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Impacts Assessment of the Expanding Urban Land Development on the Discharge of the SWAT Perennial River Utilizing GIS-Based Hydrological Models

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Abstract

Floods are a danger to property, livelihoods, and communities worldwide, and their consequences are being made worse by climate change. Particularly in Pakistan, floods are frequent and destructive; the Swat Watershed has a history of catastrophic flooding. This study examines how changes in land use affect runoff in the Swat Watershed. Our research uses GIS and hydrological modelling to investigate land cover changes' effects on runoff patterns, including urbanization. Despite the region's susceptibility to flooding, there is a need for GIS-based studies in this area. Finding the causes and effects of floods involves evaluating runoff changes, simulating rainfall-runoff transformation, and combining GIS data. We use data from various sources, including discharge statistics, precipitation records, Landsat images, and DEM data. Our research closes a gap in the literature on the Swat Watershed and offers guidance for wise land use and flood control.

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Keywords: Swat watershed, Land Use Land Cover, Swat, Urban development, rainfall-runoff, GIS, Hydrological Modeling, Flood, DEM data, Landsat imagery, precipitation records

Introduction

Globally, floods pose a serious hazard to people, their means of subsistence, and their property [1]. They are occurring more frequently and with greater severity, partially due to climate change's effects. With many severe floods in recent years, Pakistan is particularly vulnerable to flooding [2].

Devastating floods have occurred in the Swat Watershed in Pakistan, most recently in 2022, but also in 1992, 2005, and 2010. These frequent floods have long-lasting effects on the surrounding villages and the larger area [3]. The conversion of natural, vegetated land into urban and residential areas is one of the many factors that increase the danger of flooding in this watershed. This change in land use increases the risk of floods by decreasing the ground's ability to absorb rainwater and speeding up surface water flow [4].

To address these urgent issues, this study thoroughly examines the complex connection between LULC changes—specifically, the conversion of natural land to urban development—and the rising danger of flooding in the Swat Watershed. We aim to identify the root causes and effects of floods in the area. Furthermore, we strive to offer significant perspectives and suggestions for improved flood control, land use planning, and mitigation tactics. Ultimately, our research seeks to lessen the catastrophic effects of floods on this susceptible area and other flood-prone regions worldwide.

There is a notable research vacuum in the extant literature, especially regarding the Swat Watershed. One prominent feature of this disparity is the lack of focus on this particular watershed, which is significant considering its vulnerability to several environmental issues, such as urbanization and its consequences. Only some studies have examined the distinct features and difficulties of the Swat Watershed, even though many have examined the effects of urbanization on hydrology and land use changes.

Notably, few in-depth Geographic Information System (GIS)-based projects in this watershed assess surface runoff's temporal and geographical distribution. Our capacity to comprehend and resolve

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essential problems about water resources and flood risk management needs to be improved because of the lack of analytical tools and research on surface runoff dynamics in the context of LULC changes. Thus, it is clear that research projects and GIS-based projects specific to the Swat Watershed are urgently needed. These would improve our knowledge of the area and also aid in creating practical plans for flood mitigation and sustainable water resource management.

The balance between precipitation, water yield (Q), and evapotranspiration (E.T.) in watersheds is the main emphasis of Li et al.'s (2020) analysis of the effects of urbanization on watershed hydrology in the U.S. This equilibrium is drastically altered by urbanization, which is typified by changes in climate and land use. The study models the impact of urbanization on runoff, infiltration, and E.T. using the SWAT watershed model. Data from several sources, such as soil, climate, hydrology, and land use databases, inform the model. Ten watersheds undergo calibration and validation procedures. According to critical studies, urbanization can reduce E.T. by up to 20%, increase runoff by up to 50%, and decrease infiltration by up to 50%. The influence varies according to the plant cover and slope of the watershed. Due to the increase of impervious surfaces and the loss of vegetation, the southern United States is undergoing the most notable changes due to urbanization. Urbanization is one of the leading causes of the changes in watershed water balances. The study suggests proactive planning for controlling the effects of urbanization on watersheds and highlights the significance of taking these effects into account when managing water resources [5].

Improving watershed management techniques in humid regions was the primary goal of Zimale et al. (2017). Around the world, watershed management techniques successfully reduce soil erosion, raise water availability, and increase water quality. However, the heavy rainfall, steep slopes, and weak soils that make the area vulnerable to flooding and soil erosion have hampered their long-term viability in the humid African highlands. Land degradation is also a result of agricultural growth and deforestation. By examining runoff and erosion in connection to climatic and landscape factors, this research seeks to develop broad guidelines for implementing watershed management techniques in the humid and subhumid Ethiopian highlands. These results will serve as the basis for recommendations. Degraded plains and seasonally soaked bottomlands are the author's two primary

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sources of runoff and sediment in the humid Ethiopian highlands. Proposed soil and water conservation strategies for degraded fields include no-till farming, planting fruit trees, tearing following contours, and creating infiltration furrows. Measures for seasonally inundated bottomlands include pond construction, dam construction, and tree planting. Managing humid highland watersheds presents challenges such as resolving underlying issues like deforestation, creating region-specific techniques, and striking a balance between agriculture, water supply, and environmental conservation. Comprehensive data collection, GIS and remote sensing for hydrology and land use analysis, erosion control techniques, and water quality monitoring are all essential to effective watershed management. It is crucial to engage the community through education and democratic decision-making. The study stresses community involvement and the significance of adjusting conservation strategies to the unique conditions of each watershed. Drawing from earlier research conducted in the Ethiopian highlands, it emphasizes the value of conventional techniques like terracing and tree planting and measures like infiltration furrows [6].

With an emphasis on the effects of LULC variations, Fajar et al. (2022) investigate the temporal and geographical distribution of surface runoff in the upstream Citarum watershed in West Java, Indonesia. The study uses R.S. and GIS techniques to identify LULC classes in terms of space and time. The authors use the Cellular Automata-Markov model for future predictions and the maximum likelihood technique to examine historical patterns using Landsat data. The authors calculated runoff using the rational formula based on the LULC. They discovered that two major LULC classes that contribute to increasing runoff are urbanization and plantations, underscoring the significance of LULC in watershed management. The research highlights the necessity for proactive sub-watershed management to decrease runoff from rising urbanization and plantations. It fills the knowledge gap about the hydrologic behaviour of the Citarum watershed, which is the primary cause of floods in Jakarta, Indonesia [7].

They tackle Jakarta's flooding problem, emphasizing integrated watershed management as a remedy. The flat terrain, land subsidence, coastal position, excessive rainfall, and artificial factors—such as land-based commercial activity and inadequate city planning—all contribute to Jakarta's susceptibility

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to floods. To determine how land use and land cover, mainly deforestation, in the upper watershed affect downstream floods, the study uses a hydrological simulation approach with the ANSWERS model. According to the study, changes in the middle watershed brought on by growing urbanization and inadequate city planning are the primary causes of floods, even if deforestation in the upper watershed does contribute to higher runoff. Addressing problems in the middle watershed area is essential to reducing Jakarta's flooding problem, according to the study, which emphasizes the need to consider natural and manmade elements when evaluating flooding patterns. This study offers insightful information about watershed management tactics catering to Jakarta's unique difficulties. [8–10].

The impact of forestation on runoff in the Qingshui River Basin of Wutai Mountain, China, was examined by Xu et al. (2019). They discovered that the ratio of evapotranspiration to precipitation maximized at 1800 meters above sea level (m a.s.l.). Precipitation had the most impact on evapotranspiration below this height, whereas energy variables controlled it beyond 1800 m a.s.l. Farmland > grassland > subalpine meadow > evergreen coniferous shrub forest > deciduous broad-leaved forest was the order in which the research rated runoff coefficients for the various vertical vegetation belts. Grassland was found to be the primary source of runoff, contributing around 39.10% of the QRB's yearly water production. The study also highlighted the intricate interaction between plant types and hydrological processes by noting that increased forest cover may result in higher evapotranspiration and a consequent decrease in runoff [11].

The use of remote sensing and GIS technologies for land use and land cover categorization and change analysis in Thirthahalli for 20 years was the subject of research by Nischitha (2019). The study mapped land use and land cover changes using multitemporal Landsat satellite images from 1997 to 2017. The study identified classifications, including forests, agricultural plantations, agricultural croplands, wastelands, water bodies, and settlement areas, using a supervised classification method based on the Maximum Likelihood methodology. The results demonstrated how well remote sensing and GIS technologies analyzed changes in land use and cover in Thirthahalli taluk, showing notable changes mostly in regions of forest, agricultural plantations, and habitation.

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Yasmeen et al. (2017) used geographical information system (GIS) methods and remote sensing (R.S.) data to perform a flood study of the Tarbela sub-catchment. Using the hydrologic simulation model HEC-HMS with HEC-GeoHMS, the study mainly concentrated on rainfall-runoff modelling to predict surface runoff in the Tarbela basin. ASTER DEM with a resolution of 30 meters and the Arc Hydro extension of ArcGIS were used to provide various geographic information, such as drainage area, stream network, and slope. Based on LANDSAT satellite photography, soil type and land cover/use characteristics were significant determinants of surface runoff. Soil maps and land cover/use data created curve figures for Tarbela sub-catchments. In-situIn-situ weather data and the ERA-Interim dataset were used for gauged and un-gauged portions of the watershed for gauged and un-gauged portions of the watershed. At the same time, the Climate Research Unit (CRU) provided historical climatic data from 1900 to 2014. The NRCS runoff curve number approach created flood hydrographs and estimated excess precipitation. Flood control measures were made more accessible by validating the HEC-HMS simulation model output against discharge data at the catchment outlet. This showed how well geospatial tools, including remote sensing and GIS, work for flood modelling and prediction for the Tarbela sub-catchment.

The following are the study's goals:

- Evaluation of LULC's effects on runoff fluctuations
- Hydrological modelling for the translation of rainfall into runoff
- Incorporation of GIS-based LULC data
- Comparison with observed runoff data

Materials and Methods

Study Area

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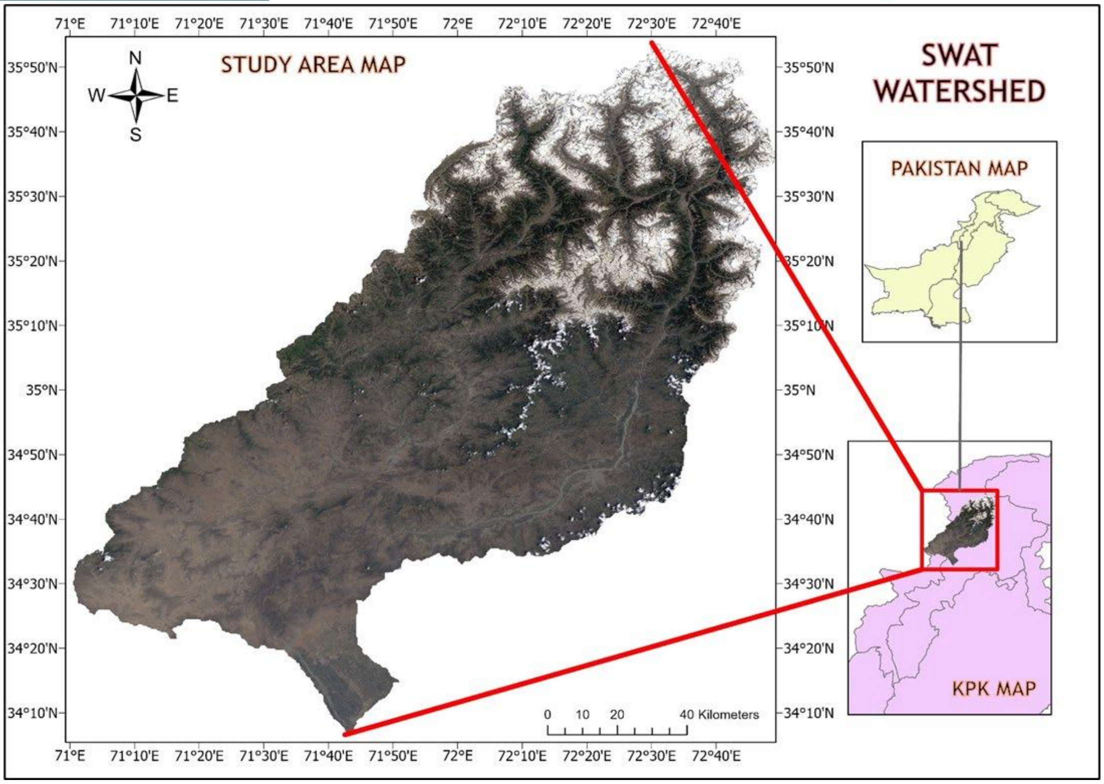

Figure 1: Location map of the Swat Watershed

The Swat Basin in Khyber Pakhtunkhwa (KPK), which is located between latitudes 34° 10′ 00′′ North and 35° 50′ 00′′ North and longitudes 71° 00′ 00′′ to 72° 40′ 00′′ East, is the study's location [14]. Geographically speaking, it is part of the 5,687 square mile Hindu Kush Himalayan range. The area's terrain is varied, with lowlands with farms along the riverside in the south and snow-capped mountains in the North. With an average height of 990 meters (3,230 feet), Swat experiences a wetter and colder climate than other parts of Pakistan [15]. Winter precipitation from the Mediterranean Sea, which frequently takes the form of snow, influences precipitation in the northern areas. On the other hand, summer monsoon rainfall occurs in southern regions. While high summer temperatures cause snow and glacier melt, low winter temperatures encourage snow and glacier accretion.

The Swat River rises in the Hindu Kush Mountains and travels south across various landscapes. It joins the Ushu and Gabral rivers in Kalam and continues through the Swat District [16]. In District Dir Lower, it finally merges with the Panjkora River, while in District Charsadda, it meets the River Kabul near Nisatta. There are flash floods upstream and river floods downstream due to the river's channel's

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steep parts in the North and softer parts in the south. Notwithstanding these difficulties, the Swat River feeds various animals, acts as an essential irrigation supply, and generates hydroelectric power from already-existing facilities, including Jabban, Dargai, and Daral Khwar, with more projects planned for future growth. However, because of climate change, complicated topography, and human activities, the area is at serious risk of flooding, particularly during the monsoon season, which runs from June to September.

We have chosen four sub-watersheds for in-depth study to understand better the various land cover types within the Swat watershed. These sub-watersheds are essential components of the wider Swat Basin and have a variety of characteristics, including:

- Batkhela Sub-watershed
- Chakdara Sub-watershed
- Swat City Sub-watershed
- Saidu Sharif Sub-watershed

These sub-watersheds have been carefully selected to reflect the Swat Basin's diverse land use patterns, habitations, and environmental circumstances. This selection thoroughly explains how various land coverings affect these locations' hydrological dynamics and flood susceptibility.

Table 1: Sub-Watersheds: Coordinates and Area

Sr.	Sub-Watershed	Latitude	Longitude	Area (km^2)
1.	Batkhela	34°33' to 34°38'30" North	71°51′ to 72°8' East	182.97
2.	Chakdara	34°38'30" to 34°48'15" North	71°56' to 72°6'30" East	163.79
3.	Swat City	34°38'15" to 34°46'45" North	72°30' to 72°16'30" East	194.70
4.	Saidu Sharif	34°47'30"to 34°54'15" North	72°19' to 72°24' East	67.84

We used multi-temporal data from 1990 to 2023, which we obtained for our LULC study from the United States Geological Survey (USGS) website (https://earthexplorer.usgs.gov/). These files contained 30-meter-resolution Landsat images. In particular, we entered LULC data using Landsat 4 and 5 satellite images for 1991 and 2001 and Landsat 8 satellite photography between 2011 and 2022. ERA5-Land (https://www.ecmwf.int/en/era5-land) provided the satellite sources from which we gathered temperature and precipitation data. The Chakdara gauging station, run by Pakistan's Water

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and Power Development Authority (https://www.wapda.gov.pk/), provided the discharge data.

We successfully investigated and computed discharge values by combining and evaluating these various data sources. It is commonly known that LULC alterations, especially the conversion of vegetative land into built-up areas, substantially affect surface runoff coefficients, increasing the danger of floods. Nevertheless, more study is needed to understand how LULC changes affect surface runoff in the Swat River Watershed. This information gap is required to improve the creation of successful flood mitigation plans for the area.

Methodology: Flow Chart and Explanation

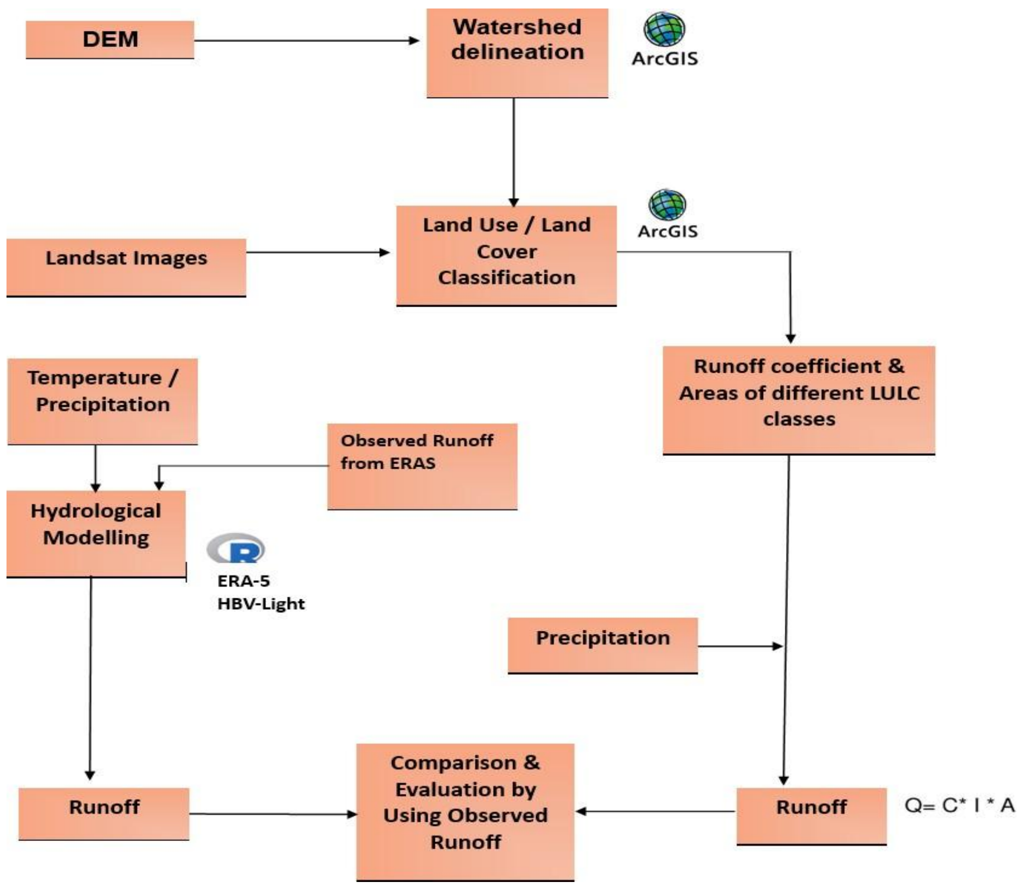

Figure 2: Steps adopted for the calculation of discharge

3.3.1 Acquisition of DEM Data and delineation of watershed

The USGS National Map provided the DEM data to delineate the Swat watershed. The data is a gridded representation of the Earth's surface elevation data. A numerical number in each grid cell (pixel) represents the height above sea level. Usually, meters or feet are used to store this data. 1/3

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arc-second NED (National Elevation Dataset) was the selected data collection. The resolution of this dataset is around 10 meters. This suggests that every pixel in the grid represents a 10-meter by 10-meter region on the surface of the Earth and corresponds to a particular elevation measurement. After that, the dataset was imported as a.tif file into ArcGIS Pro.

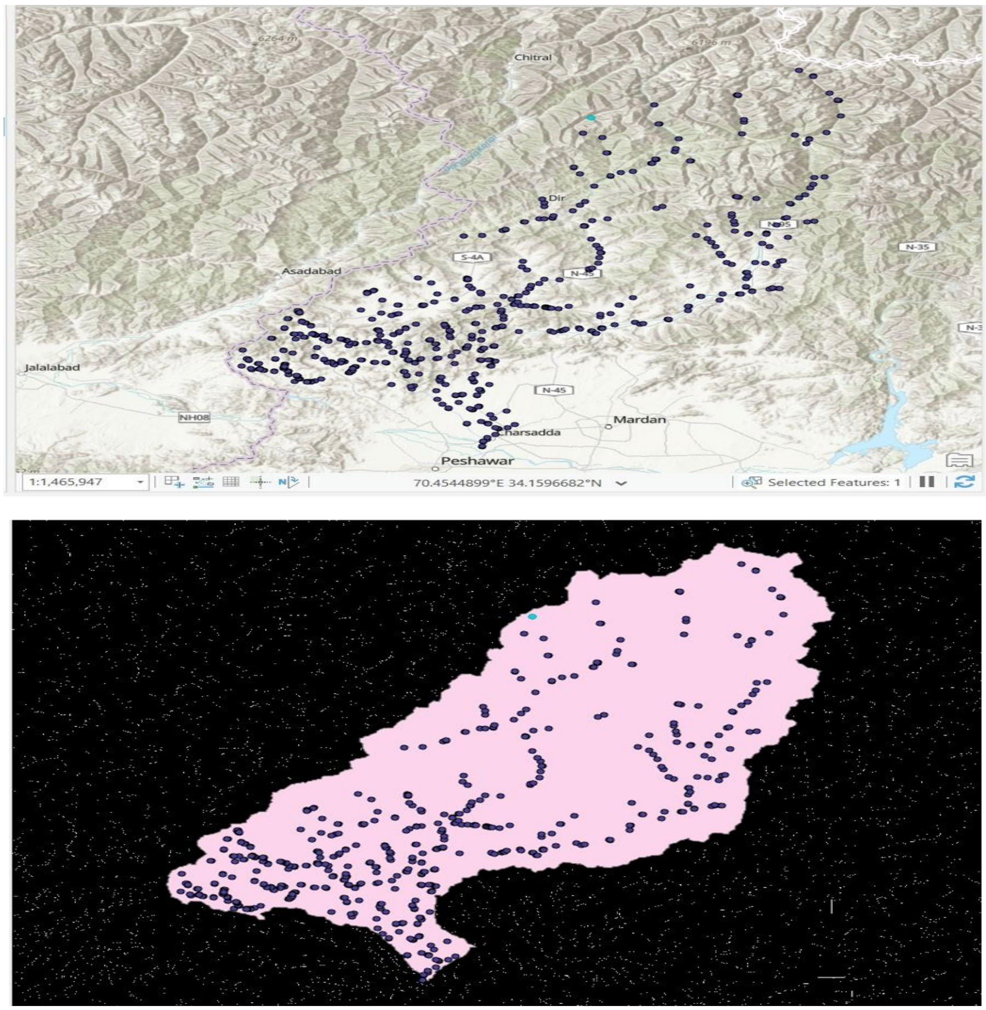

Figure 3: Process of Watershed Delineation

3.3.2 Supervised Classification

We classified the four sub-watersheds—Batkhela, Chakdara, Swat City, and Saidu Sharif—under supervision. To evaluate LULC changes in our chosen research region, we used satellite images from two Landsat satellites—Landsat 4-5 Thematic Mapper (TM) and Landsat 8-9 Operational Land Imager (OLI)/Thermal Infrared Sensor (TIRS)—for each sub-watershed. We concentrated on June, July, and August images to maintain temporal consistency.

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Four distinct years (1991, 2001, 2011, and 2022) were chosen to analyze the LULC of each sub-watershed. This allowed for a thorough evaluation of LULC variations during the designated period

.

Following satellite data collection, we carry out supervised classification for each of the years above. Using this technique, we manually train samples to classify pixels in satellite data into different classes or clusters so that we can recognize patterns and characteristics in the image.

3.3.3 Calculation of Estimated Runoff through Rational Formula

After we have the labelled picture, we can quantify the extent of each class inside the study region by doing area calculations. Using the rational formula with all the parameters entered, we computed the runoff for each sub-watershed for 1991, 2001, 2011, and 2022.

3.3.4 HBV lite model

The Swedish Meteorological and Hydrological Institute (SMHI) created the Hydrologiska Byråns Vattenavdelning (HBV) model in the 1970s to assist hydropower operations. It was selected because, compared to other models, it was practical and efficient due to its simplicity in parameterization and data needs. The HBV model simulates discharge using daily precipitation and potential evapotranspiration (PET) inputs on a daily time frame. It includes the three main hydrological processes of groundwater dynamics, soil moisture and evaporation, and snow and snow cover. However, the snow routine component of the HBV model was not included in this research for the chosen months (June, July, August, and September), which do not have snow. Below are specifics on the periods for calibration and validation.

Table 2: Period defined for Calibration and Validation

Process	Years	Months
Total (1950-2022)	73	876
Calibration (1950-2000)	51	612
Validation (2001 – 2022)	22	264

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Gap optimization for defining parameters

The model parameters were established using the Gap optimization technique. The first step in the procedure is to specify the acceptable ranges for each model parameter. These ranges provide the limits that the optimization algorithm will use to find the optimal parameter values and provide the highest level of efficiency. GAP optimization was used to run the model for each of the four sub-watersheds, each with its own set of parameters.

Results and Discussion

Analysis of Estimated Runoff through LULC

Four separate sub-watersheds—Batkhela, Chakdara, Swat City, and Saidu Sharif—were the subject of the LULC analysis. This segment's primary goal was to predict runoff by analyzing and interpreting changes in LULC patterns throughout various locations over a four-year timeframe, including 1991, 2001, 2011, and 2022. Barren, Deciduous Forest, Developed, Evergreen Forest, and Water are the five main groups into which the region was classified using the LULC. The change in LULC patterns throughout the specified years was depicted using sequential imagery. Significant changes were shown in the graphic, emphasizing the dynamic terrain.

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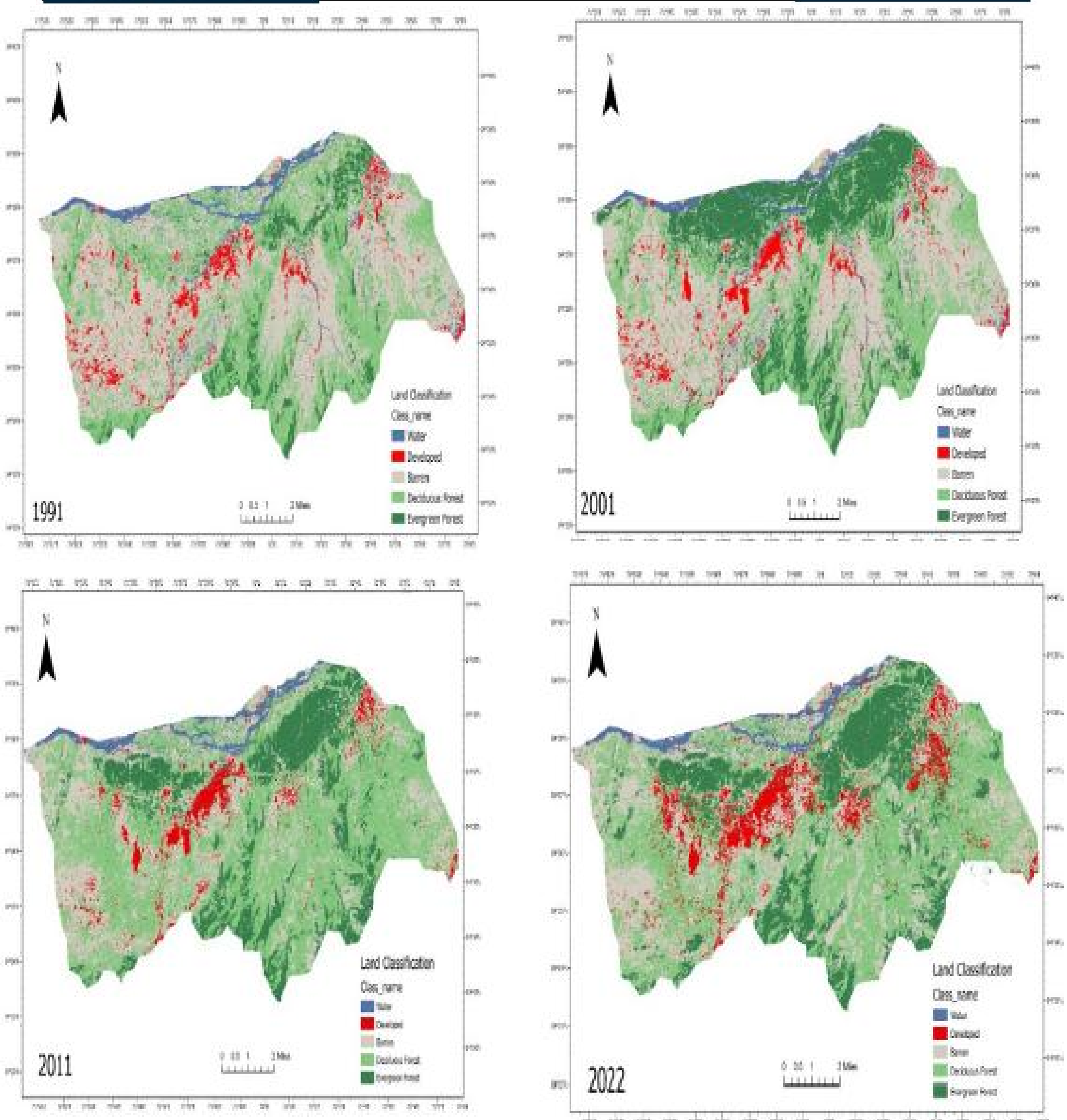

Figure 4: The LULC for the years 1991, 2001, 2011, and 2022 for the general area of Batkhela

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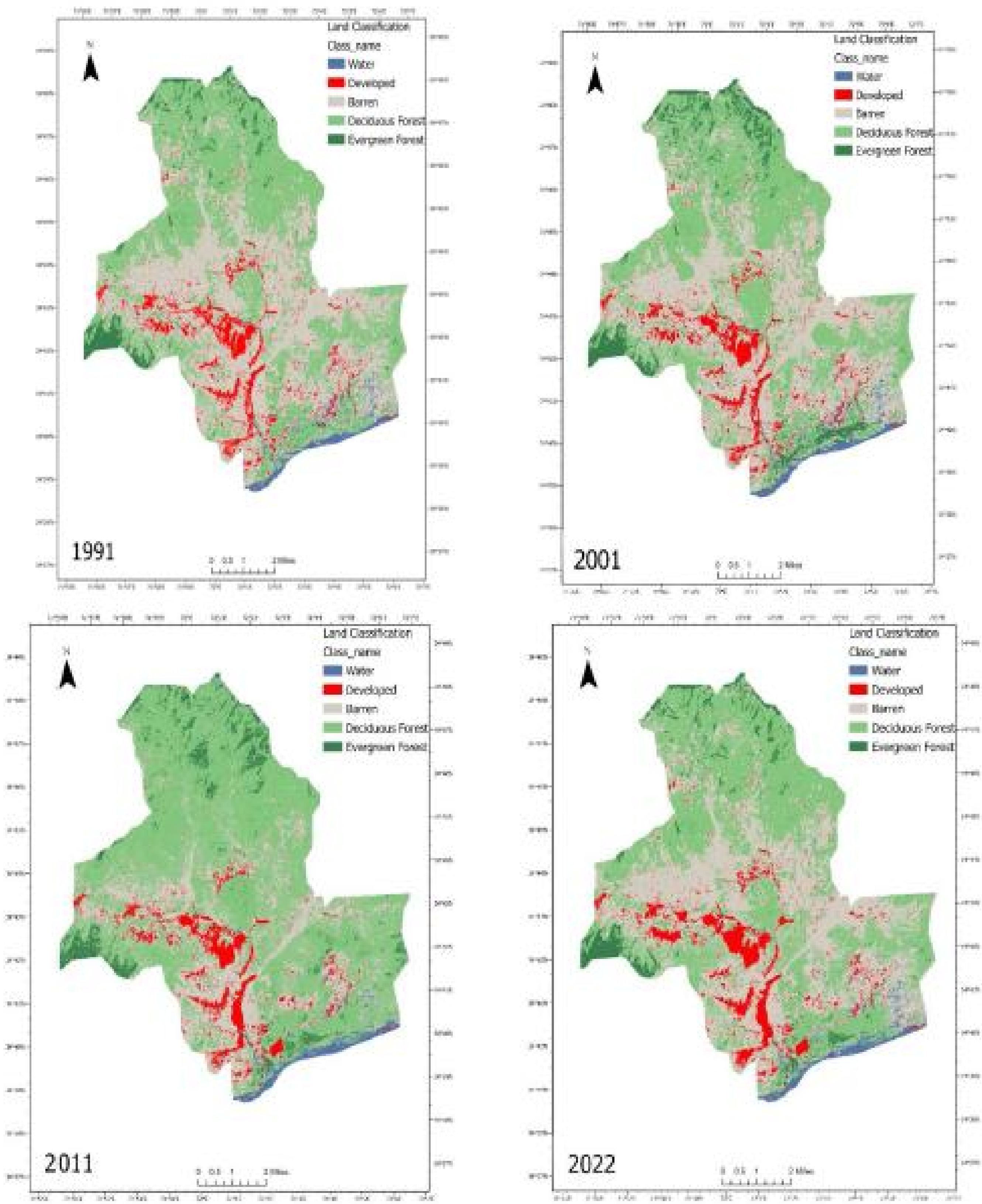

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Figure 5: The LULC for years 1991, 2001, 2011, and 2022 for the general area Chakdara

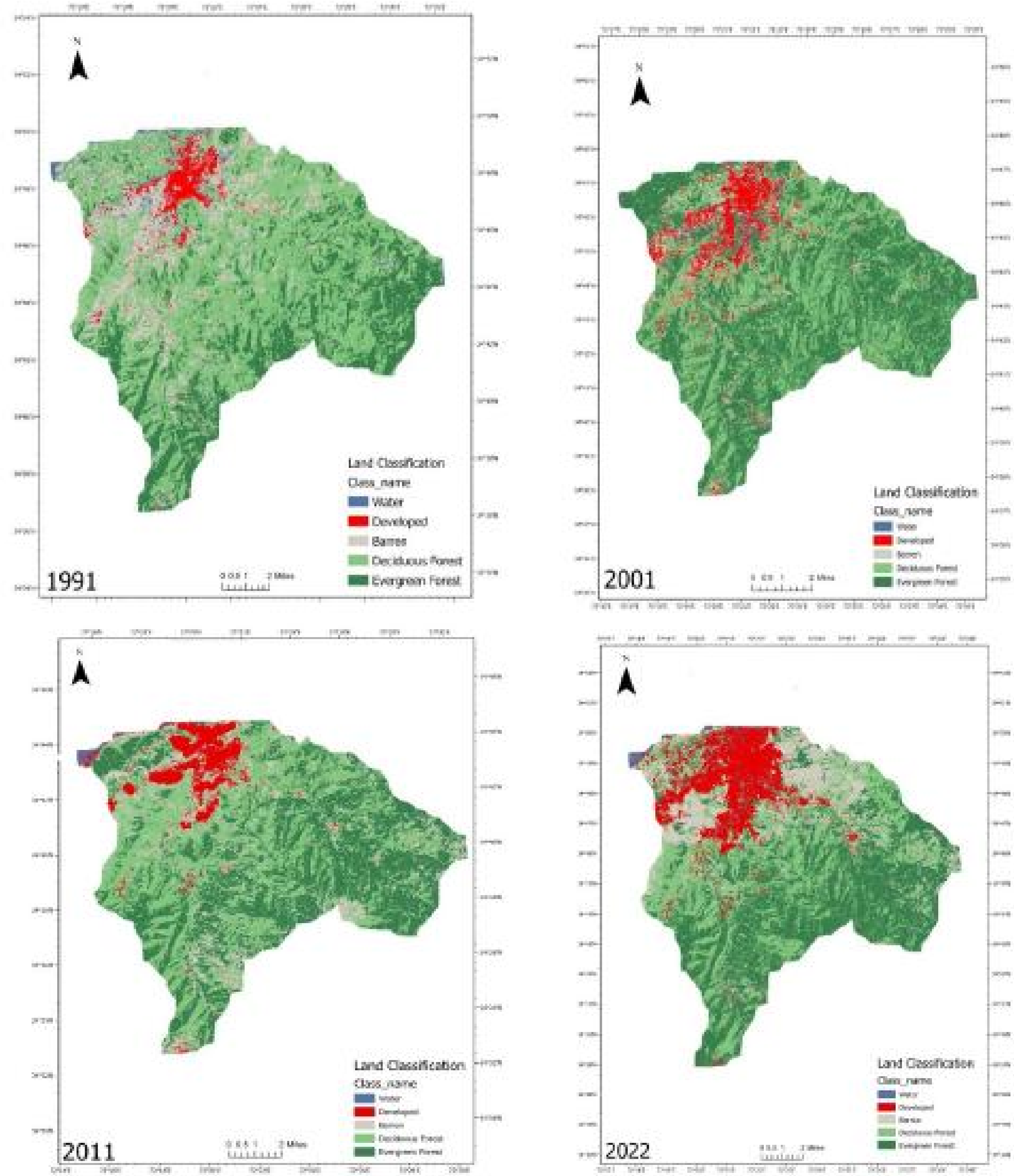

Figure 6: The LULC for the general area of Swat City in 1991, 2001, 2011, and 2022.

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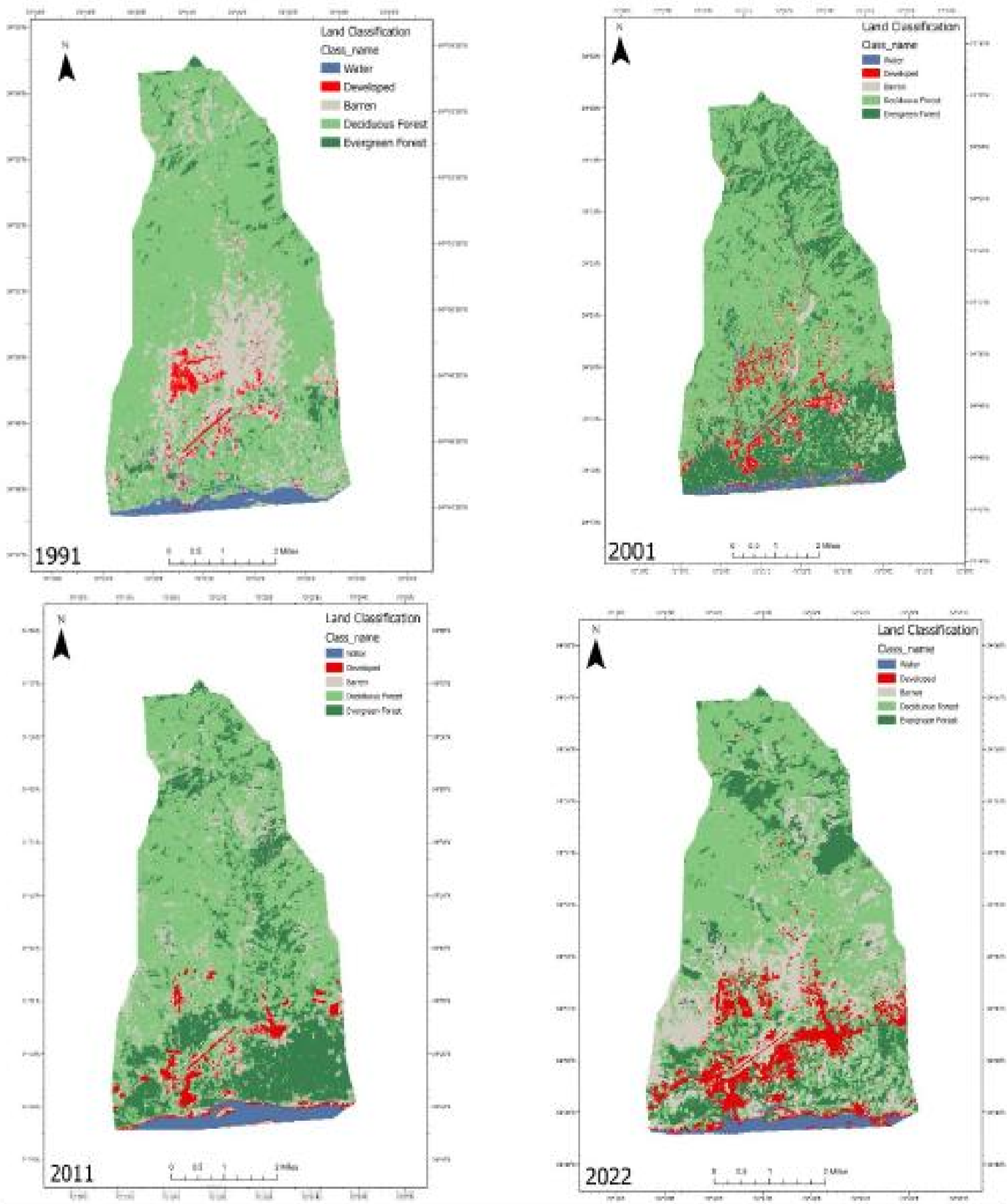

Figure 7: The LULC for the years 1991, 2001, 2011, and 2022 for the general area of SaiduSharif

4.1.1. Quantitative Analysis: Graphical Representations and Tables

Graphic representations were used to depict the changes in the various LULC classes for every sub-watershed. The graphs showed an exciting pattern, notably a steady rise in the Developed area over

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time in all sub-watersheds. The tabulated data showing the change in square kilometres (km2) for each distinct LULC class further supported this pattern.

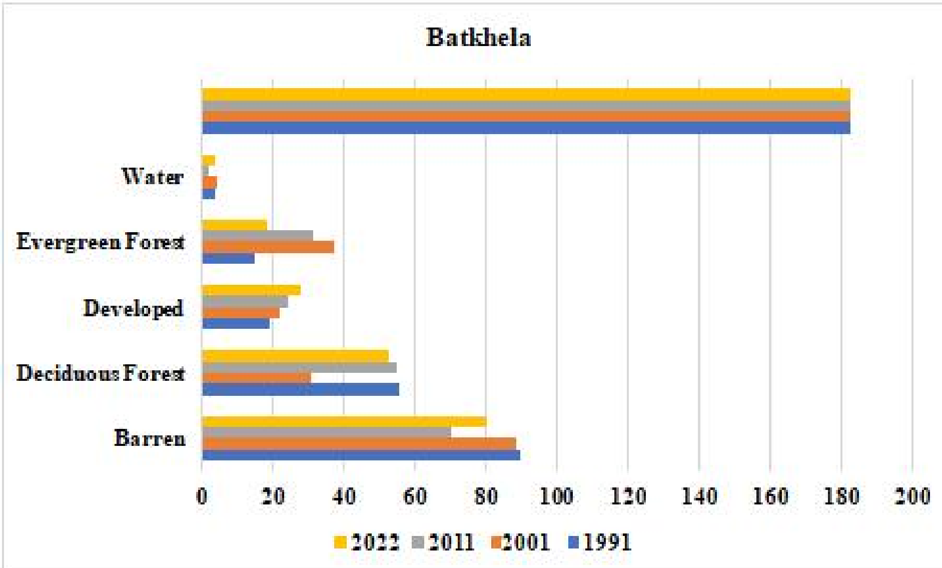

Figure 8: The graphical comparison of LULC changes for the years 1991, 2001, 2011,and 2022 for the general area of Batkhela

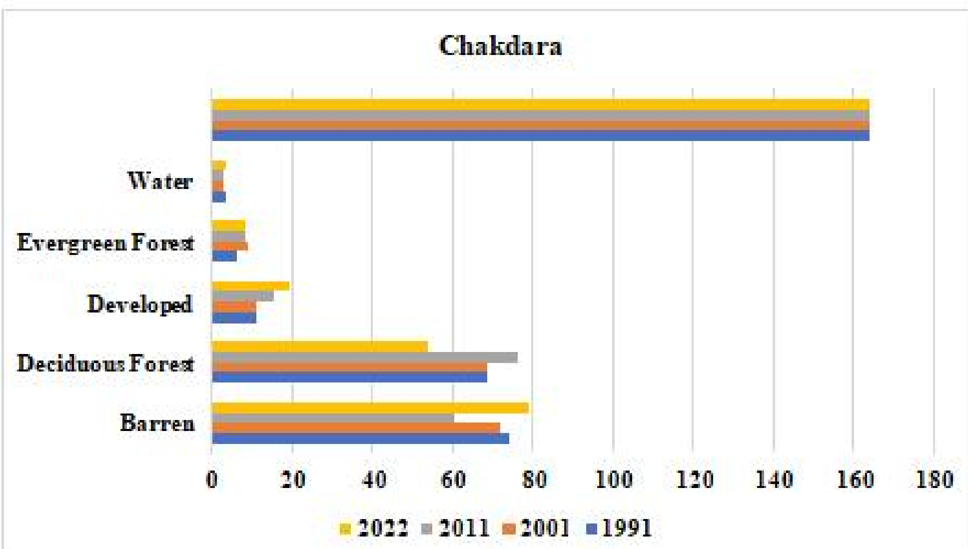

Figure 9: The graphical comparison of LULC changes for years 1991, 2001, 2011,and 2022 for the general area Chakdara

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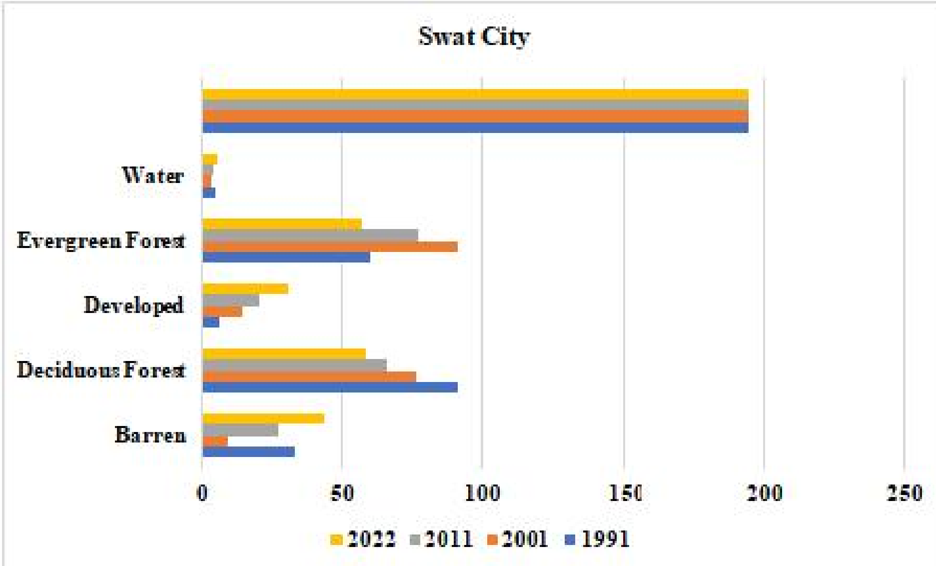

Figure 10: The graphical comparison of LULC changes for the years 1991, 2001, 2011,and 2022 for the general area of Swat City

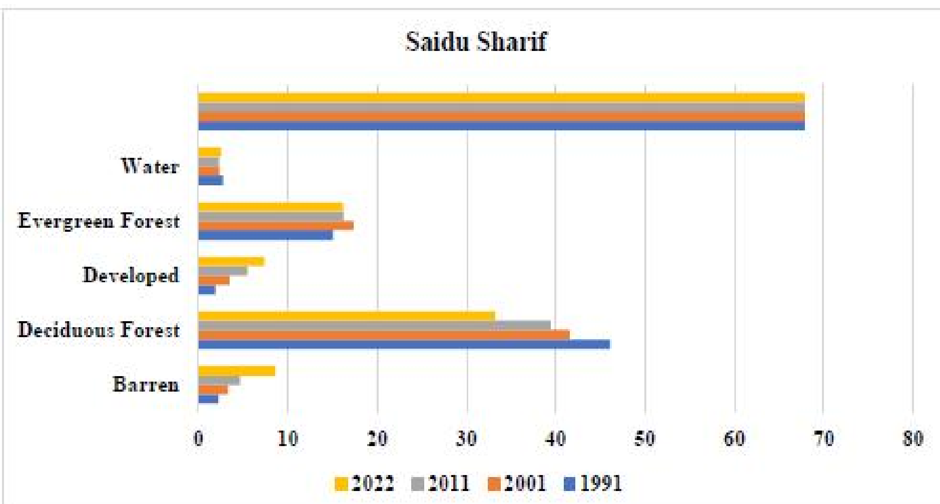

Figure 11: The graphical comparison of LULC changes for years 1991, 2001, 2011,and 2022 for the general area Saidu Sharif

Table 3: LULC changes for Batkhela

Name	1991	2001	2011	2022
Barren	89.96279	88.44147	70.09432	80.511
Deciduous Forest	55.53336	30.99056	54.79268	52.69
Developed	19.25405	22.01125	24.52859	27.8131

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Evergreen Forest	14.746126	37.15524	31.40209	18.3371
Water	3.477	4.3800	2.1613	3.6195
	182.97	182.97	182.97	182.97

Table 4: LULC changes for Chakdara

Name	1991	2001	2011	2022
Barren	74.27722	72.1093	60.512823	78.75464
Deciduous Forest	68.81619	68.42159	76.1109	53.6251672
Developed	11.09564	12.24169	15.52146	19.5093482
Evergreen Forest	6.215338	9.018543	8.632163	8.01590691
Water	3.392546	3.006754	3.015109	3.43928303
	163.79	163.79	163.79	163.79

Table 5: LULC changes for Swat City

Name	1991	2001	2011	2022
Barren	32.96736	9.352269	27.29185	43.417878
Deciduous Forest	90.7727	76.446	65.92463	58.27135
Developed	6.066085	14.49222	20.62277	30.684035
Evergreen Forest	59.84594	90.80761	77.13405	56.626657
Water	5.049976	3.60647	3.730842	5.705007
	194.70	194.70	194.70	194.70

Table 6: LULC changes for Saidu Sharif

Name	1991	2001	2011	2022
Barren	2.196404	3.244183	4.593273	8.628898
Deciduous Forest	46.04186	41.54142	39.369756	33.159232
Developed	1.847902	3.440651	5.478504	7.379517
Evergreen Forest	15.0465	17.33172	16.184471	16.165244
Water	2.716917	2.288084	2.222576	2.516959

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	67.84	67.84	67.84	67.84

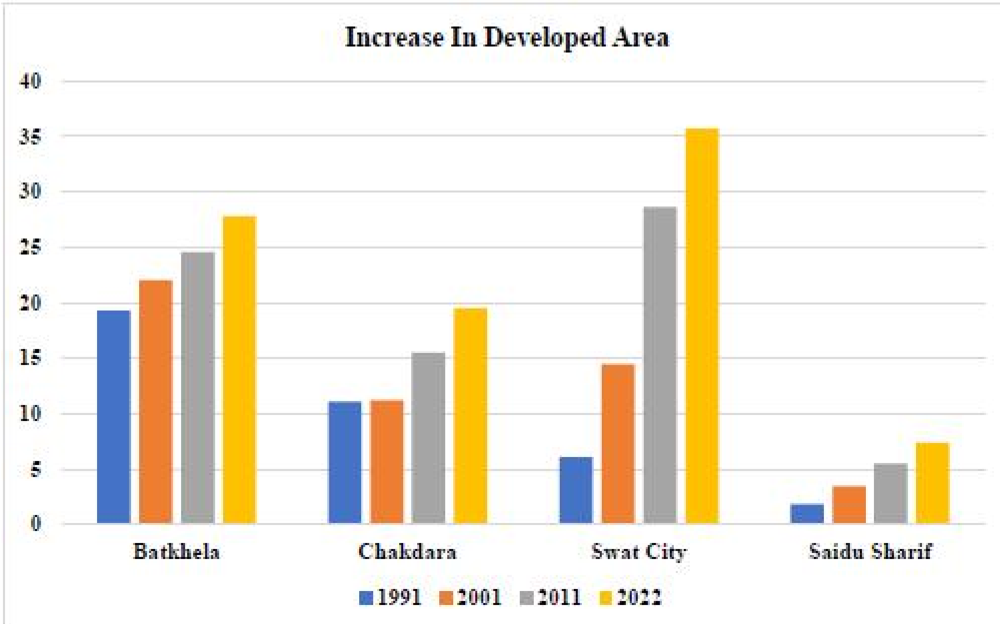

Figure 12: Graphical Representation of Increase in Developed Area

Table 7: Summary of Changes in Developed Area

Name	1991	2001	2011	2022
Batkhela	19.25405	22.01125	24.52859	27.8131736
Chakdara	11.09564	11.24169	15.52146	19.5093482
Swat City	6.066085	14.49222	28.62277	35.684035
Saidu Sharif	1.847902	3.440651	5.478504	7.379517

4.1.2. Discussion of Finding

The results showed a noticeable change in the landscape's makeup, with the Developed class showing an upward trend. This raises the possibility of infrastructure growth or urbanization in these areas. Changes in other classes coincided with the observed rise in developed regions, highlighting the dynamic nature of the environment.

4.1.3. Estimation of Runoff

The logical formula, which incorporated discharge coefficients, various land cover regions, and ERA5

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precipitation data, was used to determine the discharge values for each sub-watershed. By doing these calculations specifically for June, July, August, and September, we were able to ascertain the expected discharge for each sub-watershed for those months.

Table 8: Estimated Discharge calculated for each sub-watershed forJune, July, August, and September, along with years 1991, 2001, 2011 & 2022

	Batkhela	Chakdara	Saidu Sharif	Swat City
Jun-91	7.68	6.57	28.23	31.45
Jul-91	5.47	15.52	48.97	33.22
Aug-91	16.38	32.40	62.59	35.76
Sep-91	20.42	38.51	26.22	30.14
Jun-01	11.98	11.55	17.01	11.72
Jul-01	5.32	10.16	17.28	25.28
Aug-01	7.92	15.46	11.99	26.78
Sep-01	7.32	15.08	11.96	10.93
Jun-11	10.81	13.75	16.53	10.78
Jul-11	14.62	12.95	18.71	22.31
Aug-11	14.82	9.77	7.85	22.42
Sep-11	9.17	8.69	11.74	16.73
Jun-22	19.89	9.77	10.21	18.62
Jul-22	22.91	19.95	22.65	15.56
Aug-22	11.56	16.55	22.61	15.91
Sep-22	8.42	13.19	18.49	24.15
Total	**194.69**	**249.863**	**363.04**	**351.754**

4.2 Statistical Analysis

4.2.1. Calculation of modelled discharge through HBV lite

The observed and modelled discharge levels are then compared with estimated discharge values after

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the parameters are determined using Gap Optimization during the calibration and validation phase.

Table 9: Calculated Discharge for Batkhela & Chakdara

Batkhela	Q-est	Qobs	Qmod	Chakdara	Qest	Qobs	Qmod
Jun-91	7.68	4.51	6.63	**Jun-91**	6.57	5.46	1.28
Jul-91	5.47	6.28	22.13	**Jul-91**	15.52	20.23	12.49
Aug-91	16.38	19.24	18.67	**Aug-91**	32.40	29.63	35.49
Sep-91	20.42	23.28	10.43	**Sep-91**	38.51	35.12	39.10
Jun-01	11.98	8.86	7.79	**Jun-01**	11.55	16.02	13.81
Jul-01	5.32	7.51	6.42	**Jul-01**	10.16	12.59	16.95
Aug-01	7.92	10.93	5.18	**Aug-01**	15.46	18.25	20.98
Sep-01	7.32	11.84	6.03	**Sep-01**	15.08	18.75	13.10
Jun-11	10.81	8.26	7.96	**Jun-11**	13.75	15.16	11.43
Jul-11	14.62	16.55	15.85	**Jul-11**	12.95	17.23	13.77
Aug-11	14.82	12.12	10.76	**Aug-11**	9.77	14.23	16.82
Sep-11	9.17	6.31	5.87	**Sep-11**	8.69	11.74	7.10
Jun-22	19.89	15.17	20.34	**Jun-22**	9.77	11.45	7.78
Jul-22	22.91	25.15	26.21	**Jul-22**	19.95	24.03	18.67
Aug-22	11.56	14.34	12.67	**Aug-22**	16.55	20.14	26.36
Sep-22	8.42	5.52	5.72	**Sep-22**	13.19	15.72	8.23

Table 10: Calculated discharge for Saidu Sharif & Swat City

SaiduSharif	Qest	Qobs	Qmod	SwatCity	Qest	Qobs	Qmod
Jun-91	28.23	26.04	25.35	**Jun-91**	31.45	29.17	35.60
Jul-91	48.97	51.24	44.62	**Jul-91**	33.22	38.51	41.27
Aug-91	62.59	60.03	55.03	**Aug-91**	35.76	38.18	34.79
Sep-91	26.22	23.79	21.70	**Sep-91**	30.14	27.53	29.76
Jun-01	17.01	14.86	14.22	**Jun-01**	11.72	14.32	16.94

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Jul-01	17.28	14.87	19.39	**Jul-01**	25.28	22.31	25.18
Aug-01	11.99	14.71	16.31	**Aug-01**	26.78	24.30	21.49
Sep-01	11.96	14.56	15.36	**Sep-01**	10.93	14.28	10.51
Jun-11	16.53	14.94	10.87	**Jun-11**	10.78	14.38	12.93
Jul-11	18.71	15.38	10.65	**Jul-11**	22.31	19.34	16.45
Aug-11	17.85	15.37	19.57	**Aug-11**	22.42	17.32	12.27
Sep-11	11.74	9.21	16.38	**Sep-11**	16.73	20.31	20.97
Jun-22	10.21	12.68	13.36	**Jun-22**	18.62	14.36	10.46
Jul-22	22.65	24.44	22.89	**Jul-22**	15.56	19.34	18.86
Aug-22	22.61	25.47	30.77	**Aug-22**	15.91	23.33	21.44
Sep-22	18.49	15.47	12.03	**Sep-22**	24.15	14.32	12.68

4.2.2. Comparison of estimated discharge with observed and modelled discharge

We perform statistical procedures to compare the estimated, observed, and predicted discharge. These evaluations compare the estimated discharge, determined from LULC data, with the model to see how well it performs. This method offers a more quantitative assessment of the model's predictive accuracy for discharge and how well it matches actual data.

The statistical methods listed below were used with the discharge data:

- The standard deviation and mean
- NSE, or Nash-Sutcliffe efficiency
- The association between the predicted, observed, and estimated discharge
- RMSE, or root mean square error

The estimated discharge determined via LULC is compared with the modelled and observed discharge to calculate the NSE and RMSE.

Table 11: Calculation of Mean, SD, and RMSE & NSE for each sub-watershed

Statistical Tool	Discharge	Batkhela	Chakdara	Saidu Sharif	Swat City

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Mean (cusecs)	Qest	12.17	15.62	22.69	21.98
	Qobs	12.24	17.86	22.07	21.96
	Qmod	11.60	16.46	21.78	21.35
SD (cusecs)	Qest	5.49	8.51	14.11	8.09
	Qobs	6.30	7.19	14.09	7.98
	Qmod	5.96	10.09	12.38	9.59
RMSE (cusecs)	Qobs	2.96	3.34	2.50	4.50
	Qmod	3.23	4.45	4.92	5.80
NSE (%)	Qobs	0.69	0.84	0.97	0.67
	Qmod	0.63	0.71	0.87	0.45

Table 12: Calculation of Correlation Coefficient for each sub-watershed

Statistical Tool	Discharge	Batkhela	Chakdara	SaiduSharif	SwatCity
CorrelationCoefficient	Qobs	0.87	0.96	0.98	0.83
	Qmod	0.84	0.90	0.94	0.79

4.2.3 Explanation of the Statistical Analysis

4.2.3.1 Mean and Standard Deviation

Each sub-catchment's mean value is computed, and the average estimated, observed, and modelled discharge for each sub-catchment is displayed. The standard deviation provides information about how much the data deviates from the mean. Accordingly, the table shows that the standard deviation of discharges (Qest, Qobs, and Qmod) in Saidu Sharif and Chakdara has the most dispersed data points. In contrast, Swat City's data is somewhat dispersed, and Batkhela's data is less variable and more in line with the norm.

4.2.3.2 Root Mean Square Error (RMSE)

By contrasting the estimated discharge with the predicted and observed discharge, the RMSE is determined for every sub-catchment area. The computed mean value displays each sub-catchment's average estimated, observed, and modelled discharge. The difference between values predicted by a

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model or estimator and the actual observed values is measured by the Root Mean Square Error or RMSE. Lower RMSE values signify higher agreement between predicted and observed values, and it offers a single figure to describe the overall accuracy of the model's predictions.

Thus, a summary of each sub-catchment's RMSE values:

a. **Interpretation of RMSE for Batkhela:** In Batkhela, the RMSE between the estimated and observed discharge is 2.96 cusecs, whereas the RMSE between the modelled and estimated discharge is 3.23 cusecs. This shows the typical size of the discrepancies between Batkhela's measured discharge levels and the estimated/modelled values.

b. **Interpretation of RMSE for Chakdara:** Whereas the RMSE between the estimated and modelled discharge is 4.45 cusecs, the RMSE between the observed and estimated discharge in Chakdara is 3.34 cusecs. This implies that, compared to Batkhela, the model's projections for Chakdara deviate more from the calculated values.

c. **Interpretation of RMSE for Saidu Sharif:** In Saidu Sharif, the RMSE between the estimated and observed discharge is 2.50 cusecs, whereas the RMSE between the modelled and observed discharge is 4.92 cusecs. This suggests that when comparing the calculated and modelled discharges, the model's estimates for Saidu Sharif deviate more from the Batkhela and Chakdara.

d. **Interpretation of RMSE for Swat City:** In Swat City, the RMSE between the estimated and modelled discharge is 5.80 cusecs, whereas the RMSE between the observed and estimated discharge is 4.50 cusecs. This indicates that Swat City's model projections deviate from the most calculated values out of the four sub-catchments.

4.2.3.3 Nash-Sutcliffe Efficiency (NSE)

One metric used to assess how well hydrological models function is NSE. It shows the degree to which the estimated data and the model projections agree. It assesses how well the model predicted outcomes compared to actual observations. While a score of 0 or less indicates that the model's predictions are no more accurate than only utilizing the observed data mean, a value of 1 indicates that the model accurately predicts the observed data.

Table 13: NSE value range

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Serial No.	NSE Value	Qualification
1	≤0	Unacceptable
2	0 – 0.4	Weak (Unsatisfactory)
3	0.4 – 0.6	Moderate (Satisfactory)
4	0.6 – 0.8	Good (Satisfactory)
5	0.8 – 1	Optimal (Satisfactory)

Four sub-watersheds were examined, and the estimated discharge is contrasted with the observed and modelled discharge. Batkhela's NSE scores of 0.69 and 0.63 show the model's reasonable performance. To increase its accuracy, there remains space for development, nevertheless. On the other hand, Chakdara's NSE values of 0.84 and 0.71 indicate a comparatively strong performance, with the model consistently matching the observed and predicted discharge. With NSE values of 0.97 and 0.87, Saidu Sharif shows even better model performance, showing a close match between the predicted and observed discharge. However, as NSE values of 0.67 and 0.45 indicate, Swat City exhibits poorer model performance, especially when comparing estimated discharge with predicted discharge.

4.2.3.4 Correlation Coefficient

Additionally, we calculated the correlation coefficient, which ranges from -1 to 1 and indicates the direction and intensity of the association between two variables.

With correlation values of 0.87 and 0.84, Batkhela's observed and modelled discharges show a significant positive connection, suggesting good performance with some potential for improvement. With values of 0.96 and 0.90, Chakdara demonstrates a robust positive correlation, indicating that the link between all variables is well represented. With values of 0.98 and 0.94, Saidu Sharif shows a strong positive correlation, suggesting that the link between the variables is well-modelled. With values of 0.83 and 0.79, Swat City likewise exhibits a high positive correlation, but one is marginally smaller than the others, indicating respectable performance with room for improvement.

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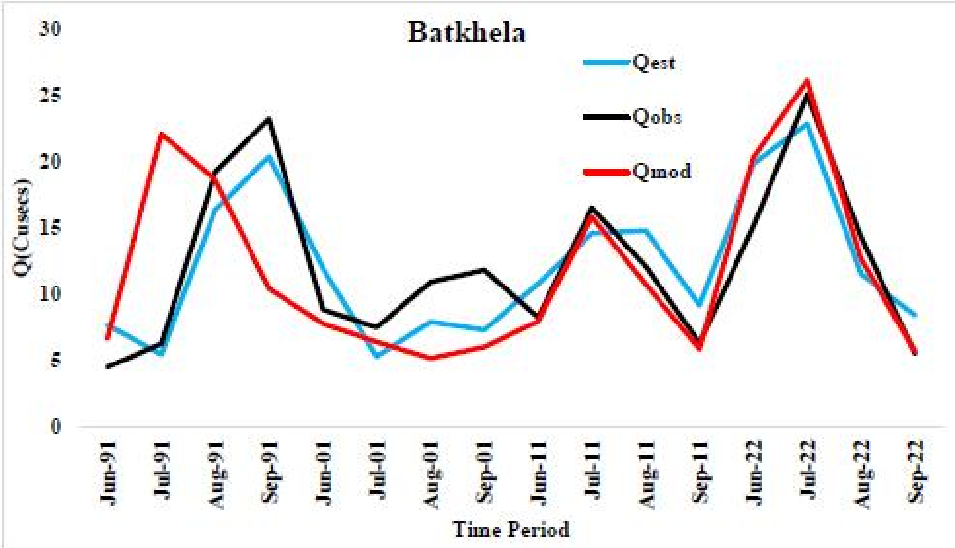

Figure 13: Relationship between Q_{est}, Q_{obs} and Q_{mod} for Batkhela Sub watershed

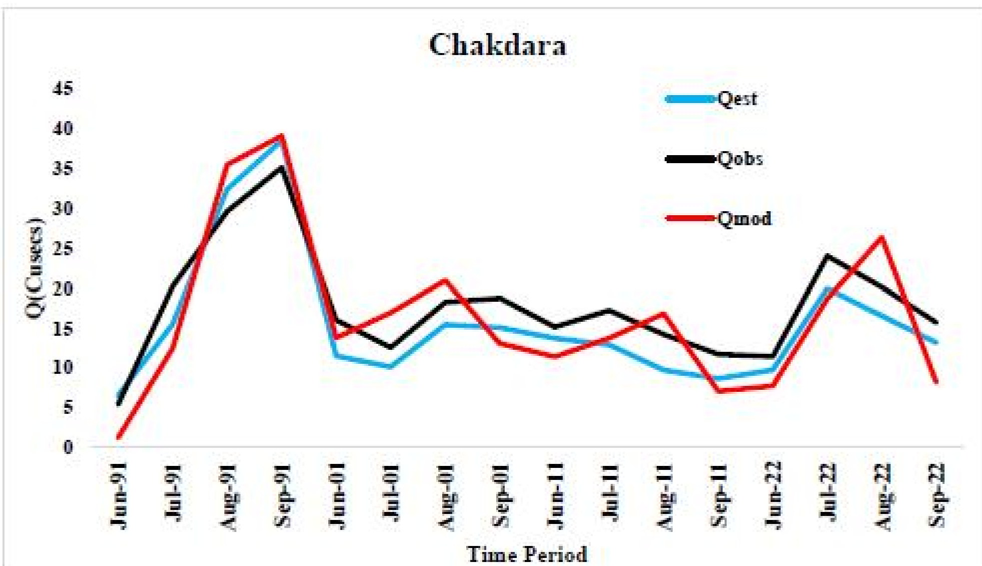

Figure 14: Relationship between Q_{est}, Q_{obs} and Q_{mod} for Chakdara Sub watershed

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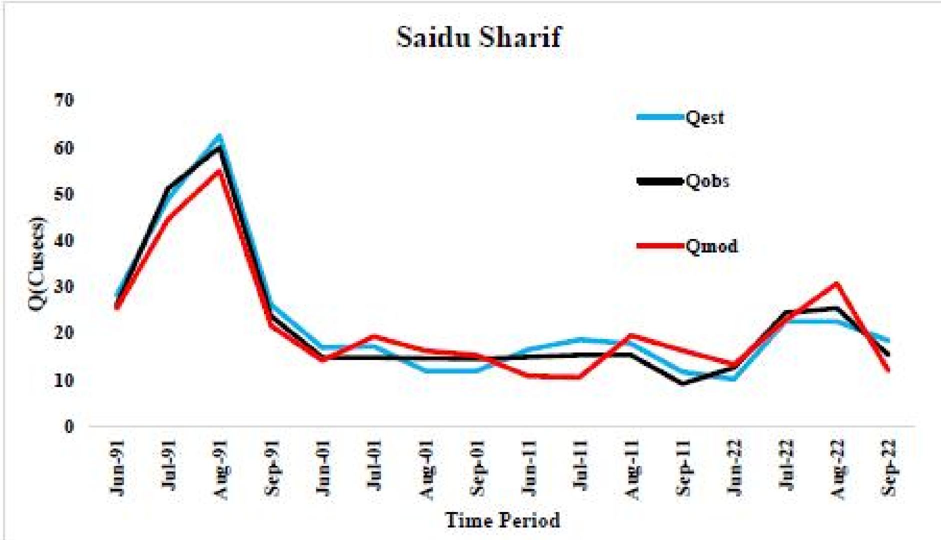

Figure 15: Relationship between Q_{est}, Q_{obs} and Q_{mod} for Saidu Sharif Sub watershed

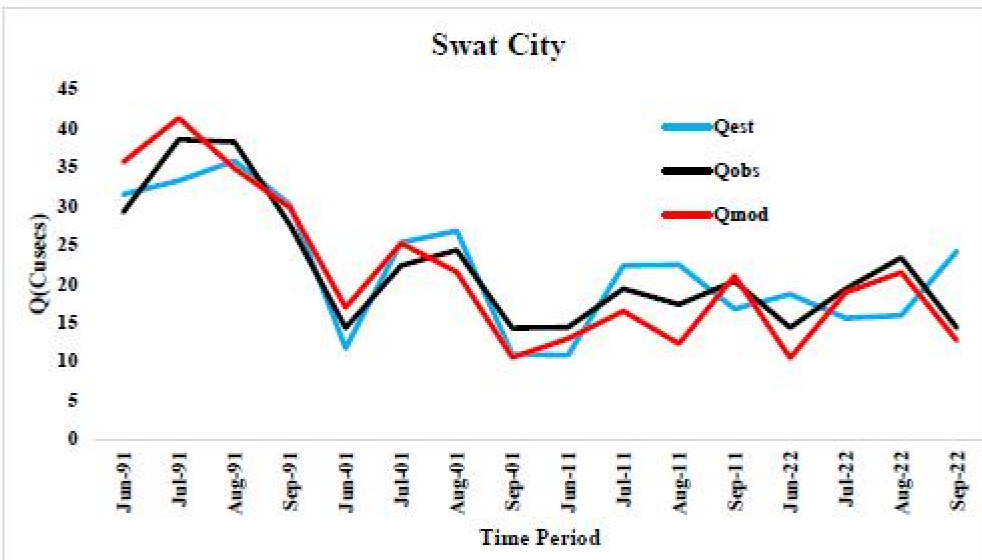

Figure 16: Relationship between Q_{est}, Q_{obs} and Q_{mod} for Swat Sub watershed

Conclusions and Recommendations

Conclusions

a. The area estimates generated from classed imagery quantitatively evaluated the extent of land use and land cover (LULC) within the research region. This served as the basis for the Rational Formula's runoff estimation. Using rainfall intensity data from ERA5 and "Runoff coefficient" values, runoff was calculated for each sub-watershed in 1991, 2001, 2011, and 2022.

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b. b. We saw an increased trend in the Developed class using GIS-based LULC data. To predict runoff data based on LULC changes, the study effectively measured runoff contributions from various sub-watersheds by utilizing the Rational Formula and supervised classification in ArcGIS in conjunction with ERA5 precipitation data.

c. c. Our goal of hydrological modelling for rainfall-runoff transformation was achieved when the HBV lite model, calibrated and validated between 1950 and 2022, and gap optimization refining parameters for each of the four sub-watersheds offered an effective and dependable method of simulating discharge.

d. The statistical analysis reveals differences in model performance among the four sub-watersheds, with Saidu Sharif exhibiting high efficiency and correlation in discharge estimation, Batkhela displaying comparatively consistent results, and Swat City highlighting the need for improvement in prediction accuracy.

Recommendations

a. This paper's methodology mostly ignores in-situ data gathering in favour of predicted and observed discharge values. In-situ measurements, acquired using devices such as stream gauges, provide precise and up-to-date data on water flow dynamics within a watershed. Researchers can enhance calibration and evaluate model outputs by monitoring discharge directly. In-situ data gathering using carefully positioned monitoring stations should be the top priority for future research. We would eventually get better outcomes with this method as it would produce a large dataset for model validation and improvement.

b. Future research should include more years beyond 1991, 2001, 2011, and 2022 and extend data collection beyond the current four-month timeframe (June to September) to gain a deeper understanding of watershed dynamics. Increasing the temporal scope improves understanding of seasonal fluctuations, long-term trends, and how climate change affects hydrological patterns.

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