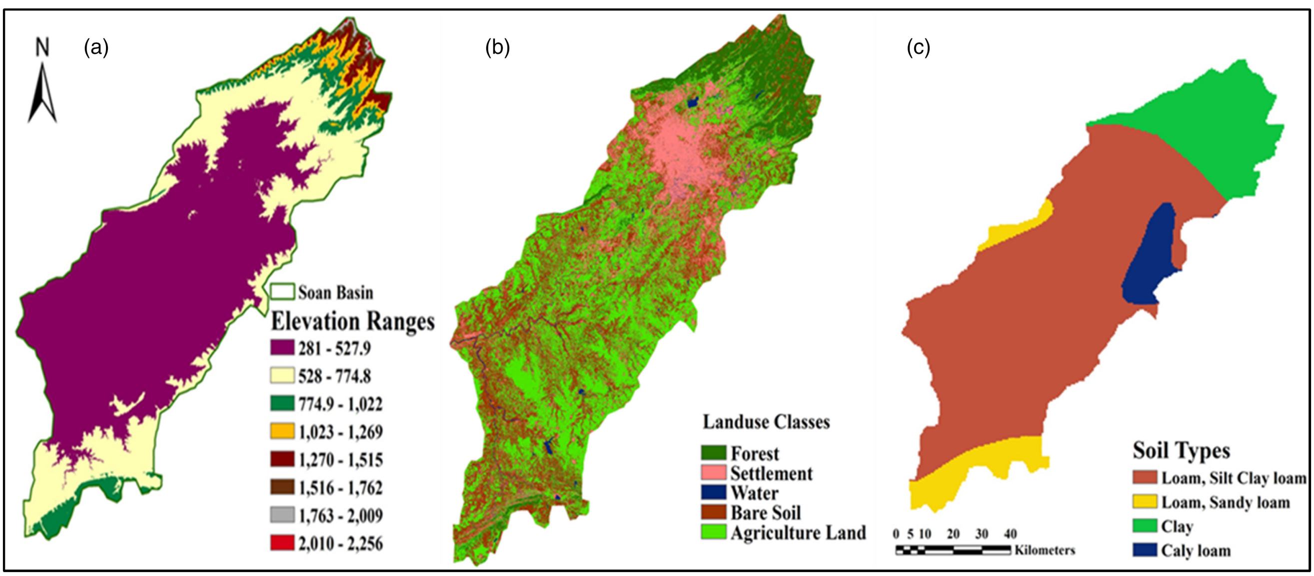

FIGURE 2 Soil and Water Assessment Tool (SWAT) input data: (a) elevation ranges; (b) land use classes; and (c) soil types.

TABLE 1 Description of the datasets used in this research study.

Sr.	Datasets	Duration	Temporal resolution	Spatial resolution
1	Hydrological dataset	1991–2015	Monthly	/
2	Meteorological dataset (precipitation, T_{max}, T_{min} wind speed, relative humidity and solar radiation)	1991–2015	Daily	/
3	Digital elevation model (DEM)	/	/	30 m

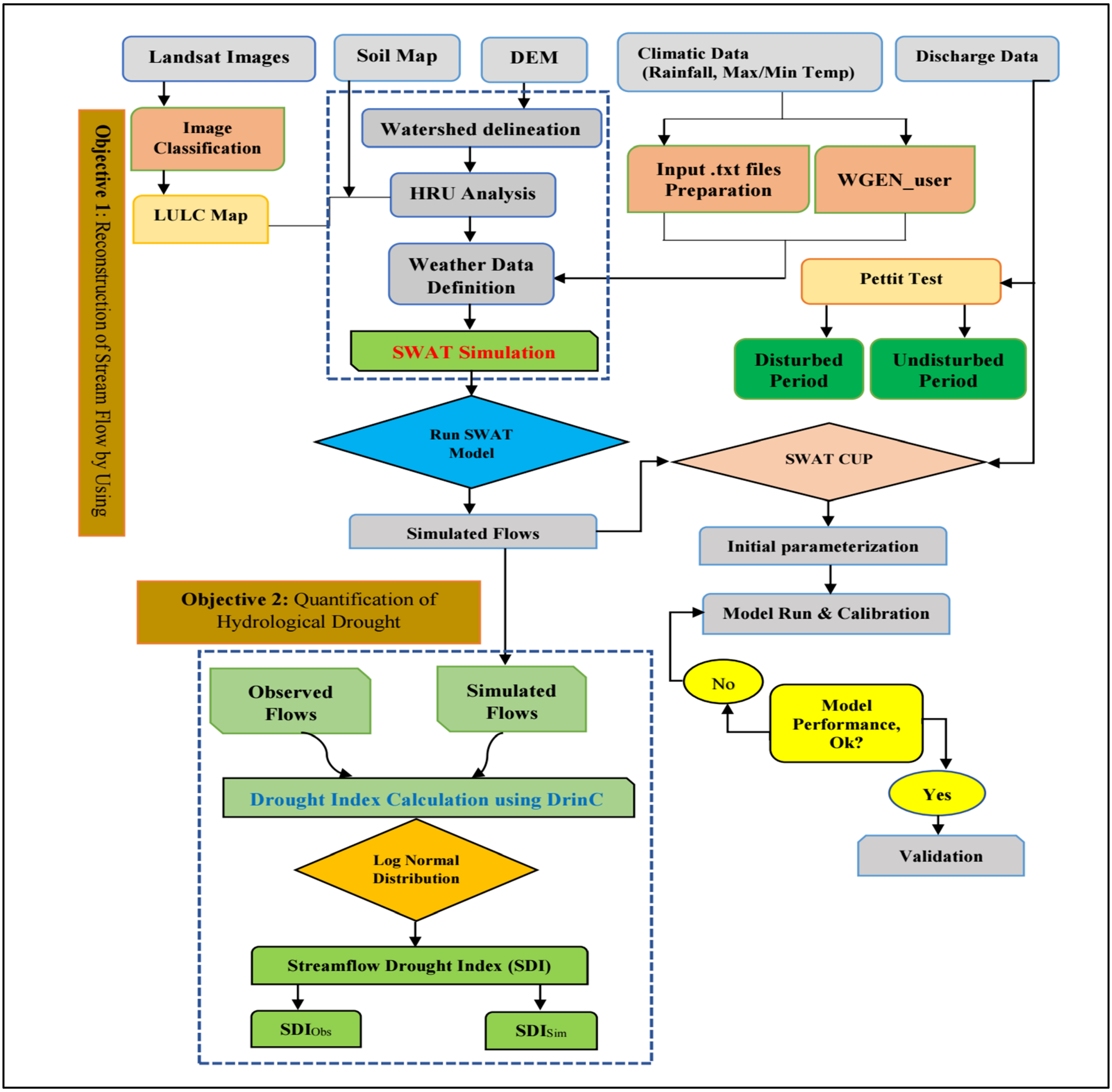

FIGURE 3 Overall schematic diagram of adopted methodology. CUP, Calibration and Uncertainty Program; HRU, Hydrological Response Unit, LULC, land use and land cover.

Subsequently, the model divides the watershed into numerous subbasins based on the threshold drainage area, which represents the smallest upstream drainage area from which channels originate. Following that, each subbasin is further fragmented into multiple aggregated land units that encompass distinct combinations of land cover types, soil classes, and slope characteristics, referred to as Hydrological Response Units. All the processes of SWAT are governed by using water balance equation, which are given below (Arnold et al., 2012).

$$SW_t = SW_0 + \sum_{i=1}^{t} \left(R_{\text{day}} - Q_{\text{surf}} - E_a - W_{\text{seep}} - Q_{\text{gw}} \right), \tag{1}$$

where, this equation involves various parameters, where SW_t represents the ending soil water content in mm, SW_0 denotes the initial soil water content on day *i* in mm, and *t* signifies the time in days. Additionally, R_{day} stands for the daily precipitation amount in mm, Q_{surf} represents the surface runoff on day *i* in mm, and E_a represents the evapotranspiration on day *i* in mm. Moreover, W_{seep} signifies the water entering the vadose zone from the soil profile on day *i* in mm, and Q_{gw} is the return flow on day *i* in mm.

Statistical parameters like Nash–Sutcliff Efficiency (NSE) and coefficient of determination (R^2) assessed the model performance and evaluated the goodness of fitness between simulated and observed streamflow. NSE determines the quantity difference between simulated and observed streamflow (Nash & Sutcliffe, 1970).

The coefficient of determination (R^2) quantifies the extent of correlation between simulated and observed streamflow data. Based on the results of these two statistical metrics, the model's performance was further assessed using the evaluation criteria recommended by the standards (Moriasi et al., 2015). The model's performance is considered "adequate" for simulating flow when $0.60 < R^2 \leq 0.75$ and $0.50 < \text{NSE} \leq 0.70$.

The most recent version of Arc SWAT (Arc GIS-SWAT), which serves as a link between the SWAT model and ArcGIS, is currently available. This study makes use of Arc SWAT version 2.3.4, which was developed for Arc Map 2.5 (Ghoraba, 2015). This research relies on the utilization of SWAT-Calibration and Uncertainty Program (CUP) and its Sequential Uncertainty Fitting 2 algorithm to attain accurate calibration. SWAT-CUP, Abbaspour et al. (1997, 2015), is a software module that is designed for automatic calibration and uncertainty analysis, utilizing the SWAT engine as its foundation. SWAT-CUP represents an advanced optimization system capable of handling various input parameters. Its sophistication enables the predefinition and optimization of model parameters either automatically during the calibration process or through manual iterations between calibration batches.

For the reconstruction of natural streamflow, the entire study period is divided into two periods: before the change, the period is called the "undisturbed period," and after the change, the period is called the "disturbed period". The observed streamflow data of the undisturbed period were used to calibrate the SWAT model. The metrological data of the "disturbed period" were used to calibrate the model to reconstruct the natural streamflow. During the disturbed period, the simulated streamflow is considered to be the natural streamflow, which is affected only by climatic factors (Chuphal & Mishra, 2023).

2.3.2 | Streamflow drought index

SDI was created by Nalbantis and Tsakiris (2009) and is a commonly employed tool for characterizing hydrological drought occurrences. In this research, only streamflow data were utilized, which is a commonly used representation of surface water resources. The practice of using streamflow as the primary variable for evaluating hydrological droughts is common, as numerous researchers have incorporated it into their investigations (Striem, 1989). SDI is categorized like mild, moderate, and severe drought according to Nalbantis and Tsakiris (2009) categories. The positive values of SDI represent the wet conditions, and the negative values represent the drought conditions (Table 2).

In this study, the severity of HD was determined using the SDI. Here, two SDI series were computed: the simulated SDI using streamflow reconstruction data, and the observed SDI using observed streamflow data. SDI values were calculated using the equation:

$$\text{SDI} = \frac{y - y_m}{\sigma}, \tag{2}$$

where *y* is the streamflow, y_m is the mean streamflow, and σ is the standard deviation of the streamflow.

2.3.3 | Pettitt test

Detecting a shift in the mean of a hydrological variable series at an unknown location can be achieved by utilizing the approach as presented by Pettitt (1980). The Pettitt test has found extensive application in identifying trends in hydroclimatic variables (Verstraeten et al., 2006; Zhang

TABLE 2 Hydrological drought states can be described using the streamflow drought index (SDI).

State	Description	Criterion
0	No drought	SDI ≥ 0.0
1	Mild drought	−1.0 ≤ SDI < 0.0
2	Moderate drought	−1.5 ≤ SDI < −1.0
3	Severe drought	−2.0 ≤ SDI < −1.5
4	Extreme drought	SDI < −2.0

& Lu, 2009). Utilizing this trend analysis and identifying change points enables the partitioning of a runoff series into segments corresponding to periods undisturbed and disturbed. The disturbed period can be defined as the period in which streamflow decreased abruptly. The period in which streamflow does not change is called the undisturbed period.

3 | RESULTS

3.1 | Hydroclimatic variations

A trend analysis was conducted for the Dhoke Pathan basin, revealing notable patterns in precipitation, streamflow, and temperature. Figure 4a,b illustrate a substantial decrease in precipitation and streamflow from 1991 to 2015. Likewise, Figure 4c,d depict a significant upward trend in both average maximum and minimum temperatures during the same period.

3.2 | Calibration and validation

The calibration and validation of the model were conducted using SWAT-CUP. An examination of the calibration and validation results of the SWAT model, as depicted in Figure 5, revealed a favorable monthly correlation between the simulated and observed flows. To

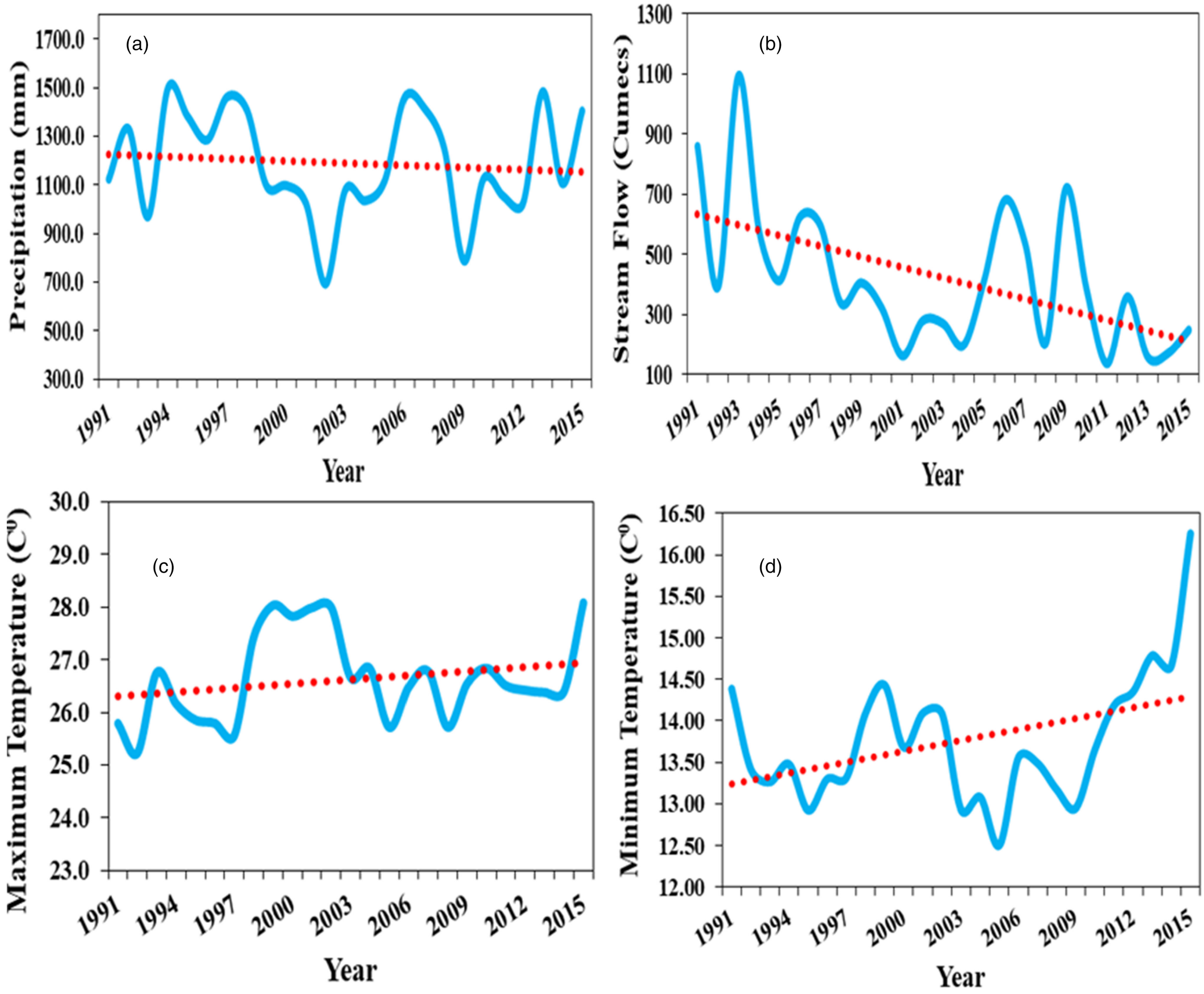

FIGURE 4 Hydroclimatic variation in (a) precipitation, (b) streamflow, (c) maximum temperature, and (d) minimum temperature.

assess the model's performance, key evaluation metrics such as the NSE and the coefficient of determination (R^2) were employed. For the Dhoke Pathan basin during the calibration period in 2006–2007, the NSE and R^2 values were determined to be 0.84 and 0.82, respectively. During the validation period in 2008–2009, for the Dhoke Pathan basin, the NSE and R^2 values were found to be 0.78 and 0.76, respectively.

3.2.1 | Reconstruction of natural streamflow by using validated SWAT model

Essentially, Figure 6 highlights the correlation between observed and simulated streamflows in the Dhoke Pathan basin from 1991 to 2015. The outcomes depicted in the figure demonstrate a favorable correlation between the observed and simulated streamflows. Figure 6 distinctly illustrates that during the undisturbed period, there was an underestimation in simulated streamflow from 1991 to 1998. This discrepancy is attributed to the increased precipitation during 1991–1998, leading to a heightened runoff. Subsequently, from 1999 to 2015, there is a substantial fluctuation in streamflow, with significant increases and decreases.

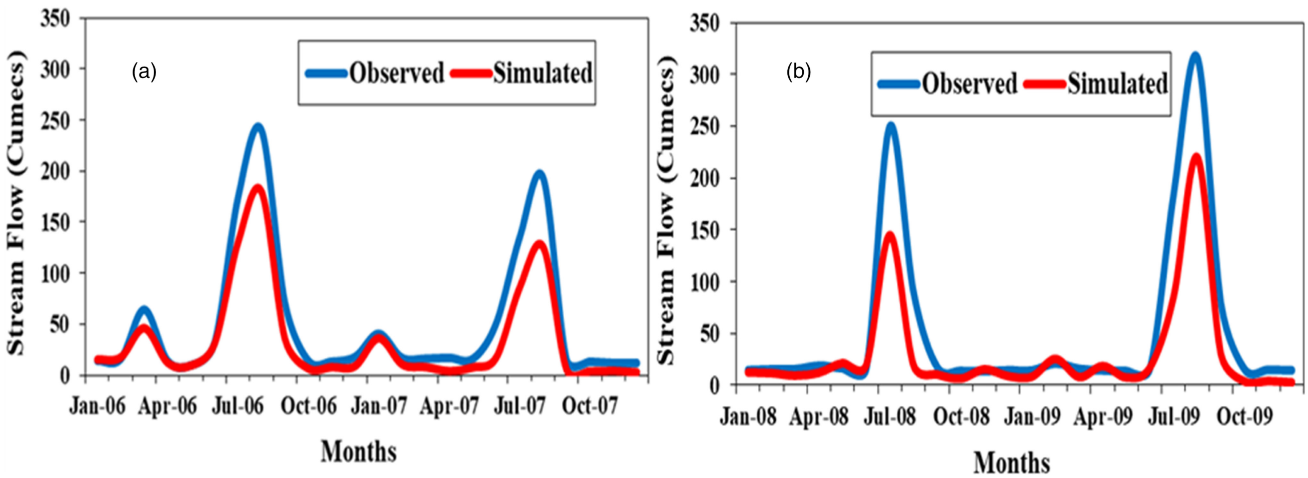

FIGURE 5 Simulated and observed streamflow in the Dhoke Pathan (a) calibration and (b) validation.

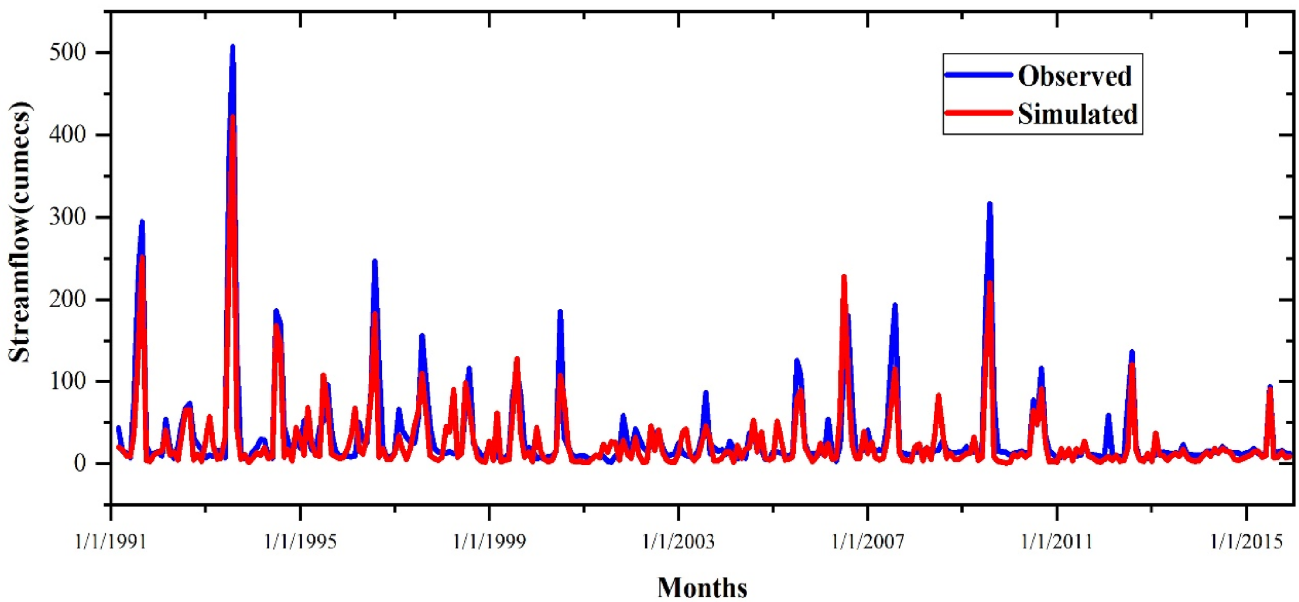

FIGURE 6 Reconstructed natural streamflow using a validated SWAT model during (1991–2015).

3.3 | Change point

Figure 7, a noticeable change point emerges around the year 1998 in the runoff data series for the Dhoke Pathan basin. This change point detection analysis suggests that the streamflow data series can be divided into two distinct phases, each characterized by particular criteria or observations. From the available information, it appears that a change point occurred in 1998, dividing the period into two phases: the undisturbed period spanning from 1991 to 1998 and the disturbed period covering the years from 1999 to 2015.

3.4 | Quantification of hydrological drought

The computation of hydrological drought in the Soan River basin utilized the SDI as the chosen metric. Within the basin, hydrological drought events exhibit substantial variability and exhibit an overall increasing trend. Figure 8 graphically represents the temporal evolution of the SDI at both monthly and annual scales, focusing on the Dhoke Pathan basin.

The findings from the analysis reveal a noteworthy pattern during the undisturbed period, there was a significant increase in streamflow observed between 1991 and 1998. However, a marked transition occurred during the disturbed period beginning in 1998, where streamflow experienced a significant and sustained decrease from 1999 through 2015.

In essence, the results presented in Figure 9 are a time series analysis of the SDI at multiple time scales, including 1-, 3-, 6-, and 12-month intervals. These findings collectively highlight a distinct pattern: during the undisturbed period spanning from 1991 to 1998, there was a notable and statistically significant increase in streamflow. However, a pivotal shift occurred in 1998, marking the onset of a disturbed period characterized by a pronounced and sustained decrease in streamflow, which extended from 1999 to 2015.

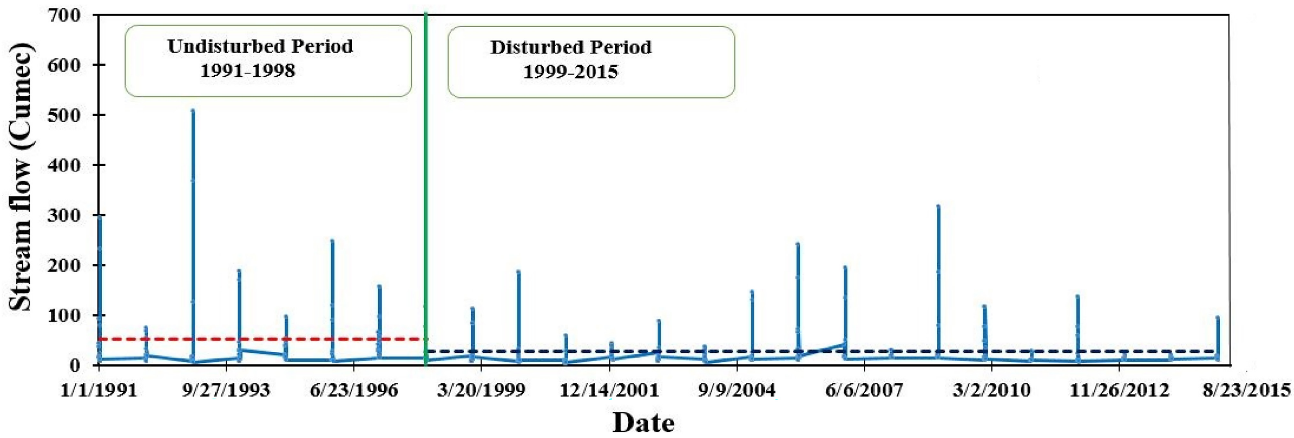

FIGURE 7 Change point analysis of streamflow in the Soan River basin by the Pettitt test.

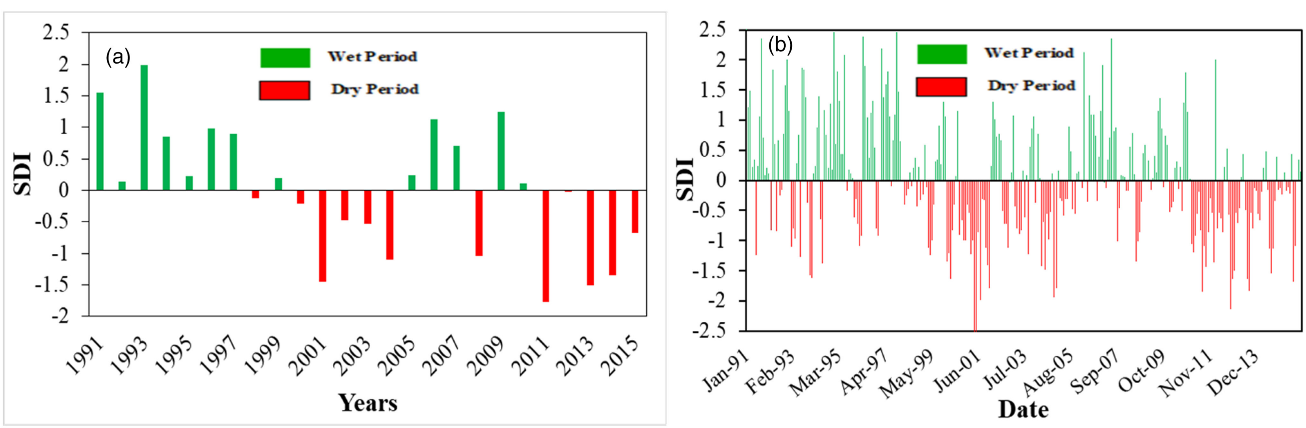

FIGURE 8 Quantification of SDI at (a) annual scale and (b) monthly scale.

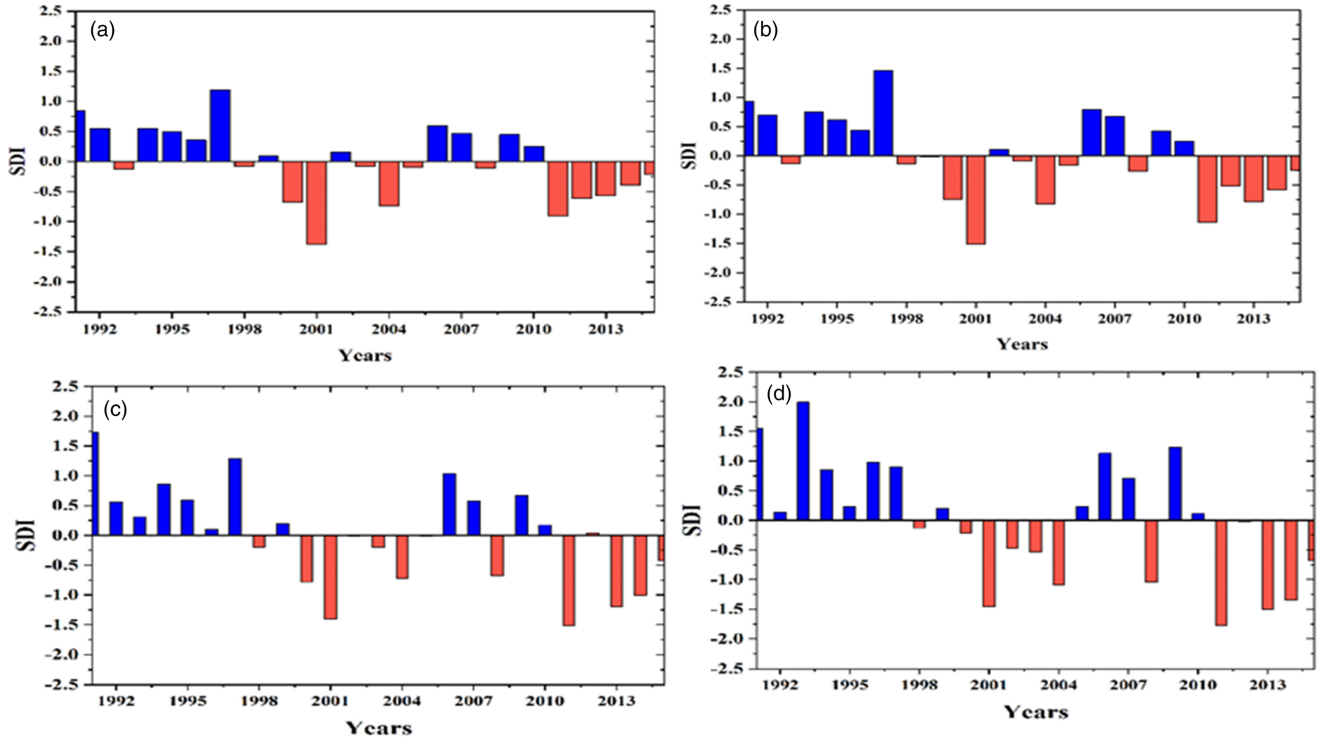

FIGURE 9 Time series of SDI at (a) 1 month, (b) 3 months, (c) 6 months, and (d) 12 months.

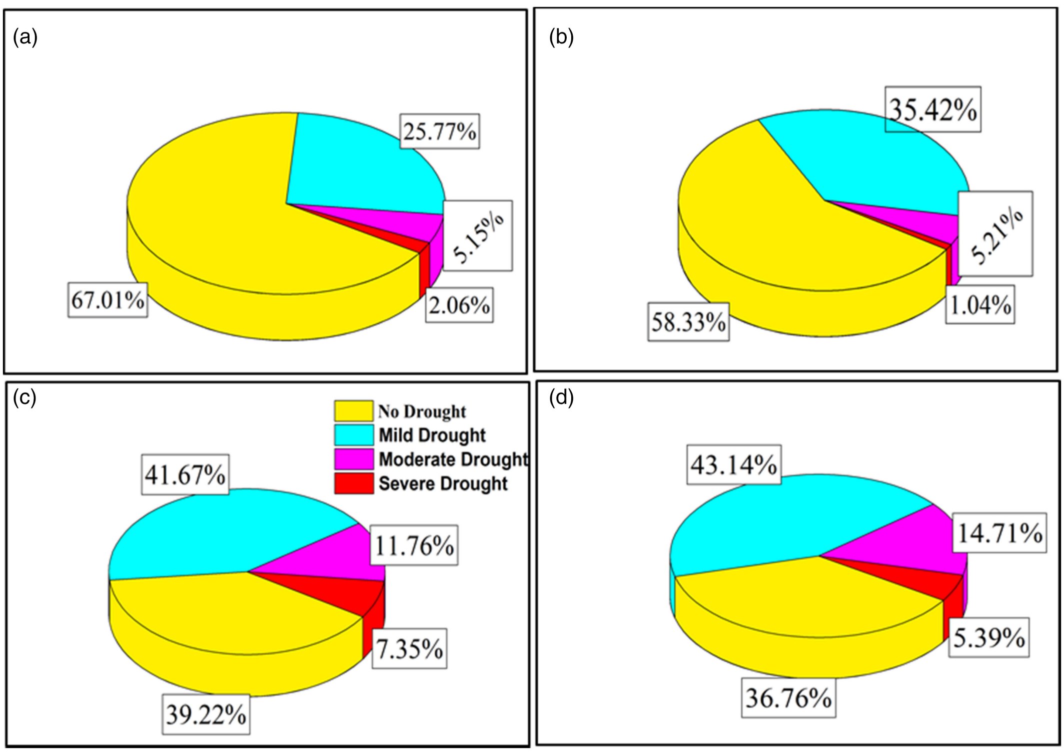

FIGURE 10 Percentages of different hydrological drought categories for the simulated and observed in the undisturbed period (a, d), and (b, c) for disturbed period.

Figure 10 shows that in the Dhoke Pathan basin during the undisturbed period from 1991 to 1998, the distribution of events was as follows: 67.01% were categorized as wet (non-drought) events, 25.77% as mild drought events, 5.15% as moderate drought events, and 2.06% as severe drought events.

However, in the simulated undisturbed period, the observed event distribution differed slightly: 58.33% were characterized as wet (non-drought) events, 35.42% as mild drought events, 5.21% as moderate drought events, and 1.04% as severe drought events.

During the disturbed period (1999–2015), 39.22% wet (non-drought) events, 41.67% mild drought events, 11.76% moderate drought events, and 7.35% severe drought events. But in the case of the simulated disturbed period, 36.76% wet drought events, 43.14% mil drought events, 14.71% moderate drought events, and 5.39% severe drought events occurred.

4 | DISCUSSION

The trend analysis showed that in the case of the Dhoke Pathan basin, a declining trend of precipitation (Figure 4a), maximum temperature (Figure 4b), and minimum temperature (Figure 4c) increasing trend was observed during the years 1991–2015. Our results matched with Muhammad et al. (2020) and Sarwar et al. (2022), who performed analyses for precipitation, streamflow, maximum temperature, and minimum temperature for the Dhoke Pathan basin for the years 1983–2015. The overall results indicated that the declining trend of precipitation in the Soan River basin runoff also decreased due to the lack of precipitation, and hydrological drought occurred more rapidly (Hussain et al., 2021; Muhammad et al., 2020; Sarwar et al., 2022; Shahid et al., 2018; Waseem et al., 2015). The temperature is also an important climatic variable. Due to the increasing temperature, evapotranspiration increased from the surface of the basin, and streamflow decreased significantly, causing the occurrence of hydrological drought in the Soan River basin (Hussain et al., 2021; Muhammad et al., 2020; Sarwar et al., 2022; Shahid et al., 2018; Waseem et al., 2015).

Overall, there is reasonably good agreement between observed and computed streamflows. The NSE for the calibration period was 0.84. Statistical analysis of computed and observed annual stream discharges for the calibration phase yield an R^2 value of 0.82. The NSE for streamflow in the validation period is 0.78. Figure 5 results stated that SWAT is capable of performing watershed simulation for predicting streamflow. However, at the larger watershed scale with higher discharge rates, the model consistently underpredicted stream flow, and both the NSE and R^2 values were low. For example, the NSE assesses the relative magnitude of residual variance to observation variance Nash and Sutcliffe (1970), and relying solely on it could lead to a potentially misleading interpretation of the model's capability (Adeyeri et al., 2020). Consequently, various objective functions, such as NSE and R^2, were employed in this study to evaluate the performance of the SWAT model during independent calibration and validation periods. These periods were chosen thoughtfully to encompass various hydrological processes, including peak, average, and low streamflow, thereby addressing the mitigation of errors (Adeyeri et al., 2020).

In this study, change point occurred in 1998 stream flow decreased significantly due to the construction of large dam, land use and land cover changes, and evaporation (Adnan et al., 2022; Jamil & Davis, 2009; Tan & Gan, 2015). Irrigation improvement projects such as the Baranai Village Development Project (BDVP) significantly enhanced agriculture in the Soan River basin. Under this development project, 235 mini dams and 161 ponds were constructed during 1991–2015. The construction of mini dams and ponds can increase the evaporation, which decreases the surface runoff. So, the construction of mini dams and ponds can be one of the possible reasons for decrease in surface runoff in the Soan River basin. The notable fluctuations were expected as a result of numerous development projects initiated by the Government of Punjab, Pakistan. These projects involve the creation of ponds and mini dams to enhance rainwater harvesting and bolster agricultural activities. The primary aim of these initiatives is to augment storage capacity for both crops and drinking water, potentially leading to elevated evaporation rates and increased water consumption due to population growth. Consequently, these factors could contribute to a decline in surface runoff and a heightened likelihood of drought occurrences. The mean annual runoff changes due to land use change are estimated (Tan & Gan, 2015). In the Soan River basin, land use and land cover decrease the runoff due to the increase of barren land converted into agricultural land (Muhammad et al., 2020). In this study, the temporal results of hydrological drought increased in disturbed periods because streamflow decreased significantly in the Soan River basin due to the lack of precipitation, land use, land cover, and agriculture practices increased from 1999 to 2015 (Muhammad et al., 2020; Sarwar et al., 2022; Shahid et al., 2018).

Additionally, hydrological droughts can be predominantly impacted by irrigation practices, as they tend to utilize both streamflow and groundwater, leading to a consequent decrease in levels of streamflow and groundwater (Wu et al., 2016). Drought events occurred continuously from 1991 to 2015, with the driest period for the study area being 1998–2004. Drought patches were also randomly observed in 1993, 1998–2004, and 2009. However, in the Dhoke Pathan basin, the frequency of hydrological drought increased from 1991 to 2015. Dhoke Pathan basin has more hydrological drought events in case of disturbed periods because climatic variables changed significantly from 1991 to 2015.

5 | CONCLUSIONS

This study proposed an effective framework for the SWAT model, change point analysis, temporal analysis of SDI, and severity of hydrological drought at multiple time scale in the Soan River basin, Pakistan. From the results, the conclusion can be summarized as follows:

- The SWAT hydrological model was calibrated and validated by using the observed streamflow, and the statistical parameters of performance evaluation revealed that there was a good correlation between observed and simulated streamflows. However, the model performed well to investigate the streamflow.
- The Pettitt test detected a change point around 1998, leading to the division of the runoff series into an undisturbed period (1991–1998) and a disturbed period (1999–2015). This change point reflected some human being interventions and the launched of BDVP.
- The temporal analysis of SDI indicated a higher occurrence of moderate to severe droughts during the disturbed period compared to the undisturbed period. SDI for 3 months predicted more severe droughts as compared to 1-, 6-, and 12-month' time scales.

This research enhances the understanding of watershed dynamics and contributes to the development of water resource management strategies. This research will offer valuable support to various stakeholders, such as climate change specialists, hydrologists, agronomists, and water resource managers, in the formulation of a robust drought mitigation strategy. Moreover, such studies experience challenges in accessing comprehensive historical streamflow data, limited hydrological monitoring stations, and potential uncertainties in modeling techniques. Future directions should focus on enhancing data collection efforts, expanding monitoring networks, and refining modeling approaches to improve the accuracy and reliability of natural streamflow reconstruction and hydrological drought quantification in the Soan River basin, Pakistan.

AUTHOR CONTRIBUTIONS

Muhammad Laraib: Conceptualization; data curation; formal analysis; software. **Mudassar Iqbal:** Writing – review and editing. **Muhammad Waseem:** Supervision. **Abu Bakar Arshed:** Resources. **Umar Sultan:** Methodology. **Hayat Ullah Khan:** Writing – review and editing. **Awais Rahman:** Writing – review and editing. **Khawar Abbas:** Writing – review and editing. **Muhammad Ayub Shah:** Data curation; writing – review and editing. **Samra Javaid:** Methodology; visualization. **Muhammad Atiq Ur Rehman Tariq:** Project administration.

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CONFLICT OF INTEREST STATEMENT

The authors collectively state that they do not possess any conflict of interest.

DATA AVAILABILITY STATEMENT

The data used in this study, including observed climatic and hydrological data, are the property of the Pakistan Meteorological Department (PMD) and Water and Power Development Authority (WAPDA), Pakistan, which can be requested via official channels. However, geospatial data which is freely available and can be accessed from the websites given in the datasets section of the manuscript.

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