Twin Calamities in the Swat River Basin: Unraveling the Hydro-Meteorological Drivers of the 2010 and 2022 Floods

Inayat Ullah[1], Sara Jamil[2], Sheraz Ahmad[3], Muhammad Zeeshan[4] and Zahid Arif[5]

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Abstract
This paper presents a comparative evaluation of the hydro-meteorological factors underlying the regressive floods of 2010 and 2022 in the Swat River Basin, a climate-sensitive and topographically predisposed location in north-western Pakistan. The research examines, through the joint application of a qualitative case study method supplemented with GIS analysis, remote sensing, NASA MERRA-2 climate data, GlobeLand30, and hydrological modelling, the patterns, intensity, and effects of the two floods. The 2010 flood was mainly exacerbated by record monsoon floods that reached more than 300 per cent above average in some regions of Khyber Pakhtunkhwa, accompanied by La Niña and glacier meltwater flow, along with poor river dikes. However, unlike 2022, the flood was caused by extended monsoon rains and an intense pre-monsoon heatwave, rapid glacial thaws, and rainfall as high as 243 per cent of normal. Analysis of land use indicated a greater extent of urbanisation, deforestation, and floodplain encroachment, which reduced the water absorption capacity of nature and thus increased risks. Although discharge peaks increased in 2010, runoff volume increased in 2022, due to enhanced hydrological responses. The study highlights the importance of reforestation, watershed development, flood zoning, warning systems, and hardy infrastructure in mitigating future calamities.

Keywords: Floods, Swat River Basin, Climate Change, Surface Runoff, Land Use Change, River Discharge, GIS, 2010 Flood, 2022 Flood

Introduction

Floods are one of the most common and catastrophic natural disasters that occur worldwide, causing severe damage to lives, livelihoods, infrastructure, and ecosystems. Due to the excess of water outside its natural limits, floods are linked to various interacting entities, including extreme precipitation, snowmelt, geomorphological conditions, and anthropogenic factors (IPCC, 2012). Floods have been occurring more frequently and intensifying in recent decades due to climate change, changes in land use, deforestation, and urbanisation. Floods have become a perilous and spiralling epidemic in Pakistan, posing a horrifying peril in areas with challenging topography and an ill-coordinated river basin (Goodwin, 2010; Khan, 2010).

The Swat River Basin in Khyber Pakhtunkhwa, a province of Pakistan, serves as an example of a vulnerable mountainous area at risk of hydro-meteorological disasters. The slopes are steep, there are concentrated settlements, and the economy relies heavily on agriculture, making the region

[1]*Centre for Disaster Preparedness & Management, University of Peshawar. Email: Inayatu.edu@gmail.com*
[2]*Centre for Disaster Preparedness & Management, University of Peshawar. Email: Jamilsara42@gmail.com*
[3]*Centre for Disaster Preparedness & Management, University of Peshawar. Email: Sheraz250000ps@gmail.com*
[4]*Centre for Disaster Preparedness & Management, University of Peshawar. Email: Zeeshansarfaraz001@gmail.com*
[5]*Centre for Disaster Preparedness & Management, University of Peshawar. Email: Zahidarif000@gmail.com*

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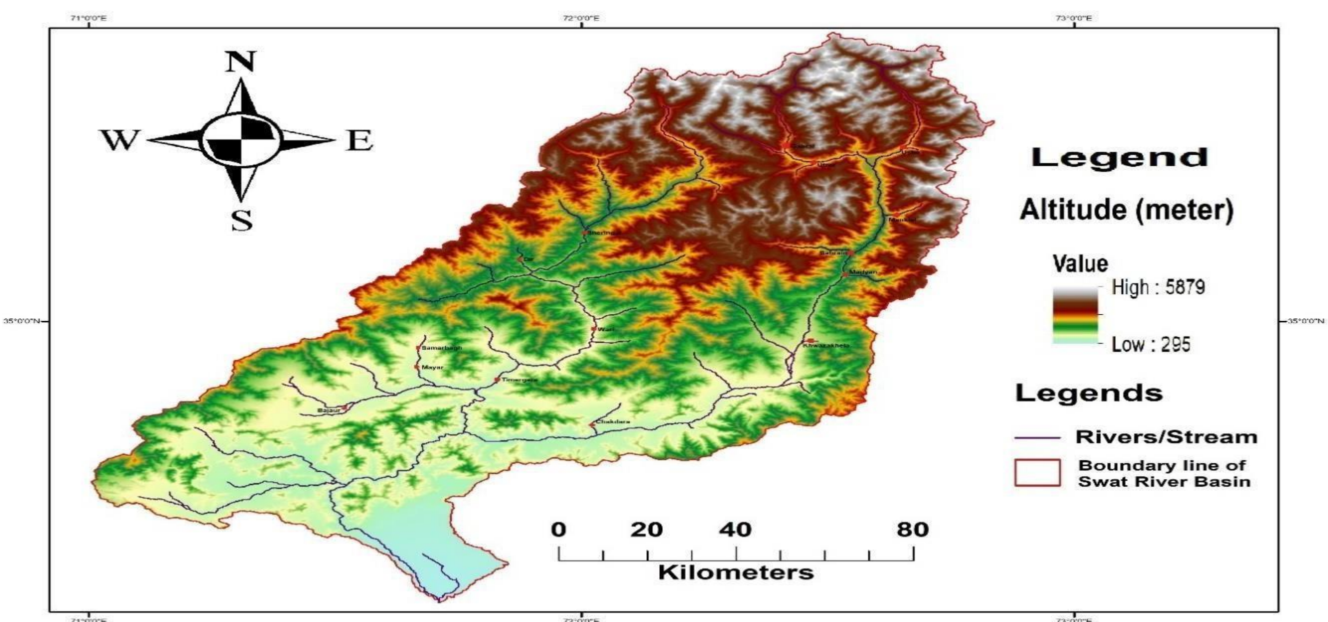
particularly prone to flash floods, riverine overflows and glacial lake outburst floods (GLOFs). Additionally, the two most devastating floods in Pakistan's history, the 2010 and 2022 floods, significantly influenced this basin and revealed weaknesses in the early warning systems, infrastructural resilience, and integrated watershed management (Ahmad et al., 2020). This was exemplified by the flood that occurred in 2010 as a result of abnormal monsoon rains and the rapid melting of glaciers, which swept away about a fifth of the country, affecting 20 million people. The Swat River and its catchment area, spanning more than 13,000 km², experienced the highest rates of discharge associated with high-intensity rains and rapid surface runoff (Merger, 2011; Baloch, 2014). Similarly, the 2022 flood was driven by multiday extreme precipitation that resulted from two atmospheric rivers, as well as humid antecedent soil moisture. This was facilitated by rainfall in July and August 2022 that broke the historical records by 181 per cent and 243 per cent, respectively, resulting in the displacement of 33 million people and economic losses due to an excess of $30 billion (Nanditha et al., 2023; Otto et al., 2023).

Although both floods may be related more in terms of causative factors, where monsoonal rainfalls are the primary cause, they differed in characteristics, such as timing, extent of flooding, severity, and socio-economic consequences. The 2010 flood clarified the inefficiency of physical barriers and fragility of rural settlements. Still, the 2022 flood demonstrated a greater pattern of the climate-related disaster unpredictability, and it was amplified by the poorer management of the lands as well as by improving the readiness to the disaster (Rehman, Khan, & Ahmad, 2023; Aziz, 2022). In this backdrop, this paper sets out to critically compare and contrast the hydro-meteorological reasons for the occurrence of the 2010 and floods in the Swat River Basin. Using rainfall intensity, hydrological patterns, surface runoff, and flood response mechanisms, the study attempts to understand the dynamic changes in flood patterns in the area. This is essential in informing disaster risk reduction (DRR), advancing flood forecasting systems, and formulating sustainable river basin management strategies that will help reduce future flood risks.

Figure 1: Digital Elevation Model (DEM) of the Swat River Basin



Literature Review

Global Overview of Flood Disasters

There is a significant amount of flooding, one of the most common and harmful natural hazards, plaguing the globe, affecting approximately 1.4 billion people, and resulting in approximately 99,900 deaths in the 20th century alone (Asri, 2009). With the rate at which climate change is accelerating, floods have been characterised by their intensity and unpredictable nature more than ever before, partly due to an increase in precipitation, glacial melting, sea level rise, and uncontrolled land Utilisation. A couple of countries that have experienced significant flooding cases around the globe include, among others, the USA, Brazil, Japan, Thailand, and Mozambique. For example, the 1993 USA flood and the 2000 flood in Mozambique resulted in significant infrastructure loss and hindered economic growth (Carbone & Hanson, 2012). The 2011 flood disasters in Queensland (Australia), Bangkok (Thailand), and Brazil present a global crisis of extreme rainfall and poor drainage (Romm, 2011). These disasters tend to disrupt entire ecosystems and socio-economic systems, and further impoverish vulnerable populations. Some of these floods are cyclical, and in most cases, the floods are intensified through deforestation, poor urban planning, as well as a lack of timely investment in infrastructure. The move towards urbanisation of flood-prone regions worldwide exposes people to a greater risk. Hence, flood dynamics, particularly in areas undergoing rapid climatic transitions, have been crucial in reducing disaster risks and planning for long-term resilience.

Flood Hazards in Pakistan

Pakistan is among the flood-affected nations in South Asia, due to its peculiar climatic and topographical conditions. The annual monsoon season (July to September) brings heavy rainfall to the northern and central parts of the country, where flooding is typically widespread. More than a dozen major floods have occurred in the country since 1947, each leaving its socio-economic and environmental impact. Floods in 1992, 2001, 2010, and 2022 can be classified as the most devastating in the history of Pakistan (NDMA, 2011). Individually, the flood of 2010 alone covered 20 per cent of the land, displaced more than 20 million people, and cost the economy close to $ 10 billion (Goodwin, 2010). Conversely, the 2022 flood affected more than 33 million individuals and resulted in an estimated loss of approximately $18 billion (Otto et al., 2023). One of the factors contributing to repeated floods in Pakistan is the lack of congruency between structural measures, such as the construction of levees and reservoirs, and non-structural mitigation strategies, including early warning systems, land-use planning, and public awareness campaigns. Besides, extensive deforestation in catchment regions, encroachments within the banks of rivers, and poor drainage systems in urban areas have made a significant contribution to flood vulnerability in the country. The example of Pakistan provides critical lessons on how developing countries can overcome weaknesses in their systems in terms of planning to confront disasters.

Causes of the 2010 Flood in Pakistan

That was the case in the 2010 flood that hit Pakistan due to a rare combination of meteorological, climatic and topographic factors. The July 2010 monsoon rains were unprecedented, recording a value over 300 per cent of the average rainfall in some areas of Khyber Pakhtunkhwa, where they played a crucial role in triggering the flood disaster. The La Niña conditions strengthened the humid monsoon winds sent by the Bay of Bengal, which clashed with the westerly troughs towards northern Pakistan, leading to continuous heavy precipitation on steep terrains (Martius et al., 2013). The Swat, Kabul, and Indus rivers, which were already overflowing with excess glacial meltwater due to above-average temperatures, breached their banks. Due to the harsh conditions of river discharge, the embankments that were not well-maintained, and drainage channels that had clogged, led to massive surface and flash flooding. The International and Pakistan Meteorological Department reports stated that the flood intensified due to the melting of glaciers, wet soils, and the deforestation of trees (Sajjad et al., 2015). The combination of meteorological abnormalities, weak infrastructure, sprawling settlements, and floodplain encroachments transformed the 2010 flood into more than just a natural disaster, portraying a reflection of systemic vulnerability. This incident is a landmark in the history of hydrology in Pakistan, as there is an immense need to interrelate climatic forecasts, floodplain zoning, and long-term sustainability plans for watersheds in Pakistan in the context of flooding.

The 2022 Flood: A New Climate Challenge

A catastrophic occurrence of a scale never before seen in Pakistan, the 2022 flood in that country was a bearer of climate-related disasters. The 2022 event was caused by prolonged monsoon rains, in contrast to the largely riverine nature of the 2010 flood, which was attributed to the impacts of climate anomalies on the weather system, including atmospheric rivers and glacial melt (Otto et al., 2023). The Pakistan Meteorological Department states that most parts of the country experienced above-normal rainfall (181 per cent and 243 per cent) in July and August 2022, respectively. Of particular concern was how it affected Balochistan and Sindh, where the urban and rural infrastructure was overloaded. Additionally, the intense heatwaves preceding the monsoon period led to the faster melting of glaciers in northern Pakistan. This factor contributed to rises in river levels and flash floods downstream (Ahmed et al., 2022). The overall number of those affected exceeded 33 million, with more than 2 million homes damaged, and overall economic losses reaching over $ 18 billion (Aziz, 2022). The flood devastated vast areas of agricultural land, severely impacted transportation and communication, and displaced many people. Among the peculiarities of the 2022 flood was the slow response, which was caused by institutional inertia, ineffective forecasting, and delays in emergency mobilisation. The incident serves as a vivid reminder of the flood threat that climate degradation poses to Pakistan and why emergency response methods must quickly shift towards a proactive and climate-resilient approach to disaster management.

Factors Contributing to Recurring Floods in Swat

A combination of natural and anthropogenic processes increases the Swat River Basin's susceptibility to floods. The rugged topography and the sourcing of snow-fed tributaries in the region mean it is susceptible hydrologically to high-intensity rainfall and glacial melt. During monsoon seasons, the runoff from upper catchments has a high velocity that may exceed the river's capacity, leading to the occurrence of flash floods and landslides (Ahmad, Shakir, & Khan, 2020). Nevertheless, floods in the Swat region are a natural occurrence, which is not the only factor at play. Deforestation, unlawful mining, and unauthorised construction on floodplains are examples of human activities that have significantly altered the basin's hydrology (Ali, Hussain, & Shah, 2019). Loss of forests decreases the soil's capacity for infiltration and accelerates surface runoff, while poorly designed infrastructure obstructs natural drainage. Moreover, unplanned urban development, high rates of population growth, and uncontrolled cases of urban sprawl, characterised by a lack of zoning and environmental restrictions, have led to high urban settlement density at risk. There is an added pressure of climate change, erratic rainfall, and temperature increases that accelerate the snowmelt. These conditions combine to increase the intensity of floods and their frequency, as experienced in 2010 and 2022. Weak governance, inadequate land-use planning, and environmental corruption continue to render Swat a high-hazard region in terms of hydro-meteorological tendencies.

Flood Management Strategies of the Swat River Basin Flood

The Swat River Basin is facing flood risks that need to be addressed through multidimensional interventions involving both structural and non-structural works. Conventional technologies for managing river flow, which include embankments, levees, and check dams, play a significant role in controlling river flow and protecting infrastructure. They are, however, usually compromised by the lack of an effective maintenance arrangement and a strategy plan (Zaidi et al., 2013). The non-structural means are also creating much attention due to the sustainability they can bring in the long run. These will include an early warning mechanism, flood modelling using GIS, zoning of floodplains, tree plantation, and community awareness.

An example is real-time hydrological observations coupled with mobile alert services, which provide vulnerable populations with invaluable time to escape or take safety precautions (Rahman et al., 2022). It is important to implement urban planning reforms. The government should limit infrastructural construction in areas prone to flooding and implement construction codes that promote water-resistant designs.

Additionally, the key to enhancing emergency response lies in the capacity-building activities of local disaster management agencies and civil society organisations. Incorporation of climate response strategies, such as afforestation and wetland reconstruction, will make the basin ecologically strong. The best way to mitigate the intensification of flood threats is a well-organised, coordinated flood management strategy that addresses the unique topography and context of Swat.

Methodology

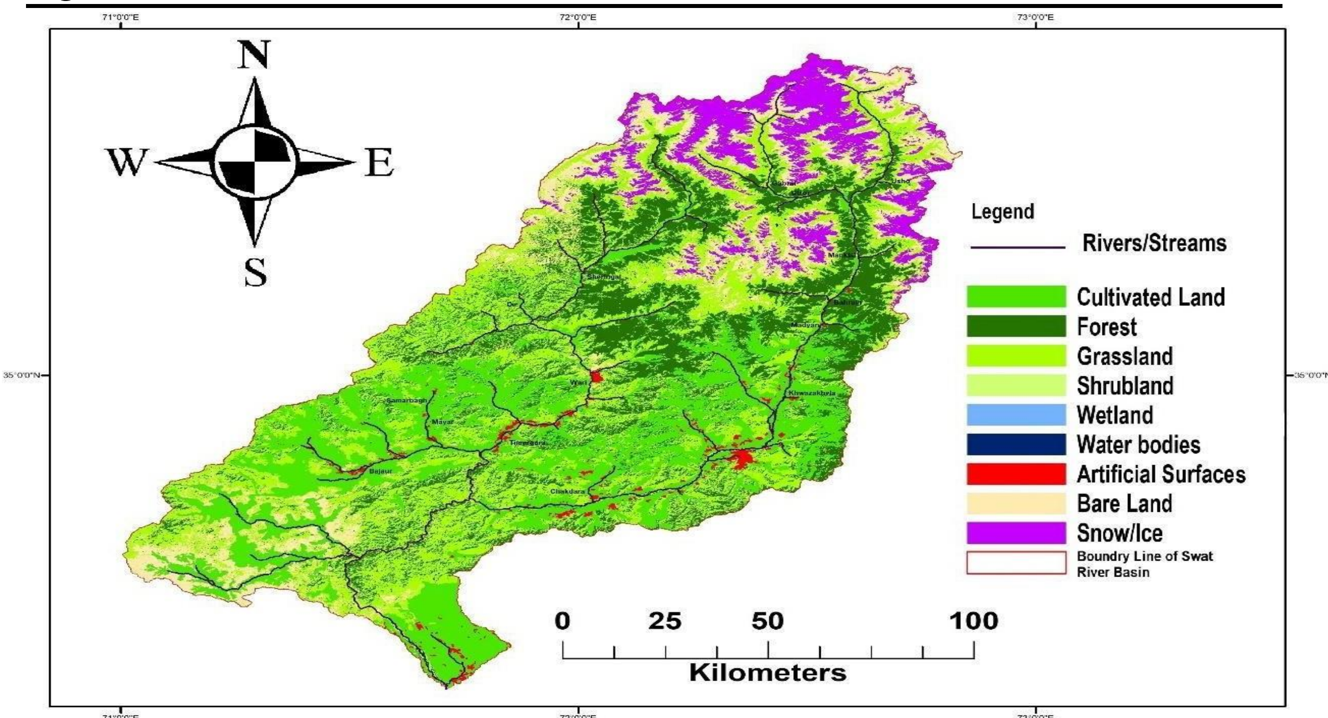
The type of study is identified as a qualitative comparative case study, as it aims to examine the role that hydro-meteorological factors played in the major flood events witnessed in the Swat River Basin in 2010 and 2022. The Swat River Basin, located within the Malakand Division of the province of Khyber Pakhtunkhwa, Pakistan, is characterised by rugged mountainous topography, snow-fed tributaries, and high residential density in flood-prone areas of vulnerable locations. The region is susceptible to extreme precipitation, snowmelt, and flash flooding, as it falls under both western disturbances and South Asian monsoon systems, which significantly increase its predisposition to such phenomena. The comparative structure of the study facilitates the comparison of changes in rainfall intensity, river discharge, surface runoff, and land use patterns over the two years of flood.

This paper adopts a comparative analysis approach to explore the hydro-meteorological aspects that contributed to the 2010 and 2022 floods in the Swat River Basin. Some of the most important variables are precipitation, the characteristics of the land use and the drainage basin. Rainfall information is obtained using the MERRA-2 database from NASA, which provides a detailed view through measurements in time and space of the magnitude and longevity of rain at various locations. The local irrigation department supplies discharge data that is crucial for providing information about river flow rates and maximum flood levels through hydrograph analysis.

The GlobeLand30 dataset used in the current study provides land cover data for the year 2020, with a resolution of 30 meters and a geographic system of WGS84 and UTM 6 projection. With this dataset, it is possible to make an accurate spatial analysis of land-use categories, including forests, cultivated land, wetlands, and artificial surfaces.

The analysis of the collected data is performed by comparing it with Geographic Information Systems (GIS) to facilitate spatial mapping, classification, and statistical analysis using Microsoft Excel, as well as calculating flow velocity and surface runoff according to the Manning Equation. The study estimates the annual surface runoff of several land cover classes by combining precipitation and discharge data with land use information. Such an approach offers a tangible insight into the flood process and contributes to successful disaster risk management activities. Although the study offers valuable insights, it has limitations. It limited the capacity to perform field-based measurements or validation on the ground due to the use of secondary data. Although the resolution of the satellite images is adequate for primary analyses, it may not be suitable for identifying topographical characteristics in a less flat region, such as the Swat River Basin, which presents rugged topography. Additionally, data on socio-economic conditions may be in scope and methodology, as proposed by various sources, raising the possibility of a lack of coherence. However, the sources of data were chosen selectively and ethically cited in order to uphold academic standards.

Figure 2: Land Cover Classification of the Swat River Basin



Results

Comparative Rainfall and Temperature – Swat Basin

The recorded rainfall of the Swat River Basin between 2009 and 2022 has demonstrated a lot of fluctuation in rain patterns as well as rainfall regimes. The amount of rainfall changed significantly over the years and ranged between 537.89 mm to 1919.53 mm in 2009 and 2020 respectively. Such variabilities portray how this region is sensitive to seasonal monsoons, and changing climatic factors. Particularly, in 2010, the annual rainfall was observed as 780.47 mm and the month July (295.31 mm) and August (137.11 mm) had the highest monthly rainfall. This heavy weather monsoon activity is accompanied with the disastrous floods that happened in the same year, and it points at the direct correlation between heavy monsoon summer rain and flood hazards.

On the same note in 2022 the total annual precipitation was 1099.3 mm, with the extreme rainfalls falling in the months of July (184.71 mm) and August (311.09 mm). The severity and aggregation of the rainfall in these months were probably some of the chief causes of extreme flooding, just as per those recorded in 2010. Conversely, the year 2020 has the largest rainfall amount recorded in the dataset especially during the months of March (342.77 mm), April (200.39 mm), and October (210.94 mm). This Rainfall was, however, more spread throughout the year and this could have helped in the incidences of such extreme flooding even though the amounts were very high.

Other years 2015 (806.84mm) and 2021 (1168.03 mm) had recorded a considerable amount of rain annually, though not leading into major flooding situations, perhaps due to fluctuations in rainfall pattern, ways of land utilization and even the responsiveness of the watershed. Conversely, other drier years such as that experienced in 2011 (574.8 mm) and 2014 (590.62 mm) had precipitations that were moderate and there were no visible flood-related effects. There seems like a steady seasonal pattern throughout all the years-rain is maximum during monsoons (July to September) and minimum during the winter months (November to January). The trend indicates that the management of the monsoonal rainfall becomes very crucial in avoiding the hazard of floods.Overall, the collected data proves that the amount of rainfall per annum is not the only factor involved in the dynamics of floods in the Swat Basin but also its intensity and the time that it occurs within a month can be decisive. Years of heavy rain fall concentrated in peak monsoon months, especially in 2010 and 2022, go hand in hand with the incident of major floods, highlighting the need of better strategies of flood forecasting and watershed management.

Table 1: Comparative Rainfall and Temperature – Swat Basin

YEAR	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	ANN
2009	73.83	116.02	79.1	137.11	26.37	10.55	31.64	31.64	5.27	5.27	15.82	5.27	537.89
2010	31.64	147.66	26.37	42.19	26.37	42.19	295.31	137.11	21.09	5.27	0	5.27	780.47
2011	10.55	158.2	36.91	47.46	26.37	21.09	47.46	126.56	36.91	26.37	36.91	0	574.8
2012	58.01	94.92	68.55	89.65	31.64	5.27	52.73	73.83	89.65	21.09	10.55	63.28	659.18
2013	21.09	152.93	126.56	79.1	15.82	52.73	47.46	94.92	26.37	15.82	31.64	5.27	669.73
2014	5.27	79.1	137.11	58.01	73.83	0	52.73	63.28	36.91	68.55	15.82	0	590.62
2015	47.46	100.2	126.56	105.47	36.91	21.09	84.38	73.83	31.64	84.38	63.28	31.64	806.84
2016	36.91	31.64	126.56	110.74	31.64	47.46	131.84	94.92	36.91	10.55	0	15.82	675
2017	126.56	73.83	58.01	68.55	5.27	31.64	63.28	100.2	36.91	0	10.55	21.09	595.9
2018	0	68.55	73.83	110.74	89.65	52.73	126.56	68.55	10.55	42.19	42.19	21.09	706.64
2019	94.92	89.65	68.55	58.01	31.64	15.82	73.83	84.38	21.09	21.09	63.28	15.82	638.09
2020	73.83	142.38	342.77	200.39	189.84	179.3	79.1	200.39	116.02	210.94	121.29	63.28	1919.53
2021	26.37	89.65	163.48	61.59	94.36	43.15	235.01	142.38	131.29	138.34	5.63	36.79	1168.03
2022	133.75	47.5	58.68	26.25	59.78	78.55	184.71	311.09	76.23	35.02	75.24	12.49	1099.3

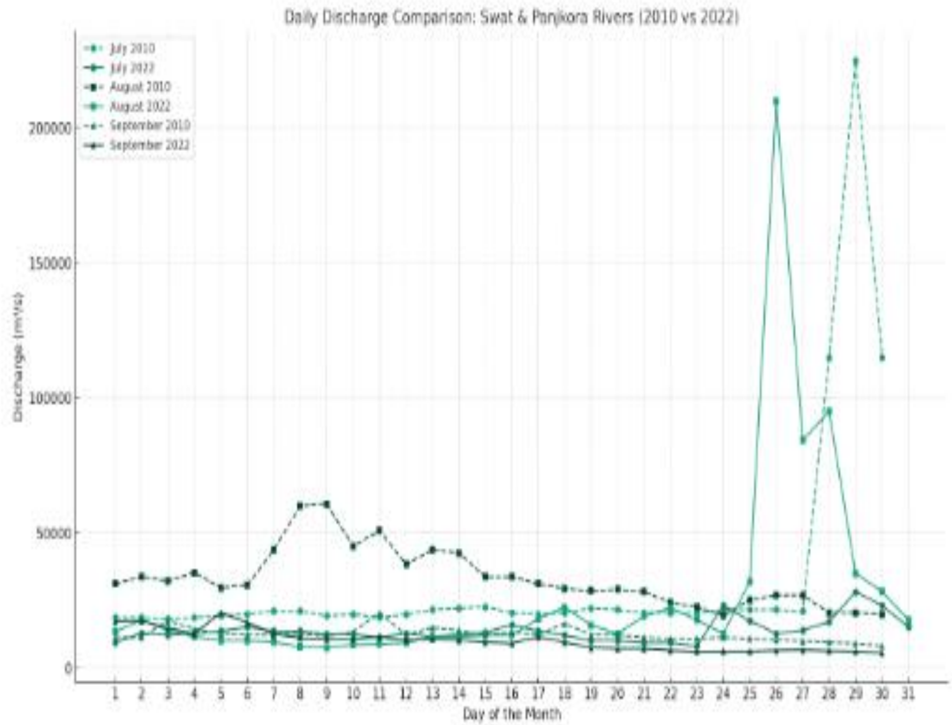
River Discharge Comparison – Swat River

By comparing the Swat River data of discharge during 2010 and 2022, it can be observed that the flow patterns highly vary and they reflect the extent of flood occurrence in the given years. In 2010, levels of discharge in July were usually within 18,000-22,000 cusecs range, but a sudden spurt was recorded on July 28 and 29 when the level rose to 115,000 and 225,000 cusecs respectively, which was the highest point of the dreadful flood. August 2010 was also a month of extreme flows with multiple days with flows over 40,000 cusecs, topping 60,000 cusecs in early and mid-August. On the contrary, the July discharge values of 2022 remained relatively low and mostly between the ranges of 9,000 to 17,000 cusecs until the sharp peak with more than 28,000 cusecs on July 29. August 2022 unusually had high spikes, the highest being 210,000 (never higher) on August, 26, and another record high of 95,000 on August 28, higher even than some the highs of the 2010 floods. The September of both years has relatively steady decrease discharge, with values below 20,000 cusecs in 2010 and below 12000 cusecs in 2022, regarding the levels of relatively normal conditions of flows. These similarities imply that though the prolonged and constant high discharge trend was a bit longer in 2010, the trend in 2022 included shorter and extreme bursts especially towards the end of August that can be associated with highly localized precipitation and/or glacier-generated runoff. This variability of discharge highlights the dynamism in flood risks in the Swat River basin and necessitates improved flood forecasting activities, early warning systems and adaptive water management tactics.

Table 2: River Discharge Comparison – Swat River

Dates	July(2010)	Aug (2010)	Sept (2010)	July(2022)	Aug(2010)	Sept(2010)
1	18,740	31,194	11,350	9,461	13,336	17,200
2	18,740	33,773	11,350	12,880	17,832	17,483
3	18,154	32,195	17,568	12,146	13,940	14,890
4	18,740	35,353	14,450	12,651	11,592	12,720
5	19,326	29,697	12,800	13,669	10,205	20,525
6	19,912	30,695	12,250	15,221	10,205	16,874
7	21,043	43,750	12,250	13,669	9,650	12,614
8	21,043	60,000	12,800	13,669	7,883	11,152
9	19,326	60,800	11,800	12,451	7,634	10,755
10	19,912	45,134	13,350	12,451	8,628	10,755
11	18,740	50,900	20,500	11,300	8,876	11,549
12	19,912	38,433	12,250	12,755	9,363	10,358
13	21,586	43,750	15,000	11,592	11,592	10,755
14	22,129	42,623	13,900	12,329	11,592	10,358
15	22,672	33,773	12,250	13,210	12,146	9,563
16	20,500	33,773	13,350	16,032	12,146	9,165
17	19,912	31,194	12,250	13,669	18,200	11,549
18	20,500	29,418	16,540	12,146	22,552	9,563
19	22,129	28,580	12,250	10,205	15,851	7,576
20	21,586	29,138	12,250	10,205	12,755	7,236
21	20,500	28,301	11,350	9,373	19,200	7,236
22	20,500	24,210	10,900	9,373	22,296	6,555
23	20,500	22,672	10,900	8,131	17,832	6,115
24	21,586	19,326	11,350	23,174	12,755	6,215
25	21,586	25,249	10,900	17,502	31,933	6,215
26	21,586	26,966	10,450	12,755	210,000	6,555
27	21,043	26,966	10,000	13,973	84,374	6,726
28	115,000	20,500	9,550	17,146	95,000	6,385
29	225,000	20,500	9,100	28,224	35,070	6,215
30	115,000	19,912	8,200	23,174	28,301	5,626
31	Nil	Nil	Nil	15,191	17,800	Nil

Figure 3: Daily Discharge Comparison



Surface Runoff Comparison

Table 3 gives the average yearly run off of Swat River Basin was estimated in the year 2010 using various types of land use, their areas, Manning roughness, and equal annual rainfall of 733.01 mm. The area of total study is roughly 13.65 billion square meters and the estimated volume of runoffs is about 609.7 million cubic meters each year. Out of the categories of land use the grassland ranks as the highest provider of the runoffs with a value of approximately 218 million cubic meters mostly because of its large coverage of close to 5 billion square meters and a moderate Manning of 0.06. Cultivated land with an area of more than 3.6 billion square meters comprises 185 million cubic meters of runoff, which is the second largest, stating that it affects the response of hydrology in the basin substantially.

Forests also have their part, and they provide a nearly 139 million cubic meters of runoff, which has moderate size because of the considerable area and infiltration ability. Less extensive lands, bare lands, yield about 61.8 million cubic meters of runoff which is quite considerable considering the low infiltration capacity that they have. On the contrary, the artificial surfaces, shrubland, and water bodies have only a little contribution, and together they have less than 2 percent of the wider runoff. The data obviously indicate that land use pattern causes substantial changes in the volume of surface runoff, with vegetative cover and roughness of the land surface (measured in terms of Manning values) being the key factors. These results indicate the significance of sustainable land management towards runoff reduction and controlling flood hazard in the Swat River Basin.

Table 3: Average Annual Surface Runoff of Swat River Basin (2010)

Land Uses	Area (Sq.m)	Manning's Values	Rainfall (mm/year)	Estimated Runoff Coefficient
Cultivated Land	3606866498	0.07	845.52	213477443
Forest	3158753011	0.06	845.52	160247331
Grassland	4962896623	0.06	845.52	251773701
Shrub land	63229604.16	0.06	845.52	3207713.69
Water Bodies	38481600.05	0.03	845.52	976108.87
Artificial Surface	139122356.1	0.02	845.52	5881536.77
Bare Land	1685350515	0.05	845.52	71249878.3
Total	13654700207	--	--	706813712.9

Table 4: Average Annual Surface Runoff of Swat River Basin (2022)

Land Uses	Area (Sq.m)	Manning's Values	Rainfall (mm/year)	Estimated Runoff Coefficient
Cultivated Land	3606866498.00	0.07	733.01	185070845
Forest	3158753011.00	0.06	733.01	138923853
Grassland	4962896623.00	0.06	733.01	218271171
shrub land	63229604.16	0.06	733.01	2780875.99
Water Bodies	38481600.05	0.03	733.01	846221.99
Artificial Surface	139122356.10	0.02	733.01	2039561.56
Bare Land	1685350515.00	0.05	733.01	61768939
Total	13654700207.00			609701467.3

Table 4 has been plotted to reflect an estimate of the annual average surface runoff of the Swat River Basin in year 2022, based on rainfall (845.52 mm/ year) and land use area as well as the roughness coefficient values of Manning and runoff coefficients of Swat River Basin. The land area evaluated does not vary with 2010 of 13.65 billion square meters and the total volume in 2022 of surface runoffs is quite high of about 706.81 million cubic meters as opposed to 2010 of 609.7 million cubic meters. Such a drastic uptrend corresponds to an increment of the annual rainfall, such as the increase of 733.01mm rainfall in 2010 to 845.52mm in 2022.The runoff highest is still encountered in grassland areas with an amount of 251.77 million cubic meters as a result of its large area and average infiltration capability. The area of cultivated land, more than 3.6 billion square meters, adds about 213.48 million cubic meters or significantly higher as compared to 2010 owing to increased levels of rain. Forested land areas contribute around 160.25 million cubic meters again, expressing how large their hydrological influence is regardless of having the improved capacity of absorbing water. Bare land runoff reaches 71.25 million cubic meters showing also an increase in the use of bare lands with little vegetation cover and poor infiltration which result into runoff in case of high rainfall years. Although the area covered by artificial surfaces and shrublands is less than water bodies, the runoff outputs are still recognized to be quite factful, and different types of water bodies account the least. Generally, the comparison with 2010 shows that there is a distinct increase in the surface runoff in the three categories of land uses with the primary cause being the increment of precipitation in 2022. This development of an increase in runoff production signifies the increase in flood risks and an enhanced land use planning and flood prevention strategies. The information identifies how the rainfall patterns modifications along with current land use distribution have a direct impact on the hydrological area reaction of the basin as well as the possibility of flood dangers.

Land Use / Land Cover Classification of the River Swat Basin

The distribution of land use and land cover (LULC) of Swat River Basin in terms of area in square meters as well as percentage share over a period between 2010 and 2022 is presented in Table 5. The statistics demonstrate that the most prevalent land cover type is the grassland type displaying an area of about 4.96 billion square meters that comprises 36.35 percent of the total area of the basin. It is succeeded by cultivated land which takes 3.61 billion square meters (26.41%), and forest areas also occupy approximately 3.16 billion square meters (23.13 percent) of the total area covered by land. The mere existence of these three categories makes about 86 percent of the total basin area, meaning land usage that comprises vegetative plantation is predominant in the area. Bare land is 12.34 percent, and this signifies areas that have little vegetation with high level of surface runoff. Urban or built-up areas are artificial coverage with only 1.02%, but their contribution to the hydrological processes can be exceptionally high as its surface drainage usually is impervious and no distinguishable. Smaller proportions are the scrublands and the water bodies with 0.46 percent and 0.28 percent, respectively.

The statistics indicate that land use distribution did not fluctuate too drastically over the 12 years, although small changes in the proportions of artificial surfaces or in the area of forest cover would have drastic effects in regards to flood risk and watershed behavior. This is to reiterate the importance of proper land management and city planning, especially since rising rainfalls and floods have been recorded in the recent years.

Table 5: Land Use / Land Cover (LULC) Classification

Land Uses	Area (Sq. m)	%Age Share
Cultivated land	3606866498.28	26.41
Forest	3158753010.95	23.13
Grassland	4962896622.61	36.35
Shrub land	63229604.16	0.46
Water bodies	38481600.05	0.28
Artificial surface	139122356.13	1.02
Bare land	1685350514.69	12.34
Total	13654700206.87	100.00

Discussion

As the results of the comparative study of the floods in the Swat River Basin, which occurred in 2010 and 2022, show, there was a definite increase in hydro-meteorological hazards over the period, influenced by both climatic factors and anthropogenic effects. There are also other factors, such as the high pre-monsoon temperatures, which must have enhanced glacier melting. This was compounded by the other impacts of rising rainwater, as well as the higher discharge of rivers compared to previous times. A comparison of the 2010 and 2022 editions of the Swat River discharge regimes reveals that the difference between the magnitude and timing of critical floods is substantial. The 2010 flood was characterised by extended high discharge levels in both July and August. Discharge peaked at 225,000 cusecs towards the end of July and remained above 40,000 to 60,000 cusecs for several subsequent days, indicating a prolonged hydrological crisis. On the contrast, 2022 had relatively average flows throughout the majority of July with sudden, extreme fluctuations in late August, reaching previously unseen peaks of 210,000 cusecs on August 26 and then an equally significant 95,000 cusecs on August 28, both of which individually exceeded many of the 2010 peaks in volume, yet took much less time to cross each other. These observations suggest that the 2022 event was shorter and featured very high-intensity discharge surges, compared to the 2010 event, which had wider but longer-duration discharge surges. These discharges might be influenced by extreme rainfall events occurring in concentrated areas and the melt contribution of glaciers. Such a change in the character of floods raises concerns about the development of hydrological patterns in the Swat River basin, which are relevant to the adoption of flood control policies, the strength and capacity of infrastructures, and climate change.

The increased severity of flood events is further brought to the forefront by data on river discharges. The findings of this study provide compelling evidence of the intensifying nature of flood events in the Swat River Basin, driven by both climatic and anthropogenic factors. The comparative analysis between the 2010 and 2022 floods reveals a clear escalation in rainfall intensity, runoff volumes, and river discharge. Notably, the 2022 flood surpassed the 2010 event in terms of peak rainfall and glacial melt, indicating the increasing influence of climate anomalies. Elevated temperatures recorded during the 2022 pre-monsoon season likely accelerated snow and glacier melt, compounding the effects of already excessive rainfall. This aligns with global climate change patterns that predict an increased frequency of compound extreme events in mountainous regions.

Another critical insight from the data is the significant increase in surface runoff during the 2022 flood, which is attributable not only to heavier rainfall but also to reduced vegetative cover and poor watershed management. The GIS and LULC analysis showed a decline in forest areas and a notable expansion in built-up zones, particularly in hazard-prone regions. These land use changes have directly contributed to the reduction of natural buffers that previously absorbed excess water and slowed down surface flow. The loss of forest cover, combined with urban encroachment on riverbanks, has drastically increased flood vulnerability in the Swat region.

The local tributaries, such as the Ushu River, Gabral River, Mankial River, Panjkora River, and Bahrain River, are associated with glaciers. During periods of high precipitation and snowmelt in their catchment areas, these rivers are prone to flooding. The Swat River Basin has an extensive drainage area of approximately 13,650 square kilometres, characterised by an elongated and irregular shape, with a mix of narrow and broad sections. This shape facilitates rapid runoff, particularly in the narrower upper regions, which contributes to the potential for flash floods downstream at critical points, such as Munda headwork.

In July and August 2010, significant precipitation ranging from 89 mm to 295 mm and from 42 mm to 179 mm, respectively, occurred, coinciding with the snowmelt season. The peak discharge at the Munda Headwork reached 225,000 cusecs on July 29, 2010, generating an estimated 609.7 million cubic meters of surface runoff, leading to substantial physical damage. From July to August 2022, the basin experienced heavy rainfall, ranging from 29.34 mm to 184.7 mm in July and from 115.17 mm to 311.09 mm in August, during the snowmelt season. The peak discharge at the Munda Headworks was 210,000 cusecs on August 26, 2022, resulting in 706,813,712.86 cubic meters (m^3) of surface runoff. The 2022 floods affected a larger area with frequent events, despite individual events being less intense than those in 2010.

The 2010 flood in the Swat River Basin was caused by intense rainfall over a short period, affecting smaller areas for several hours to a few days. In contrast, the 2022 flood resulted from prolonged high rainfall over three months, which covered a much larger area and led to widespread flooding. In 2020, the flood with a peak discharge of 49,706 cusecs on June 15, resulted in an exceptionally high surface runoff of 1.10 billion cubic meters, significantly influenced by the annual rainfall of 1317.48 mm.

Conclusion

This paper presents a comparison of the hydro-meteorological antecedents of the catastrophic floods in 2010 and 2022 of the Swat River Basin. The findings establish that, although both floods were caused by violent rainfall, the one that occurred in 2022 was significantly exacerbated by the rise in temperatures, accelerated glacial melt, and anthropogenic factors such as deforestation and poorly planned development. The research paper has shown that natural hazards are becoming a thing of the past due to the growing impact of climate change, especially in mountainous areas sensitive to climate change, such as Swat. Of significant interest is the intense rate of rainfall, overland flow, and river flow in 2022 compared to 2010. Moreover, LULC analysis using GIS indicates a worrying trend involving the declining coverage of forests and increasing coverage of built-up areas in flood-prone areas. Such modifications have reduced the inherent strength of the river basin, causing greater and more devastating flooding.

To sum up, the cases of flooding in the Swat region are likely to become more frequent and active in the future unless mitigation measures are implemented as soon as possible. Based on this study, more integrated, climate-wise, and community-driven flood risk management is required, which mainly focuses on ecological protection as well as strengthening of infrastructural reinforcements. Such action is necessary to avoid an increase in the socio-economic and environmental expenditure of future calamities.

Recommendations

As the results of the study can suggest, some critical recommendations can be used to reduce risks of possible future floods and improve climate resiliency within the Swat River Basin:

FWM: Integrated Watershed Management

Institute reforestation and soil stabilisation schemes in higher catchments where runoff velocities are high and where infiltration of water takes place. Reclaim deforested land and incorporate landslide bioengineering in the landslide-prone areas.

Use of land zoning and enforcement of regulations

Enforce rigorous land-use zoning in floodplains, particularly along riverbanks and tributaries. Stop developments in high-risk zones and require flood-resistant infrastructure on developments located in buffer zones.

Flood Forecasting and Early Warning Systems

Enhance early warning systems through real-time monitoring of rainfall and snowmelt by automated weather stations, Earth observation satellite information, and localised early warning systems. Enhance the channels of communication among meteorological and related agencies with communities.

Putting in place Flood Diversion and Segmentation Plans

Construct diversion channels and a flood retention basin to control water influx in specific areas, rather than as a single flood flow. This approach can slow and moderate downstream maximum discharge as compared to the 2022 entirely uncontrolled situation.

Hydraulic Infrastructural Design
Refresh older embankments, culverts, and bridges to make them suitable for capturing subsequent discharge levels. Invest in nature-based infrastructure, such as green buffers, bio-swales, and sediment retention structures.

Community building and awareness
Conduct awareness programs on flooding and train local people as volunteers in flood response and evacuation. Ensure that schools, community halls, or mosques are used as disaster information centres to make society prepared and resilient.

Regionalised expenditure control as well as researching
Equip local governments with localised flood action planning funds and tools, as well as flood modelling technology. Support such academic-policy partnerships to refine model-driven forecasts of rainfall, runoff, and glacial melt.

Responsive Urban Planning
Include climate risk analysis in municipal and regional development plans. Encourage green infrastructure, rooftop rain harvesting and permeable paving to limit urban surface runoff.

Tributaries and Cryospheric Areas Observation
Install flow meters and snow gauges in high-altitude Swat tributaries, such as Ushu, Gabral, Bahrain, and Panjkora, to forecast how much melt and snowpack runoff will feed into the main river.

Segmented strategy of Flood Management
Create a lead-time action plan on the crucial hours between the onset of rain and the peak of discharge. Such a segmentation can reduce the severity of flash floods and ensure the timely evacuation.

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