Chapter 1: **INTRODUCTION**

1.1. **Prelude**

Runoff is the most significant indicator to assess our valuable water resources which are profoundly altered by the simultaneous effect of climate variability and human activities around the globe, exerting enormous pressure on freshwater availability and modifying catchment hydrology (Giambelluca, 2005) with potentially significant consequences for water availability, floods and droughts, erosion and sedimentation, ecosystem health, and human well-being, irrespective of its spatial and temporal extents. Two types of alterations or changes can be found in basin runoff: one is the *gradual change* (also called *trend*), and another is called *step change* (also called *sudden* or *abrupt change*). However, climate variability (or climate change) and human activities are the two major driving forces that independently cause such runoff alteration at the basin scale, although at the larger scale (e.g., hemispheric or global scale), both the factors are functionally found to be dependent to each other (Wang, Ishidaira, & Xu, 2012; Seyoum, Milewski, & Durham, 2015).

Direct human intervention in the basin hydrologic system like water abstraction for domestic water use, irrigation, and agricultural practices, industrialization (Liu et al., 2019) and water diversion (Wang, Wang, Fu, & Zhang, 2016) etc., and ensuing runoff change can be easily discernible and accordingly, the remedial measures can be formulated, but indirect human interference that occurs through a change in LULC (Afonso de Oliveira Serrão et al., 2022) very often remains invisible and, that is why, in water resource planning the issue does not get priority and importance. But this LULC change coupled with climate variability cause irreversible change in basin scale hydrologic system and its adverse impact on human society extends far beyond in future generations (Rivas-Tabares, Tarquis, De Miguel, Gobin, & Willaarts, 2022).

Although it is a global phenomenon, the issue has regional implications because of much geographical variations in river basin characteristics across the continents, and hence, the runoff response is getting manifested differently around the globe (V rty, Green, Salisbury, & Lammers, 2000) depending upon the scale of river basin (Xu, Yang, Yang, & Lei, 2014; Anil & Ramesh, 2017; Khoi, Nguyen, Sam, & Nhi, 2019; Pirnia et al., 2019; M. Wang et al., 2020), degree of human interference in the river basin (J. Chen, Li, & Zhang, 2005; Liang et al., 2015; H. Zhang, Meng, Wang, Wang, & Li, 2020; X. Tang et al., 2021), variation of geophysical condition of river basin (Khoi et al., 2019; Ma, Xu, Luo, Prasad Aggarwal, & Li, 2009; Zeng, Zhan, Sun, Du, & Wang, 2015; S. Zhou, Zhang,

& Guo, 2020), climate types (L. Juan Li, Li, Liang, Li, & Liu, 2010; Y. Zhang et al., 2017; Guoqing Wang et al., 2017; S. Wang, Li, & Wang, 2021) and many more.

The general scenario that can be deduced from previous studies (Wang, Ishidaira, & Xu, 2012; Anil & Ramesh, 2017) is that indirect human intervention that occurs through LULC change causes alteration in runoff in either direction, i.e., LULC change causes either increase or decrease in runoff depending upon the nature of intervention but the direct intervention that occurs through dam and reservoir, flow diversion, water withdrawal for domestic or other uses etc., causes a reduction in streamflow. The climate change impact, on the other hand, is not fully explored.

Moreover, there is no consensus among the researchers on which factors – climate change or human activity – are more impactful in the alteration of runoff. Swain & Patra (2019) studied 32 ungauged catchments of tropical monsoon climate in India spreading over Jharkhand, West Bengal, Chhattisgarh, Orissa, Telangana, Andhra Pradesh, Tamil Nadu, Karnataka, and Maharashtra, and their findings suggested that the role of climate variability is greater than the human activities to reduce the runoff during 1990-2011. Musie, Sen, & Chaubey (2020), on the other hand, reported the exact opposite result for Ketar and Meki Watersheds in Ethiopia.

Since the process is not straightforward, a region-specific investigation is needed to explore the functional relationship between river response and LULC changes amidst the changing climate. Otherwise, it would be very difficult to formulate a region-specific effective remedial strategy.

The present study intends to address such issues with special reference to South Koel River Basin in Eastern India.

1.2. **Statement of Research Problem**

In this research, an attempt was made to assess the impact of climate variability and human activities on the alteration of the runoff in the South Koel River basin in Eastern India under the tropical monsoon climate. The present research problem involves quantification and assessment of change in the runoff generation mechanism that occurs over time through complex interactions between climate variations and changing human activities.

Here, the South Koel River basin has been chosen as the study area because of its diverse surface characteristics, as reported in many literatures (CWC, 2014; Tirkey, Ghosh, Pandey, & Shekhar, 2018). The basin extends over the plateau and plain region, and hence there is diversity in soil types that lead to diverse land use land cover (LULC), particularly agricultural practices. A lot of changes have occurred in climate and LULC over the past couple of decades (Section: The Study Area), and that is why the area seems to be ideal for addressing the runoff change mechanism with the full extent of its complexity.

As reported by many researchers (Tang, Tang, Tian, Zhang, & Liu, 2013; Uniyal, Jha, & Verma, 2015; Wu, Zheng, & Xi, 2019; Yuan et al., 2019), the response of basin hydrologic system varies across the regions depending upon geographical conditions like climate, topography, soil, human culture and many other factors and even, basins with similar geophysical conditions produce different response depending upon the extent of the basin. Similar catchment responses were also found by many researchers (Li et al., 2019; Afonso de Oliveira Serrão et al., 2022) when they explored only the role of human activities in the alteration of runoff. So, it indicates that the runoff generation mechanism has become more complex under the condition of climate change.

There is also no uniformity across the spaces in the magnitude of the contribution of climate variability and human activity to cause a change in system response due to having non-linearity in the functional relationship between these two, which makes the system response more complex (Ashu & Lee, 2020; Mahmoodi, Wagner, Kiesel, & Fohrer, 2021).

The research problem which is stated here is already explored in many parts of the globe, but no attempt has been made to trace the issue under such diversified geophysical conditions which are found in the South Koel River basin. It would not be rational to infer those findings to the present study area since the system dynamics, as mentioned earlier, differs across the geophysical environments. A few studies (Pandey, 2017; Swain & Patra, 2019; Stuti, Pandey, & Gupta, 2020; Chaudhary & Pandey, 2022), on the other hand, have been carried out in the South Koel River basin, but they have not addressed the present problem. So, the response pattern of streamflow to climate variability and human activity is really an unknown aspect of the hydrological system in the context of the South Koel River basin that has created a research gap, and the present study is an attempt to fulfill the same.

1.3. **Description of Study Area**

1.3.1. **Location and Extent**

River South Koel originates near Nagri village in the Ranchi district of Jharkhand at an elevation of about 630 m and outfalls at river Sankh, and then the combined flow goes by the name Brahmani. North Karo and South Karo are two important tributaries of the river South Koel. The present study was exercised over the catchment above Jarikela (approx. 22º19′N and 85 º5′E), a village located about 50 km downstream of the South

Karo-South Koel confluence (CWC, 2014). It has an area of 10356.3 km^2 and is roughly elongated in shape. The basin extends from 21°54′N to 23°37′N and 84°24′E to 85°44′E that encompasses seven districts of Jharkhand, namely Latehar, Lohardaga, Ranchi, Gumla, Khunti, Simdega, and Paschim Singhbhum and two districts of Odisha namely Kendujhar and Sundargarh (Figure 1.1). Most of the basin is in Jharkhand, with only small areas extending into Odisha (Figure 1.2).

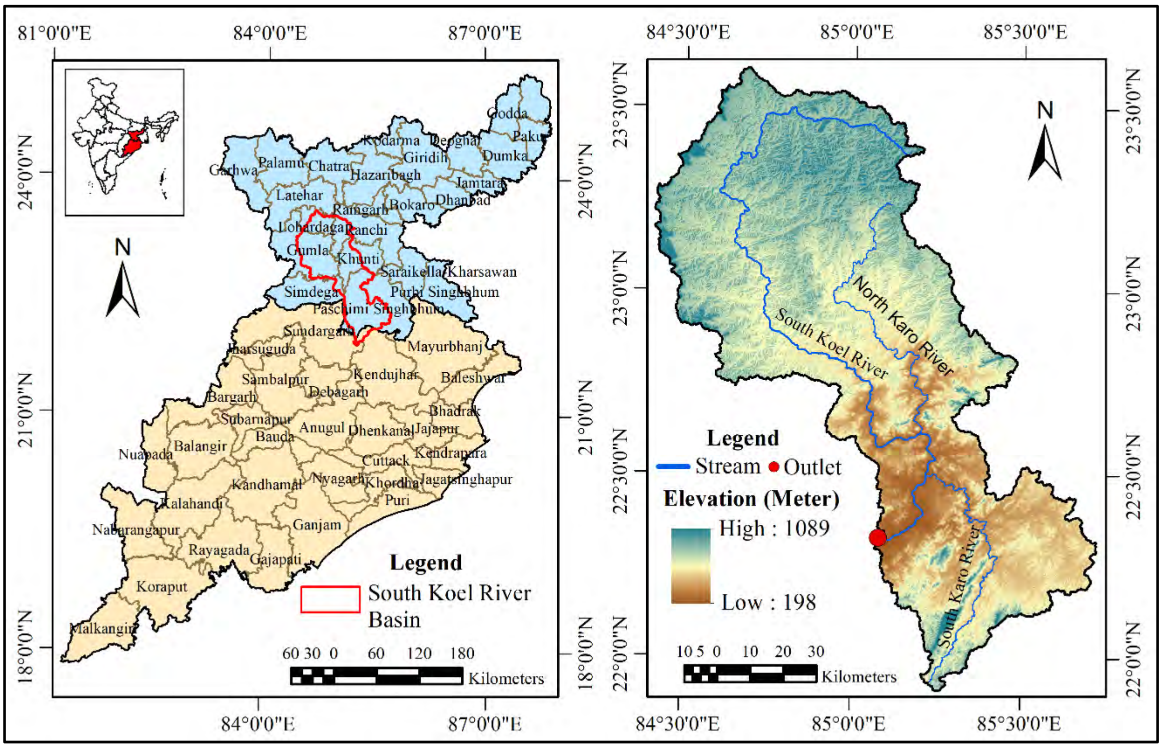


Figure 1.1 Location of the study area (*Source:* 2011 Census of India and SRTM DEM, 2022).

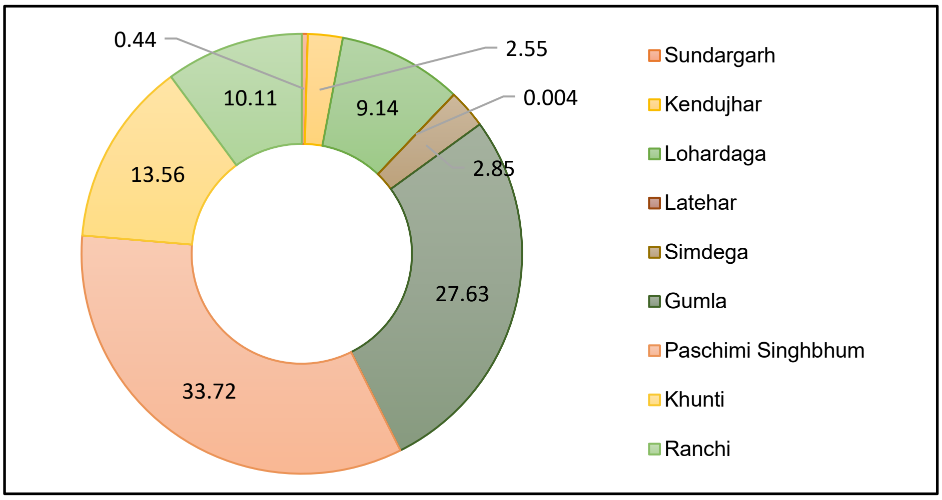


Figure 1.2 District-wise areal coverage of the basin (%) (*Source:* 2011 Census of India).

1.3.2. **Geo-lithological Characteristics**

The study area bears the imprints of various geological ages, with Proterozoic materials being the most dominant at 48.10% of the basin area, followed by Paleoproterozoic (29.85%), Archaean-Paleoproterozoic (12.76%), and Holocene (7.58%) materials. The Chhotanagpur gneissic complex is the most prominent geological formation, accounting for 49.51% of the area, whereas the Upper Bonai group, Lower Bonai group, and sediments make up the 14.08%, 9.24%, and 7.83% area of the basin respectively (GSI, 2022). Granite and gneiss cover about 46.79% of the basin, while slate, phyllite, and mica schist together occupy 20.80%, and the remaining part is characterized by other rock types (GSI, 2022) (Figure 1.3).

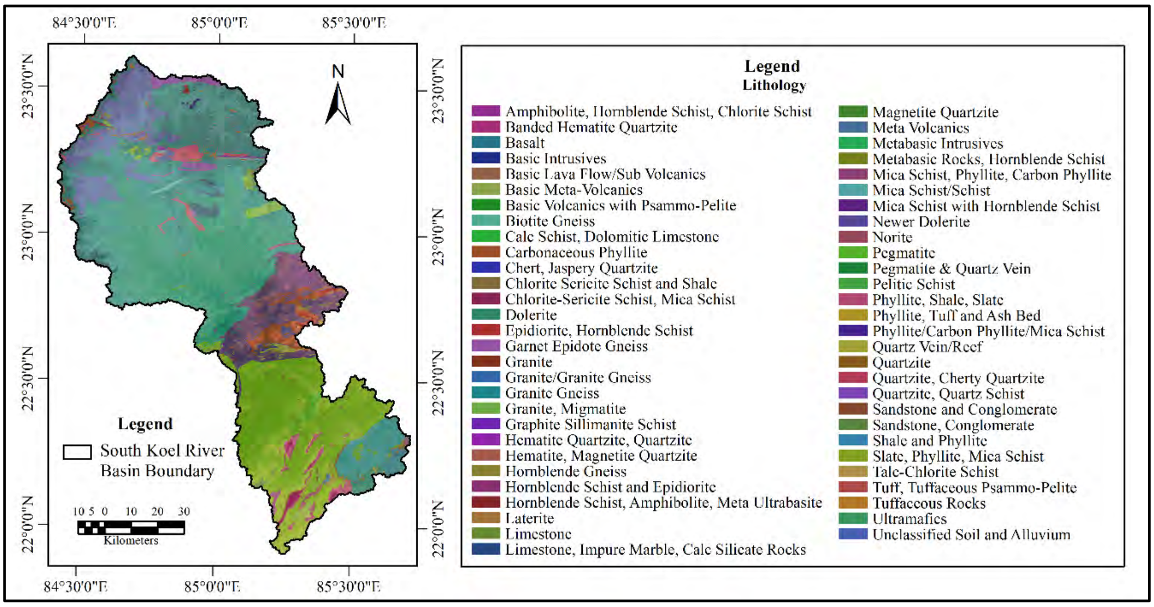


Figure 1.3 Lithology of the study area (*Source:* Geological Survey of India, 2022).

1.3.3. **Topography and Landforms**

The basin's elevation varies between 198 and 1089 m (WGS84 datum), with an average elevation of 643.5 m. Situated on the fringes of the Chhotanagpur plateau, approximately 90% of the basin's area is located above the 300 m contour line. The northern section of the basin has higher elevations ranging from 569 to 1089 m, characterized by undulating terrain and heavily dissected regions. Similar elevation and topographic characteristics are also found in some parts of the southern portion of the basin. In contrast, the middle and most of the southern portions have lower elevations ranging from 198 to 568 m. More than 64% of the basin's area consists of nearly level and gentle slopes (Figure 1.4 and Table 1.1).

Table 1.1 Elevation and slope zone of South Koel River Basin.

Sl. No.	Elevation (m)	% of the basin area	Slope (degree)	% of the basin area
1	198-302	6.54	0-2.32	32.81
2	303-378	8.3	2.33-4.89	32.06
3	379-448	11.07	4.90-8.23	14.5
4	449-511	11.09	8.24-11.84	7.52
5	512-568	15.36	11.85-15.44	5.07
6	569-620	15.3	15.45-19.04	3.45
7	621-670	16.45	19.05-22.90	2.37
8	671-753	13.9	22.91-27.28	1.41
9	754-882	1.34	27.29-33.20	0.65
10	883-1089	0.65	33.21-65.62	0.16

Source: Computed by the researcher from SRTM DEM, 2022.

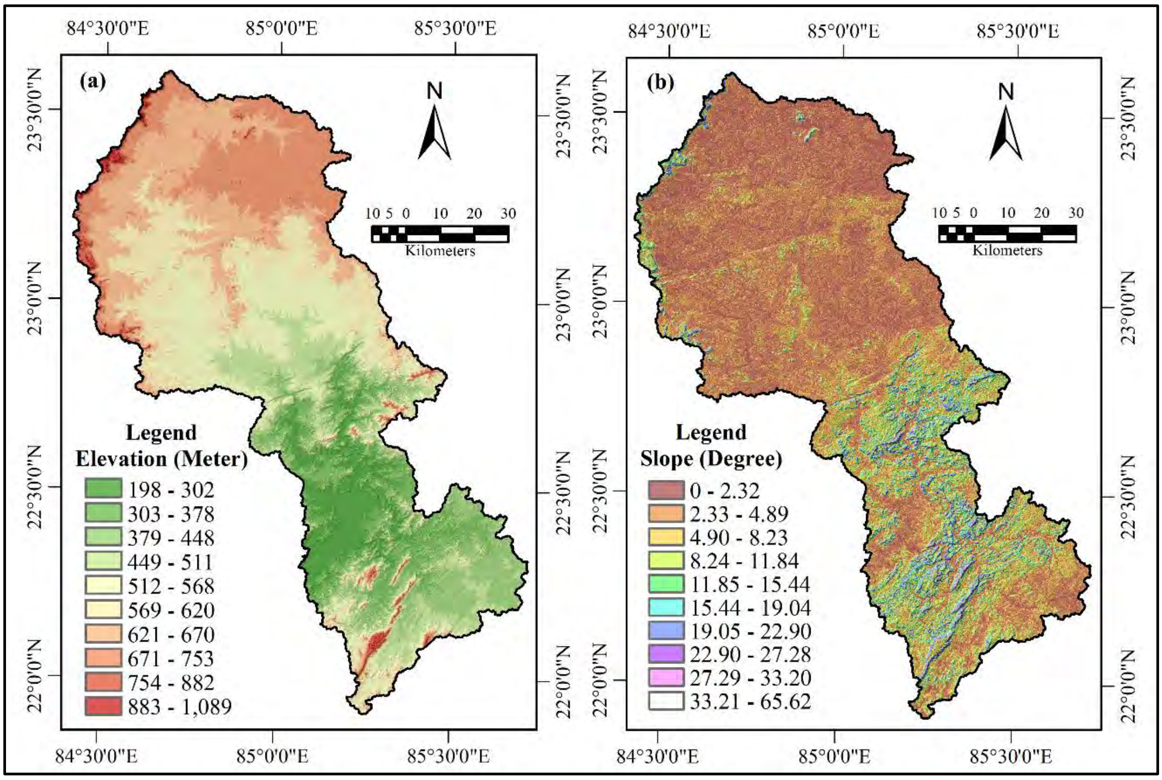


Figure 1.4 (a) Elevation and (b) Slope of the study area (*Source:* SRTM DEM, 2022).

The study area is mainly characterized by a pediment-peneplain complex resulting from denudational activities and covering about 62% of the basin. In addition, the area has moderately dissected hills and valleys formed by both denudational and fluvial processes, each sharing about 15% of the basin. The denudational process also moderately dissected the upper plateau, which occupies 2.19% of the basin (GSI, 2022). The distribution of geomorphic features is shown in Figure 1.5.

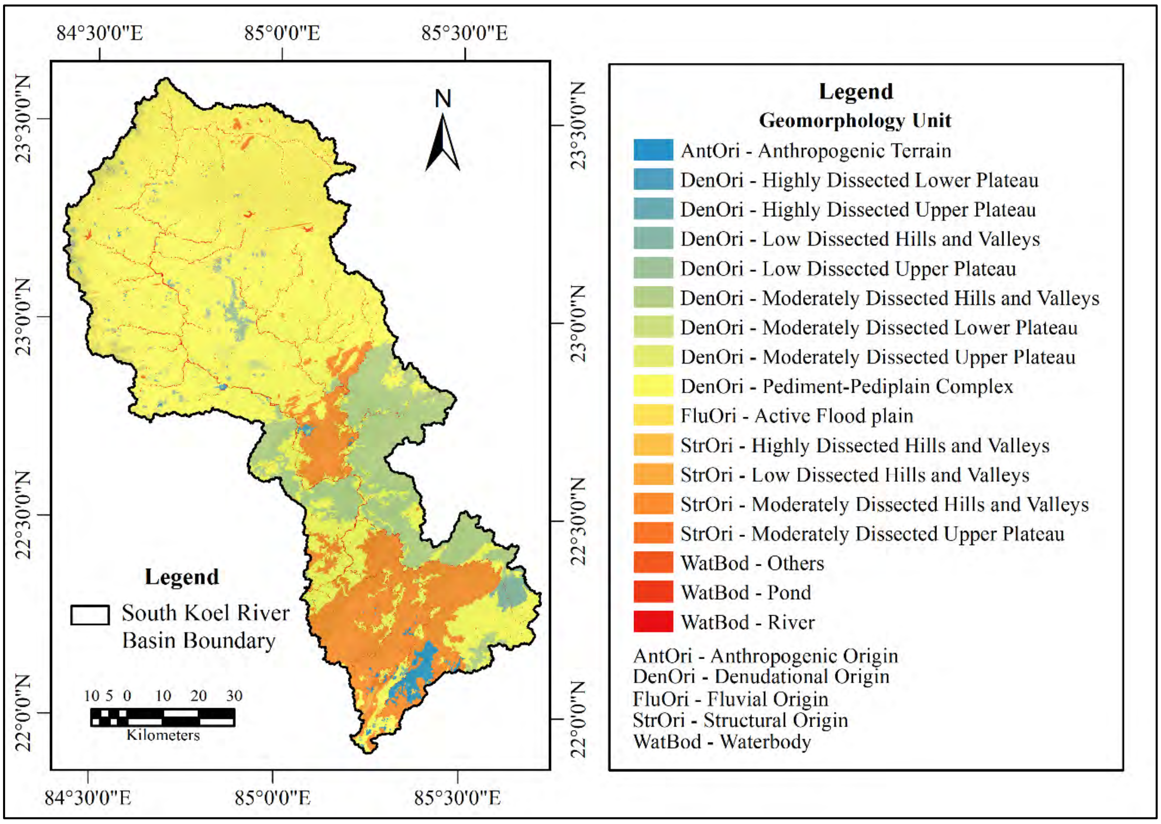
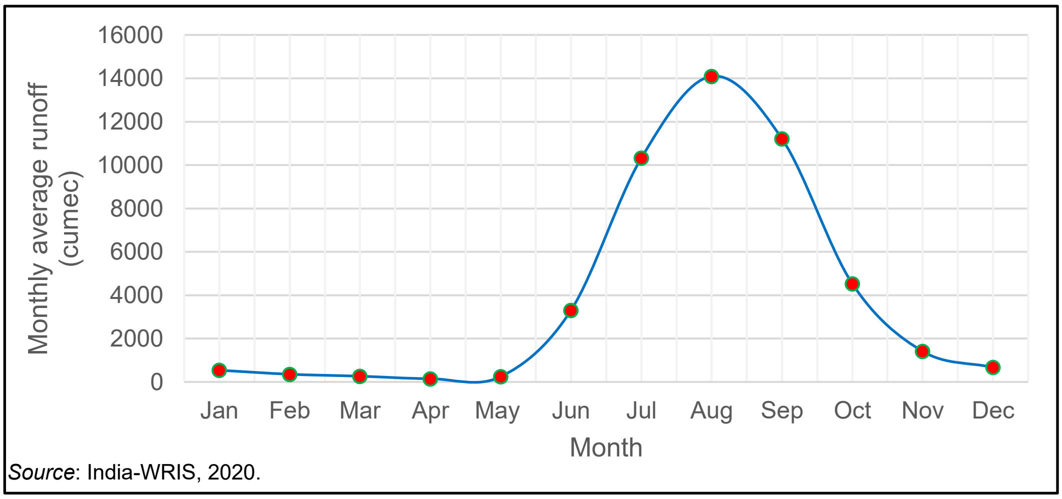


Figure 1.5 Geomorphic features of the South Koel River basin (*Source:* Geological Survey of India, 2022).

1.3.4. **The Hydrological Characteristics**

The basin has a maximum length of about 197 km and a width of approximately 90 km. The trunk stream of the basin, up to Jarikela, spans around 292.90 km, while the length of the North Karo River and South Karo River are 131.94 km and 115.85 km, respectively. The drainage primarily follows a dendritic pattern.



Source: India-WRIS, 2020.

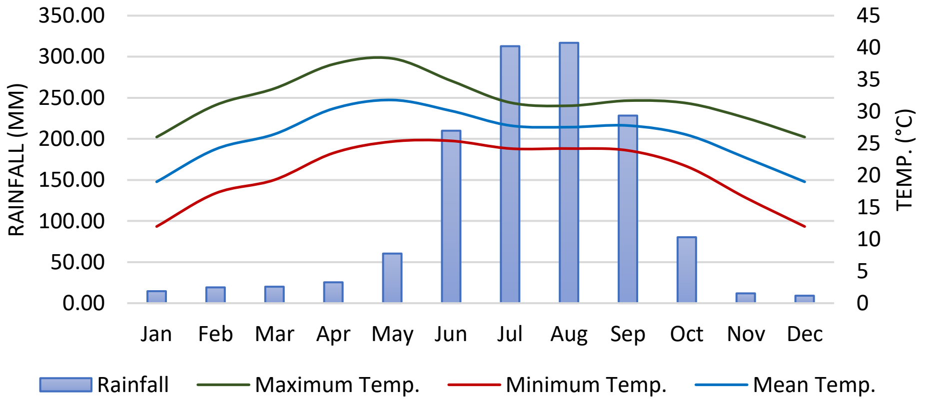
Figure 1.6 Monthly average discharge of South Koel River at Jarikela (1981-2018).

South Koel is a perennial river having the highest stream flow in August (14095 cumecs), followed by September (11212 cumecs) and July (10324 cumecs), while the lowest flow is observed in April (149 cumecs) (Figure 1.6). Over the past 20 years, no floods have been recorded in this river basin. However, there have been some instances of water scarcity in certain years, namely 2001, 2004, 2005, 2010, 2012, 2015, and 2017 (Chaudhary & Pandey, 2022).

In addition to that, since 2008-2009, a substantial portion of stream flow (1281 MCM) is getting diverted every year to the Subarnarekha River through a canal which accelerates the shortage of water resources (Sinha, 2017).

1.3.5. **Climate and Climate Variability**

As per the IMD cited in CWC (2014), the coldest months in the basin are December and January, with a minimum temperature of 12°C. On the other hand, the hottest months are April and May, with maximum temperatures ranging from 35°C to 38°C. The mean annual maximum temperature in the basin is 37.67°C, while the mean annual minimum temperature is 20.32°C. The basin receives a mean annual rainfall of 1442.53 mm, with approximately 82% of it occurring during the rainy season (June to September). Around 90% of the total basin area experiences a mean annual rainfall between 1400 and 1600 mm (CWC, 2014) (Figure 1.7).



Source: Computed by the researcher from IMD gridded data.

Figure 1.7 Mean monthly temperature and rainfall of the study area (1973-2018).

Tirkey et al. (2018) have reported that the basin is gradually experiencing by warming effect, and rainfall is likely to be decreasing, which is thought to have an adverse impact on stream flow and water resources. Guhathakurta & Rajeevan (2008) observed a decline in annual rainfall in Chhattisgarh, Jharkhand, and Kerala. Sharma & Singh (2017) also noted a significant decrease in annual, monsoon, and winter rainfall from 1901-2002, which could affect agricultural activities in Jharkhand. However, Praveen et al. (2020) found that while pre-monsoon and post-monsoon rainfall decreased, there was an increase in monsoon, winter, and annual rainfall during the period of 1901-2015, specifically in the state of Jharkhand.

1.3.6. **Soil and Vegetation**

The Plateau region is characterized by coarse texture and rocky soil, while medium texture soil is the dominant soil type in the plain land part. The rock exposure is observed in many patches in the plateau region, especially in the northern part of the basin. About 63.45% area of the basin has fine texture soil, followed by rocky soil (19.57%), medium texture soil (15.44%), and coarse texture soil (1.54%), respectively. Most of the fine texture soil (78.55% out of the total) is found in the elevation zone of 512-753 m, while less than 1% of fine texture soil is located above the 753 m elevation (CWC, 2014) (Figure 1.8).

The river basin is primarily characterized by a dominant deciduous forest type, which covers more than 30% of the total area. During the field survey, it is observed that Sal trees are the dominant tree species in the forest. Moreover, there are smaller areas observed within the basin during field visits that are covered by scrub forests and plantations.

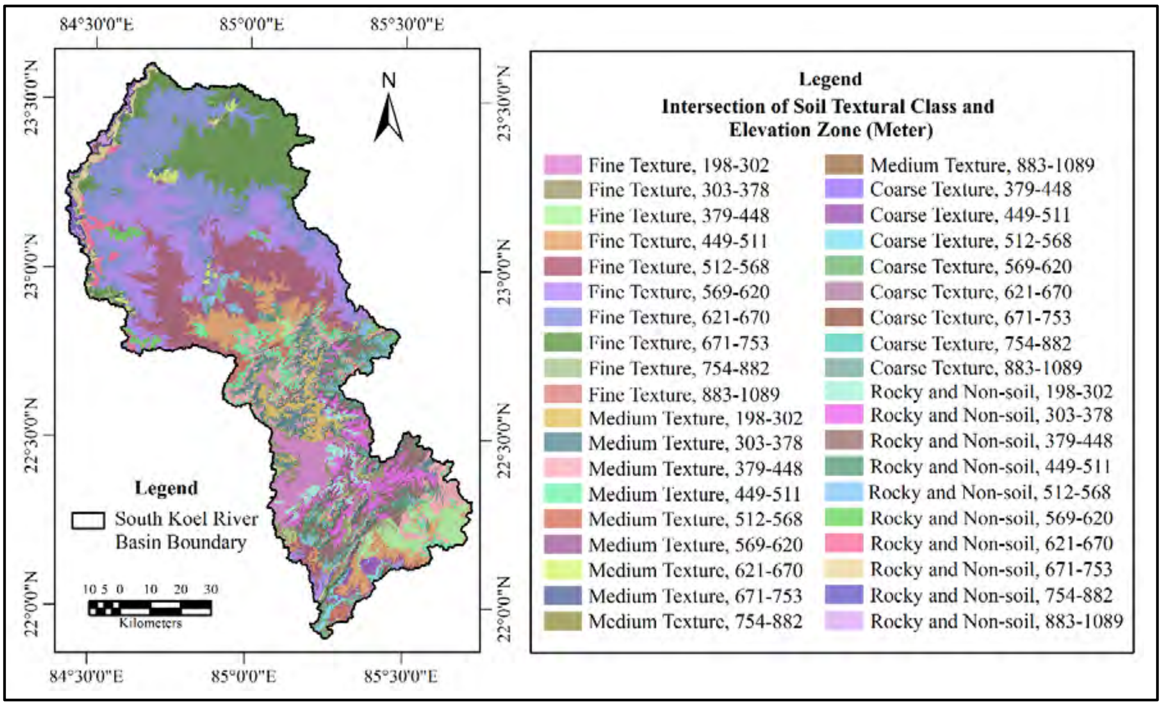


Figure 1.8 Intersection of soil textural classes and elevation zones (*Source:* Central Water Commission, Govt. of India 2014 and SRTM DEM, 2022).

1.3.7. **LULC and Human Activities**

As per the analysis of Landsat OLI satellite image, Nov 2016, and the subsequent ground truth verification, it is observed that agriculture constitutes the predominant land use in the basin, covering approximately 57.95% of its total area. The main crop cultivated in the area is paddy, which is grown once a year during the monsoon season from July to September. Forested areas encompass around 37.23% of the basin, while built-up areas account for 4.12%. Water bodies and bare ground cover 0.51% and 0.19% of the basin, respectively.

The highest population density (person/km^2) is found in Ranchi district (572), followed by Lohardaga (307), Kendujhar (217), Sundargarh (216), Khunti (210), Paschimi Singhbhum (208), Gumla (191), Latehar (169), and Simdega (159) districts respectively. Gumla and Lohardaga are the two notable urban centers in the basin, while there are many small towns like Sisai, Palkot, Kamdara, Ghagra, Basia (Gumla district), Kisko, Senha, Kuru (Lohardaga district), Mandar, Bero (Ranchi district), Khunti, Karra, Torpa (Khunti district), and Goilkera, Monaharpur, Noamundi, Jagannathpur (Paschimi Singhbhum). (Census of India, 2011).

The majority of rural inhabitants in the basin are primarily engaged in agricultural activities, which are carried out exclusively only during the monsoon season. In the areas, on the other hand, wherever there are irrigation facilities, agriculture goes around the year. There are no significant large-scale industrial establishments in the basin. However, in the southern part of the basin, there are some mining areas.

Tirkey et al. (2018) have reported that the destruction of the forest to create new agricultural fields is the old tradition of this basin, while on the other hand, lack of water resources, some agricultural fields are turning into fallow and barren lands. So, an in-depth study is the need of the hour to assess the runoff impact of all these major changes in the basin so that accordingly remedial measures can be taken before the situation gets at its worst, and the present study is likely to address the issue.

1.4. **Literature Review**

1.4.1. **Selection and Categorisation of Literatures**

A systematic literature review (SLR) was conducted based on some relevant research questions to evaluate the systematic progress of knowledge, identify knowledge gaps, define the research problem, set objectives, design research methodology, and understand the future needs and directions required to accelerate the contemporary field of research (Table 1.2).

The literatures were searched by accessing databases of Google Scholar, Scopus, and Soil and Water Assessment Tool (SWAT) using some pre-defined search string (Table 1.2). A total of 536 pieces of literature were collected and out of which 110 papers pertaining to the assessment of the impact of climate variability and human activities on runoff alteration were selected for full-text evaluation after a thorough screening of the titles of the literature followed by abstracts, findings, and full-text assessment. Additional literatures were collected from the search of the reference list (n=19), citation list (n=11), and authors' personal desk (n=9) (Table 1.2).

Table 1.2 Process followed in the systematic literature review (SLR).

Sl. No.	**Name of the Process**	**Details**
1	Formulation of the questions	a. How does the functional response of runoff change in relation to the spatial scale of the area under study? b. How does the degree of human interference affect the variability of runoff responses? c. What are the variations in the functional response of runoff due to changes in climate regions? d. Does the variation in elevation affect the responses of runoff? e. How has the impact on runoff alteration been analyzed?
2	Name of the search string	"Runoff climate human activities" "Runoff change climate variability human activities" "Runoff alteration climate human activities" “Runoff variability climate change human activities" “Runoff climate land use land cover" “Runoff climate forest" "Stream flow climate human activities" "Discharge climate human activities" "Runoff climate variability human activities" “Runoff climate human activities India” “Runoff climate land use and land cover India” “Runoff climate land use and land cover Jharkhand” “Runoff climate human activities South Koel”
3	Screening of the collected literature (536)	Literature excluded based on the title screening, n=216 Literature excluded based on the abstract, n= 147 Literature excluded based on the findings, n=28 Excluded after full-text evaluation, n=35 Eligible literature, n=110
4	Literature included in the present study (149)	Full-text evaluation, n=110 Searching reference list, n=19 Searching citation list, n=11 Authors' personal desk, n=9

Source: Prepared by the researcher based on selected literatures.

Table 1.3 Studies performed in different climatic regions.

Type	Number of journal articles	Percentage
Tropical climate	10	6.37
Sub-tropical Climate	31	21.02
Semi-humid to sub-arid climate	7	4.46
Semi-arid climate	32	21.66
Semi-arid to arid climate	17	11.46
Arid climate	7	4.46
Monsoon climate	14	9.55
Mediterranean climate	5	3.18
Temperate climate	25	15.92
Sub-arctic	3	1.91

Source: Prepared by the researcher.

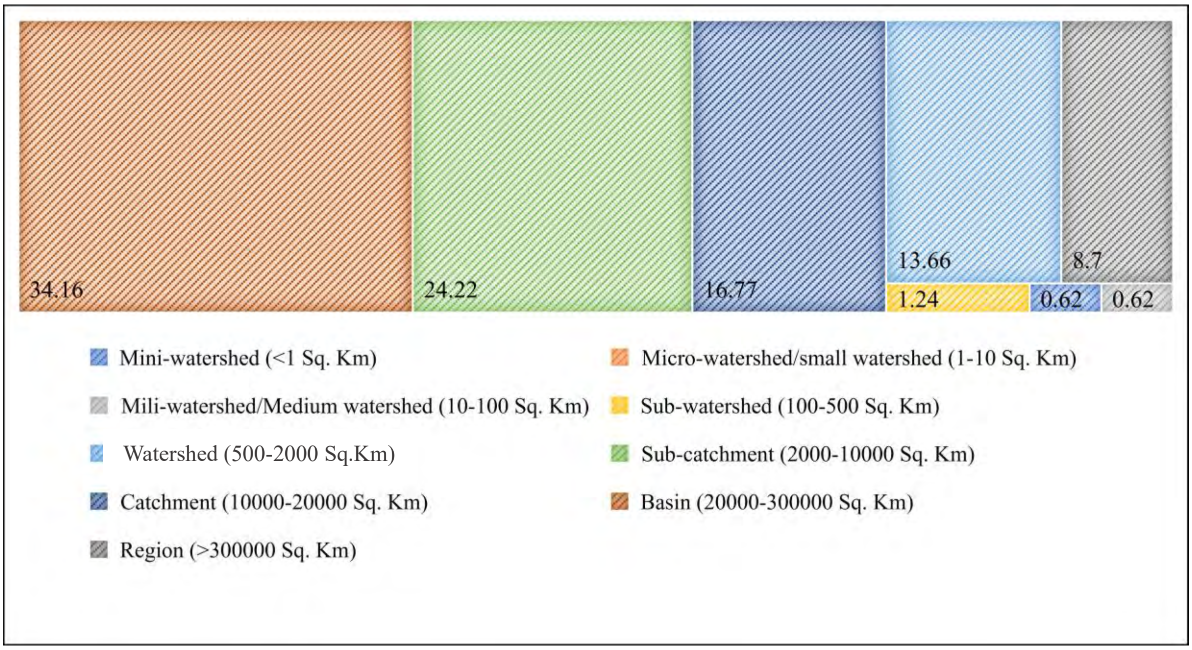


Figure 1.9 Literatures classified based on the spatial scale of the study area reported in literatures (After All India Soil and Land Use Survey, 1990; Singh, 1994).

Figure 1.10 Classification of basin based on dominant land use land cover as reported in literatures.

The selected 149 pieces of literature were then categorized based on the spatial scale of the study, prevailing climate, dominant LULC, and physiographic characteristics of the basin (Appendix 1.1 and 1.2).

It was found that most of the research was conducted at the basin level (34.16%), followed by sub-catchment (24.22%), catchment (16.77%), watershed (13.66%), and regional (8.70%) scales. Only a small number of researchers have focused on the mini-watershed to sub-watershed scale to investigate runoff alteration due to climate variability and changing human activities (Figure 1.9).

The issues were extensively explored in semi-arid (21.66%) and sub-tropical climatic regions (21.02%), followed by temperate climates (15.92%), areas transitioning from semi-arid to arid climates (11.46%), monsoon climates (9.55%), tropical climates (6.37%), transitional zones from semi-humid to sub-arid climates and arid climates (4.46% each), and Mediterranean climates (3.18%) respectively (Table 1.3).

So far as the dominant LULC is considered, it is observed that most of the works were carried out in agricultural watersheds (60.49%), followed by mixed watersheds (25.31%), forested watersheds (7.41%), grassland watersheds (6.17%), and urban watersheds (0.62%). However, runoff responses have not yet been investigated in coastal, wetland/marsh, and desert watersheds (Figure 1.10).

On the other hand, a significant amount of research has been conducted in mainly two physiographic regions, namely plain plateau complexes and plateau regions. Nonetheless, there is still insufficient research regarding alterations in runoff within other climatic regions.

1.4.2. **Methodological Review**

The study of runoff response to changes in geophysical conditions dates back to the beginning of the 20th century when the investigation began using paired catchment approaches. The pioneers workers in that field (Engler,1919; Bates & Henry, 1928; Hoyt & Troxell, 1934; Hoover, 1944; Dunford & Fletcher, 1947; Langbein & Wrather, 1949) were successful in deriving that forest cover is inversely proportional to basin runoff.

The major limitation of this early approach is that only the hydrologic impact of vegetation cover and settlement in some cases could be assessed. Secondly, the approach could not be applied to medium and large catchments. Since the 1960s, the paired catchment approach started to be superseded by empirical studies based on statistical models, particularly multiple regression, to find out the causal relationship among hydrological variables. The pioneers in this field are Eschner & Satterlund (1966), Emery

(1966), Hibbert (1967), and many more. Their works obviously validated the previous findings, and the relative contribution of individual causal and controlling variables was possible to be captured in their attempt.

From the 1970s and 1980s onward, researchers started paying much attention to formulating physical-based models to explore the exact functional relationship of the catchment variables in the framework of the hydrological system. It became possible to address many applied hydrological issues related to river basin management under the condition of climate change (e.g., Karl & Riebsame, 1989; Bultot, Dupriez, & Gellens, 1990; L. L. Nash & Gleick, 1991).

The runoff prediction by using a mathematical model then became the major area of investigation in order to estimate and assess the availability of fresh water for future use. Karunanithi, Grenney, Whitley, & Bovee (1994), Lorrai & Sechi (1995), and Zealand, Burn, & Simonovic (1999) suggested that the ANN can be used as a good predictor model for rainfall-runoff analysis.

Presently, researchers across the globe, e.g., Changnon & Demissie (1996), Kristian, Christian, & Mazvimavi (1998), McCabe & Wolock (2002), Costa, Botta, & Cardille (2003), Jones, Chiew, Boughton, & Zhang (2006), Poelmans, Rompaey, Ntegeka, & Willems (2011), Liang et al. (2015) and many more, are mostly concentrating on mathematical model-based studies to capture relative contribution of climate change and human activity on runoff alterations.

Dey & Mishra (2017) has reviewed the available approaches to the study of catchment response, and they have classified the approaches into four categories: *first* is the hydrological modelling approaches; *second* is the conceptual approaches that include Budyko hypothesis (decomposition and sensitivity method) and Tomer Schilling framework; *third* is the analytical approaches; and *fourth* is the experimental approaches/ methods based on hydrological field data that include the paired catchment observations and analysis.

1.4.3. **Review of Research Outcomes**

Close examination of all selected literatures reveals that runoff response to changing climate and human activities is largely controlled by factors such as the spatial scale of the basin, types of human activities, climate types, geophysical characteristics of the basin, etc., each of which is reported below in brief (Appendix 1.1 and 1.2).

(a) Spatial Scale and Runoff Response

Generally, larger basins tend to be more resilient to climate variability than smaller ones (Palmer et al., 2008). On the other hand, changes in land use and land cover over smaller basins may have a more significant impact on the hydrology than in larger basins (Dos Santos, Laurent, Abe, & Messner, 2018). In this study, the basins were classified into nine categories based on their spatial extent to address the issue, and the definition of each category is shown in Figure 1.9.

In their findings in China, Li et al. (2009), Xu, Yang, Yang, & Lei (2014), Yang, Yang, & Hu (2014), Zhang et al. (2014), Zhang, Zhang, Li, & Liu (2014), Wang et al. (2017), and Wang et al. (2020) showed that the climate variability caused reduction in runoff by about 19% to 95.8%, while human activities accounted for change in runoff by 40% to 81%. These wide range of variation in relative contribution of climate change and human activities is due to variation in size of the basin under investigation.

Similar kind of studies were carried out by Beguería, López-Moreno, Lorente, Seeger, & García-Ruiz (2003), Wang, Xia, & Che (2009), Bao et al. (2012), Zhang, Karthikeyan, Bai, & Srinivasan (2017), Pirnia et al. (2019), Andaryani et al. (2021) and many others in different parts of the globe at the sub-catchment level. They revealed that climate variability was responsible for reducing the runoff by 70%, 29.9%, 42%, 39.1%, 29.86-40.19%, and 83.6%, respectively. On the other hand, human activities accounted for a reduction in runoff by 30%, 70.1%, 59%, 63.1-64.8%, 59.81-70.14%, and 16.4%, respectively. As per their reporting, all these differences are due to variation in spatial extent of catchment under study.

Appendix 1.1 and 1.2 show the list of selected literatures from different parts of the globe which have reported the variation in catchment response caused by climate change and human activities across the basins of different spatial extents.

(b) Types of Human Activities and Runoff Response

The pattern of runoff responses was also influenced by the degree of human activity that alters the landscape by modifying the LULC under changing climate conditions. Studies reviewed in this research have shown that the LULC of basins can be agricultural, forest, grassland, mixed, and urban (Appendix 1.1 and 1.2).

Several research studies carried out by Chen, Li, & Zhang (2005), Wang, Zhang, He, Jiang, & Jing (2009), Bao et al. (2012), Liang et al. (2015), and Wang et al. (2020) over agriculture dominated basins in various locations have revealed that climate variability was responsible for 60-80%, 29.9%, 26%, 38%, and 60% reduction in runoff in the respective area while reduction in runoff by about 20%, 70.1%, 74%, 62%, and 40% were attributed to human activities. So, climate change and human activities have led to offsetting responses in agriculture-dominated basins.

Over forested basin, as reported by Beguería et al. (2003), Liu et al. (2010), Li et al. (2013), and H. Zhang, Meng, Wang, Wang, & Li (2020), the climate variability contributed to the reduction in the runoff by 70%, 50%, 45%, and 83% respectively whereas it was respectively 30%, 50%, 55%, and 17% due to human activities (Appendix 1.1 and 1.2). On the other hand, the contribution rate of climate variability (ranging from 83.58% to 90.5%) and human activities (ranging from 9.5%-16.42%) to the reduction of runoff in grassland basins were found to be almost consistent in different areas of the world as reported by Chen et al. (2013), Shang et al. (2019), Andaryani et al. (2019) and Yan et al. (2020). For urban catchment, as reported by Aboelnour et al. (2019) for Little Eagle Creek in the USA, climate change has a higher contribution rate than human activities. According to the studies conducted by Fan et al. (2010), Bao et al. (2012), Xu et al. (2014), and Tang et al. (2021), mixed basins have shown different responses, but in all cases, human activities had a higher impact than climate variability in reducing runoff (Appendix 1.1 and 1.2).

In many research outcomes, it is also observed that there is an increase in runoff due to climate change, whereas human activities have caused runoff reduction, although their relative contribution differs across the basin of different LULCs. The notable researchers in this context are Ma, Xu, Luo, Aggarwal, & Li (2009), and Shi et al. (2013) (for agricultural watershed), Zhou, Zhang, & Guo (2020) (for forested watershed), Zhang et al. (2018) (for grassland basin), Gibson et al. (2006), and Khoi et al. (2019) (for mixed basin) (Appendix 1.1 and 1.2).

(c) Climatic Types and Runoff Response

The literature survey reveals that climate variability and change in human activities have positive as well as negative impacts on runoff, and there is wide variation in the relative contribution of both factors across the climatic zones.

In the tropical region, the contribution of human activities in the reduction of runoff ranges from 54.19 to 68.39%, whereas the percentage share caused by climate change is 31.61 to 45.81%, as reported by Wang et al. (2012), Wang, Li, & Wang (2021), Zhang et al. (2020), and many others (Appendix 1.1 and 1.2). Exact opposite results are found for the sub-tropical region, as reported by Chen et al. (2005), Zhang et al. (2017), and Zhou et al. (2018), and the same scenario is also found for the region having transitional climate from semi-humid to semi-arid region as reported by Li, Li, Liang, Li, & Liu (2010), Bao et al. (2012), and many others.

In many cases, the scenario over purely semi-arid regions is found to be consistent with what is observed in the tropical region, i.e., in the semi-arid region, the percentage share of climate change impact on reducing runoff was relatively small as compared to that caused by the change in human activities as reported by Li et al. (2007), Fan et al. (2010), and Seyoum et al. (2015) (Appendix 1.1 and 1.2). At the same time, there are many examples of just the opposite scenario for semi-arid and arid regions, e.g., the Rwizi catchment in Uganda (Onyutha et al., 2021), Kaidu River basin in China (Chen et al., 2013), wherein climate variability was the main contributor to the reduction in runoff.

Many studies reported the positive impact of climate variability and human activities on runoff, i.e., both factors cause an increase in runoff (Tomer & Schilling, 2009; Juckem et al., 2008; Heo et al., 2015; Napoli et al., 2017; Yang et al., 2019; Nkhoma et al., 2021). Many authors, on the other hand, observed in many places that there is an increase in runoff due to climate variability and a decrease due to human activities (Ma et al., 2009; Ye et al., 2013; Yang et al., 2017). Just opposite results are also reported from many places by Peña-Arancibia et al. (2012) and Zhou et al. (2020). All these are experienced by the region irrespective of climate type.

(d) Geophysical Conditions and Runoff Response

Geophysical condition is hardly found to have any control over runoff response to changing climate and human activities. Hence, regions with similar geophysical conditions, i.e., regions having similar relief and similar physiography, show different runoff responses (Wang et al., 2010; Seyoum et al., 2015; Wang et al., 2017; Zhang et al., 2018; Khoi et al., 2019; Zhang et al., 2021). The response, here, depends upon the magnitude and extent of change in climate and human activities, which may occur irrespective of surface characteristics in basin scale hydrologic system.

1.4.4. **Identifying the Research Gap**

There has been a lot of methodological advancement in the field of runoff alteration studies under changing climatic conditions and human activities that started with paired catchment approach followed by empirical statistical methods and more recently by physically-based hydrological models with machine learning and artificial intelligence approaches. But the fundamental field of inquiry has remained the same, and it is the functional relationship among hydrologic variables in the framework of the hydrologic system.

It is because, till the present, there is no satisfactory answer to the question – Why is the hydrologic response of one basin not always found to be consistent with that of another one with similar geophysical conditions? There is also no consensus regarding the relative contribution of climate variability and human activity to cause a change in system response. Moreover, the number of studies is not sufficient to state how the difference in the spatial scale of the hydrologic system affects the relationship among hydrologic variables (Appendix 1.1 and 1.2).

So, the knowledge gap exists, and to fulfil this gap, more investigation is required on this specific aspect under different geoeconomic environments to understand fully how the runoff generation mechanism is getting changed due to the combined effect of climate change and change in the degree of human interference. The present research is aligned with the same field of enquiry with the intention to find the regulative principles which the hydrologic system dynamic follows. The focus is on finding the basic mechanism of runoff generation, which is getting changed through the complex interactions between climate change and human activity in the South Koel River basin, which has a contrasting physiographic and cultural landscape under a monsoonal climate.

1.5. **Research Questions**

The present study addressed the following questions in reference to the study area:

(i) What type of changes has occurred in the stream flow: gradual change (trend) or sudden change (step change) or both?

(ii) How much change in runoff is due to climate variability and how much is due to human activities?

(iii) What is the threshold change value in forest cover, agricultural land, and urban built-up area that has functional impact on runoff alteration?

1.6. **Objectives**

The present study was carried out to fulfill the following three objectives:

(i) To assess the temporal variability of rainfall and runoff since 1973 in terms of trend and step change in South Koel River Basin.

(ii) To assess the relative contribution of climate variability and human activities to cause the alteration of runoff in the study area.

(iii) To capture the runoff sensitivity to changes in individual land use land cover class with special reference to forest cover, agricultural land use, and urban built-up area in the concerned river basin.

1.7. **Database and Methodology**

1.7.1. **The Parameters and the Databases**

The observations were made for the time period since 1973 to the recent date as the database on many of the parameters is not available for the period prior to 1973.

As per the *first objective* adopted for the present study, *rainfall* and *runoff* are the response variables which were analysed to detect step change and trend in the series against time in view to trace their temporal variability. So, it is a kind of univariate analysis.

As per the *second objective,* the only *response variable* is the *runoff,* whereas *climate* and *human activity* are the explanatory variables. The *rainfall, mean maximum* and *mean minimum temperature, humidity, solar radiation, and wind speed* were used as representative variables for *climate* and land use and land cover (LULC), on the other hand, was used as the only representative parameters for human activities.

As per the *third objective,* again, runoff is the only *response variable,* and three specific LULC classes, namely forest *cover*, *agricultural land use,* and *built-up area,* are the *explanatory variables*. The effect of rainfall, in this context, was controlled during the assessment of the functional relationship between response and explanatory variables. Here, two specific aspects of agricultural land use were taken into consideration: one was the *net shown area,* and the other was the *area-specific crop type* since this crop type has implications in the runoff generation mechanism. The database on crop type was generated by *primary survey* using the *questionnaire and schedule* in which stratified random sampling was used as the sampling technique, and the sample strata were generated based on elevation differences and soil types.

The Soil and Water Assessment Tool (SWAT), which is explained in detail in the third chapter, was used as a part of the whole data analysis method to achieve the second and third objectives. SWAT model requires four types of input data which include soil data, elevation data, LULC, and a weather database that include all the meteorological parameters as mentioned above, i.e., rainfall, maximum and minimum temperature, solar radiation, humidity, and wind speed. The discharge data was required for calibration and validation of the SWAT model.

The sources and applications of all the databases used in the present study have been categorically mentioned in Table 1.4.

Table 1.4 Sources and applications of all the databases used in the study area.

Sl. No.	Databases	Sources	Applications	Software used
1	Administrative, geological, lithological, and geomorphological maps	The administrative map was collected from the 2011 Census of India, and the remaining three maps were obtained from the Geological Survey of India 2022.	To understand the basin's geophysical conditions.	ArcMap 10.5
2	Daily river discharge and reservoir discharge data.	CWC, Department of water resources, River Development & Ganga Rejuvenation, Ministry of Jal Shakti, Govt. of India (India-WRIS, 2020) (https://indiawris.gov.in/wris/#/)	The response variable in achieving all three objectives and also as input data for calibration and validation of the SWAT model.	MS Excel 2021 RStudio v 1.2.5042 SPSS v.17.0 ArcSWAT 2012.10.5.24
3	Daily Weather Data on maximum and minimum temperature, rainfall, solar radiation, humidity, and wind speed.	NASA Power Data Access, Langley Research Center (NASA, 2020) (https://power.larc.nasa.gov/data-access-viewer/)	Rainfall was used as the response variable in the first objective, while for the other two objectives, it was used as input data for calibration and validation of the SWAT model. All other weather data was used as SWAT input data.	MS Excel 2021 RStudio v 1.2.5042 SPSS v.17.0 ArcSWAT 2012.10.5.24
4	Landsat TM and OLI image with 30 m resolution.	USGS Earth Explorer, https://earthexplorer.usgs.gov (USGS Earth Explorer, 2022)	To generate LULC, which was used as SWAT input data. The LULC map was available from NRSC and CWC, Govt. of India, and was also used as reference data for producing LULC maps from satellite images.	QGIS 3.28.4 Erdas Imagine 2015 ArcMap 10.5 ArcSWAT 2012.10.5.24
5	Soil grid data with 250 m spatial resolution and also soil map.	Soil grid data from https://soilgrids.org (ISRIC-WDC, 2020) and soil map from Brahmani Baitarani Basin Report (CWC, 2014) Govt. of India.	It was used as SWAT input data.	ArcMap 10.5 ArcSWAT 2012.10.5.24
6	SRTM DEM with 30 m resolution.	https://earthexplorer.usgs.gov (USGS Earth Explorer, 2022)	It was used as input data for the SWAT model.	ArcMap 10.5 ArcSWAT 2012.10.5.24
7	The area-specific crop type cultivated during monsoon seasons.	Primary Survey through questionnaire and schedule using stratified random sampling.	Explanatory variable to achieve the third objective.	MS Excel 2021 ArcMap 10.5 ArcSWAT 2012.10.5.24

Source: Compiled by the researcher.

1.7.2. **Data Pre-Processing**

The primary data on crop type was tabulated and cleaned properly in MS Excel. Similarly, the discharge and weather databases that were available on daily time steps from respective secondary sources were also cleaned properly and transformed into the desired format, e.g., daily to monthly or annual series, which was required at subsequent steps for model formulation and statistical analysis. The monthly time series of discharge data was required for validating the SWAT model, while the annual time series on the same parameter was used for statistical analysis that has been described in the next subsection. For SWAT run weather database was kept as a daily time series.

The missing value imputation was done by replacing the blank cell with an average value conditioned to corresponding points of time and places at which the observations were made. The data were checked for normality and autocorrelation in order to choose the required statistical tools for data analysis. Lag one autocorrelation was assessed by using Pearson's correlation coefficient, and normality was checked by using the Kolmogorov-Smirnov test and Shapiro-Wilk test. GIS data like DEM, Landsat TM/OLI, soil raster, etc., were processed accordingly in the GIS environment to make the data ready for use in the SWAT model.

1.7.3. **Method of Data Analysis**

First Objective: For step change analysis of rainfall and discharge series, the Buishand U test, the Buishand R test, and the Standard Normal Homogeneity test (SNHT) were applied if data were found to be normally distributed. Otherwise, Pettitt's test and the Sequential Mann Kendall test were used. The last one can detect multiple change points, whereas all others can detect only a single change point in the time series. It is usually recommended to apply more than one test so that one test result can be used to substantiate the other, and it is done in order to avoid the possibility of detecting any disguised break point in the series (Kundzewicz & Robson, 2004). For trend analysis, the Mann-Kendall test and modified Mann-Kendall test were used for independent series and autocorrelated series, respectively. The magnitude of the trend's slope was assessed by Sen's slope estimator (Figure 1.11).

Second Objective: To assess the impact of climate variability and change in LULC on runoff alteration, the whole study period (1981–2018) was divided into two parts based on the result of step change analysis for runoff, and the earlier part was used as reference period while latter part as interference period.

The SWAT model was calibrated to LULC of both periods separately, and thereafter runoff was simulated separately using separate weather data sets of respective periods. The simulation of the reference period, here, is noted as 'Sim 1' while the notation 'Sim 2' is used to denote the simulation of the interference period. The mean difference between these two simulated runoff series, i.e., Sim 2 and Sim 1, is the total runoff alteration caused by both climate variability and human activity. Then, the model calibrated to reference period

LULC was run using weather data of interference period, and this simulation is denoted by 'Sim 3'. Now, the mean difference between Sim 3 and Sim 1 is the portion of runoff alteration caused by climate variation since LULC was the same for both simulations, but the weather dataset was different. On the other hand, the mean difference between Sim 2 and Sim 3 is the runoff alteration caused by human activity since, here, LULC is different, but the weather database is kept the same (Figure 1.11).

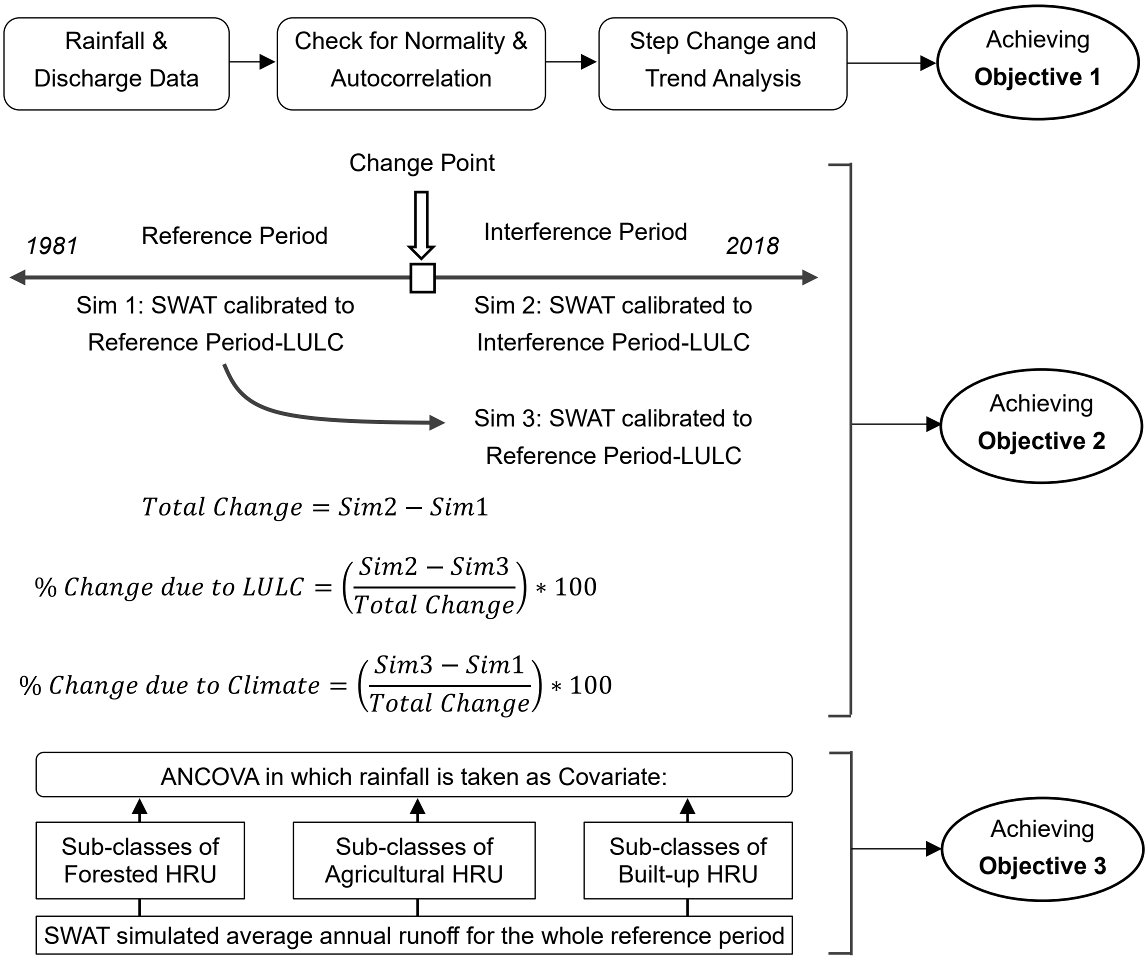


Figure 1.11 Methodology of the study (Term 'Sim' stands for Simulation).

Third Objective: To assess the runoff sensitivity to changing areal coverage of three specific individual LULC classes: forest cover, agriculture, and built-up area, the whole basin area was divided into a manageable number of homogeneous units technically called *Hydrologic Response Unit* (HRU) in such a way that each HRU contains only a single LULC class, i.e., either forest or agriculture or built-up, etc. Then the SWAT model was run for the reference period, and the average annual runoff was computed for each of the HRU(s) belonging to only LULC classes forest, agriculture, and built-up. The runoff values of each individual HRU belonging to the forest, agriculture, and built-up were further classified into four sub-categories based on the areal coverage of corresponding HRU(s) by using the quantile method and then three separate ANCOVA models with rainfall as a covariate were run for three respective LULC classes to analyse the sensitivity of runoff to changing areal coverage of respective HRU(s) belonging to corresponding LULC class (Figure 1.11).

1.8. **Scope and Limitation**

It is expected that the database which has been produced in current research would be very useful input for formulating a sustainable water resource management plan in the South Koel River basin. At the same time, the study is likely to have some limitations due to the lack of a proper database on many soil and rock parameters. For example, saturated hydraulic conductivity data at regular spatial intervals is essential to get accurate simulation results, but these data are not available. To meet up the present requirement, this kind of parameter was estimated using pedo-transfer functions (PTF) but observed data gives the best result, which is beyond the scope of the present study. Soil data, on the other hand, has a spatial resolution of 250 m which is also not good for such a basin where topographic diversity is more, and that is why soil diversity is expected to occur. However, the methodology is robust enough to produce the expected result that can contribute to addressing the water-related crisis.

1.9. **Concluding Remarks**

The impact of climate variability coupled with changing human activities in the river basin hydrologic system is nowadays a global issue though it has its own regional implication due to wide variations in surface characteristics across the basins. So, observation in one basin cannot be inferred for another basin. Hence, basin-wise systematic scientific investigation is of utmost importance in view to get insight into this aspect in the regional context.

The present study in South Koel River Basin has been formulated in view to address this global issue but in the regional context. The methodology which has been adopted here is already verified in many previous works, and in the present study, it has been designed carefully to make it more relevant to the existing geophysical characteristics of the selected basin. So, the findings of current research are expected to be reliable outcomes that can be an effective contribution to the discipline.